Proceedings from the Fifth International Symposium on Tunnel Safety and Security, New York, USA, March 14-16, 2012

Edited by Anders Lönnemark and Haukur Ingason

Volume 1
ABSTRACT

This report includes the Proceedings of the 5th International Symposium on Tunnel Safety and Security (ISTSS) held in New York, 14-16th of March, 2012. The Proceedings include 68 papers given by session speakers and 19 papers presenting posters exhibited at the Symposium. The papers were presented in 12 different sessions. Among them are Security, Explosions, Risk and Cost Benefit, Human Behaviour and Evacuation, Passive Fire Protection, Active Fire Protection, Ventilation, and Fire Dynamics.

Each day was opened by two invited Keynote Speakers addressing broad topics of pressing interest. The Keynote Speakers, selected as leaders in their field, consisted of Martin Brown, Transport of London, UK, Ricky Carvel, Edinburgh University, UK, William Connell, Parson Brinkerhoff, USA, William H. Arrington, U.S. Department of Homeland Security, USA, Peter Johnson, Arup, Australia and Marieke Martens, TNO, The Netherlands.
PREFACE

These proceedings include papers presented at the 5th International Symposium on Tunnel Safety and Security (ISTSS) held in New York 14-16th in March 2012. The success of the International Symposium on Tunnel Safety and Security is a tribute to the pressing need for continued international research and dialogue on these issues, in particular connected to complex infrastructure such as tunnels and tunnel networks. These proceedings provide an overview of emerging research and regulatory actions coupled to state-of-the-art knowledge in the field of safety and security in undergrounds structures.

We are very proud to have been able to establish this symposium which regularly attracts over 250 delegates from all parts of the world. This symposium represents an arena for researchers to discuss safety and security issues associated with complex underground transportation systems. The Symposium is unique in the sense that it is the only conference that combines safety and security issues and introduces separate security sessions focussed on underground facilities and their specific needs. The need for expertise in this field, is increasing and we feel confident that ISTSS will provide a leading forum for information exchange between researchers and engineers, regulators and the fire services and other stakeholders in the future.

In particular, we see that active fire protection has become a major field of interest. Further, risk and engineering analysis continues to be an area that attract many papers. Numerous renowned researchers and engineers have contributed to these and other topics at this symposium for which we are very thankful. Fire related issues still attract many presentations but the focus has shifted towards technical solutions that can mitigate the fire development should a fire occur. The enormous costs for underground structures forces engineers to design alternative solutions. The sessions that have greatest focus on mitigation of fire development include those dealing with the effects of ventilation systems, active and passive fire protection, fire fighting and human behaviour.

We received over 100 papers in response to our Call for Papers (not including our six invited Keynote Speakers) and believe that the quality of the papers is a testament to the calibre of research that is on-going around the world. Unfortunately, we were only able to accept 74 papers for presentations but have a strong poster session with 19 papers to canvas other interesting emerging research and an exhibit to allow producers to present their particular solutions. The selection process was carried out by a Scientific Committee, established for this symposium, consisting of many of the most well known researchers in this field (a list can be found on the Symposium website). We are grateful for their contribution to make this symposium as the leading one on fire and safety science in tunnels.

Finally, we would like to thank our Event Partners the National Infrastructure Institute Centre for Infrastructure Expertise (NI2CIE) and L-surf Services for their co-operation and help.

Haukur Ingason
Anders Lönnermark
TABLE OF CONTENTS

VOLUME 1

KEYNOTE SPEAKERS

Martin Brown, Transport for London (TfL), UK

Mitigation of Tunnel Fires
Ricky Carvel, University of Edinburgh, UK

Regulating Road Tunnel Fire Safety
William G. Connell, Parsons Brinkerhoff, USA

Risk Reduction for Today’s Critical Infrastructure

Fire Safety Engineering – a Tool in Tunnel Design
Peter Johnson, Arup, Australia

Human Behaviour in Tunnels
Marieke H. Martens, TNO, The Netherlands
Gunnar D. Jensen, SINTEF, Norway

ACTIVE FIRE PROTECTION; SUPRESSION SYSTEMS

Advantages of Electronically Controlled Sprinklers (ECS) for fire protection of tunnels
Sergey Kopylov, Russian Research Institute for Fire Protection, Russia
Leonid Tanklevskiy, Mikhail Vasilev and Varvara Zima, Gefest Enterprise Group, Russia,
Alexander Snegirev, St.-Petersburg State Polytechnic University, Russia

Benefit of Sprinkler Systems in Protection of Tunnel Structure from Fire
Bobby J. Melvin and Kenneth J. Harris, Parsons Brinckerhoff, USA

Water Mist Concept – Effective Choice for Improving Safety in Road Tunnels
Pasi Vuolle, Marioff Corporation Oy, Finland

Automatic sprinkler system in tunnel fires
Ying Zhen Li and Haukur Ingason, SP Technical Research Institute of Sweden

A study of the interactions between a water suppression system and a longitudinal ventilation system in a tunnel
Yoon Ko and George Hadjisophocleous, Carleton University, Canada

ACTIVE FIRE PROTECTION; DETECTION & SUPRESSION

Automated Fire Detection and Mitigation in Railway Tunnels Designed for Freight Trains
Frank de Vries, Covalent Infra Technology Solutions BV, The Netherlands
### Gas Analytics for the Early Detection of Fires in Road Tunnels
Maximilian Wietek, VSH Hagerbach Test Gallery Ltd., Switzerland
Christian Berweger, Xirrus GmbH, Switzerland
Christian Lämmle, Combustion and flow solutions GmbH, Switzerland

Gas Analytics for the Early Detection of Fires in Road Tunnels

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>141</td>
</tr>
</tbody>
</table>

### CFD-based Assessment of Fixed Fire-Fighting Systems in Tunnels
Xavier Ponticq, CETU (Tunnels Study Centre), France

CFD-based Assessment of Fixed Fire-Fighting Systems in Tunnels

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>147</td>
</tr>
</tbody>
</table>

### Design & Functional Safety

**An Integrated Functional Design Approach for Safety Related Tunnel Processes**

An Integrated Functional Design Approach for Safety Related Tunnel Processes

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>167</td>
</tr>
</tbody>
</table>

**The Stockholm Bypass – Enhanced Design and Interaction Between Safety Systems**
Leif Eklöf and Ulf Lundström, Swedish Transport Administration, Sweden
Henric Modig and Bo Wahlström, Faveo Projektledning AB, Sweden

The Stockholm Bypass – Enhanced Design and Interaction Between Safety Systems

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>177</td>
</tr>
</tbody>
</table>

**Decision Support to Determine Safe Tunnel Availability**
Diderick Oerlemans, Covalent Infra Technology Solutions, The Netherlands

Decision Support to Determine Safe Tunnel Availability

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>185</td>
</tr>
</tbody>
</table>

**Problems with Tunnel Safety Systems**
Gary English, City of Seattle Fire Department, USA

Problems with Tunnel Safety Systems

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>193</td>
</tr>
</tbody>
</table>

### Explosions

**Protective Design Guideline of Tunnels**
Sunghoon Choi, Parsons Brinckerhoff, New York, USA

Protective Design Guideline of Tunnels

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>203</td>
</tr>
</tbody>
</table>

**Design Loads and Methods for Prestressed Open Cut Tunnels under Severe Accidental and Malicious Threats – Explosions**
Assad Nawabi, Andreas Bach and Ingo Müllers, Schüller-Plan Ingenieurgesellschaft mbH, Germany and BRS-Design, Germany
Alexander Stolz, Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, Germany and BRS-Design, Germany
Markus Nöldgen, Cologne University of Applied Science, CUAS, Germany

Design Loads and Methods for Prestressed Open Cut Tunnels under Severe Accidental and Malicious Threats – Explosions

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>213</td>
</tr>
</tbody>
</table>

**Rescue Operations in Underground Mass Transport Systems at Fires and Deliberate Attacks**
Mia Kumm, Mälardalen University, Sweden
Anders Palm, Mälardalen University, Sweden and Greater Stockholm Fire Brigade, Sweden

Rescue Operations in Underground Mass Transport Systems at Fires and Deliberate Attacks

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>223</td>
</tr>
</tbody>
</table>

**Studies of Explosions Occurring in a Metro Carriage in a Tunnel**
Gero Meyer, Mälardalen University, Sweden
Anders Bryntse, Swedish Defence Research Agency, Sweden
Bo Janzon, Mälardalen University, Sweden

Studies of Explosions Occurring in a Metro Carriage in a Tunnel

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>233</td>
</tr>
</tbody>
</table>
SECURITY

Safety and Security of Underground Infrastructure – New Concepts for Evaluating and Mitigating Risks of Tunnels

Goetz Vollmann and Markus Thewes, Ruhr University Bochum, Institute for Tunnelling and Construction management, Germany

Frank Heimbecher, Federal Highway Research Institute, Germany

Influence of Different Tunnel Ventilation Systems on the Dispersion of Light and Heavy Gases due to Car Accidents

Marion Meinert, Muenster University of Applied Science, Germany

Wolfram Klingsch, University of Wuppertal, Germany

Identification of Critical Tunnels in a Road Network

Ingo Kaundinya and Frank Heimbecher, Federal Highway Research Institute, Germany

SAFETY AND REGULATORY FRAMEWORK

Some of the NFPA 130 Improvements Proposed for the 2014 Edition

Harold L. Levitt, the Port Authority of New York & New Jersey (PANYNJ), USA

William D. Kennedy, Parsons Brinckerhoff, USA

Safety of Dutch Tunnels Guaranteed by Standard Approach

Hans A. Ruijter and Fred Bouwmeester, Directorate General of Public Works and Water Management (Rijkswaterstaat), The Netherlands.

Current Practice of Fire Design for Road & Rail Tunnels in Austria

Johannes Wageneder, GEOCONSULT Wien ZT GmbH, Austria

A North-American Approach to the Refurbishing of Existing Tunnels Based on European Specific Hazard Investigations

Hubert Dubois, CIMA+ Consulting Engineers, CANADA

VENTILATION

Some Effects on Natural Ventilation System for Subway Tunnel Fires

Ahmed Kashef, Institute for Research in Construction, National Research Council, Canada

Zhongyuan Yuan and Bo Lei, School of Mechanical Engineering, Southwest Jiaotong University, China

External conditions have a significant impact on the air flow in tunnels using transverse ventilation for smoke extraction.

Jonas Andersson, City of Stockholm Traffic Administration, Sweden

Anders Lönermark, SP Technical Research Institute of Sweden

Dynamics of Natural Air Flow Inside Subway Tunnels

Markus Brüne, Andreas Pflitsch, Ruhr-University of Bochum, Germany

Brian Agnew, University of Northumbria, Newcastle upon Tyne, United Kingdom

Jonathan Spiegel, Ruhr-University of Bochum, Germany
Multiscale Modelling of Fire Emergencies in a Transverse Ventilated Tunnel
Francesco Colella, Adriano Sciacovelli, Vittorio Verda, Romano Borchiellini,
DENERG, Politecnico di Torino, Italy
Guillermo Rein, Ricky Carvel, BRE Centre for Fire Safety Engineering, University of
Edinburgh, UK

Design Fires in Road Tunnels & the Impact on Ventilation Systems
Norman Rhodes, Kirit Kottam and David Hartman, Hatch Mott MacDonald,
USA

Theoretical Analysis on Longitudinal Tunnel Ventilation in Fire Emergency
Qihui Zhang, Attilio Canfora, Eugenio Trussoni, Giuseppe Astore, Shulin Xu and
Piergiorgio Grasso, GEODATA Engineering SpA, Italy

The Influence of Blockages on Backlayering in Tunnel Fires: A Numerical Study
Ricky Carvel, David Bishop & Stephen Welch, University of Edinburgh, UK

Design, Simulations and Implementation of Ventilation System for Metro Line 9, at Barcelona
City in Spain
Ana M. Ruiz-Jimenez & A. Matas, TD&T S.L., Spain

The Dynamics of Tunnel Ventilation and Fire Development
Yajue Wu, Sheffield University, UK

The Importance of Exit Spacing to the Choice of Tunnel Ventilation System
Paul Williams, Norman Disney & Young, New Zealand
VOLUME 2

FIRE DYNAMICS

Rickard Hansen, Mälardalen University, Sweden

Large Scale Fire Tests for the “Calle 30 Project”
Fernández, S., FFII - CEMIM. Madrid, Spain.
Del Rey, I., ETSII-Universidad Politécnica de Madrid, Spain
Grande, A., Espinosa, I., FFII - CEMIM. Madrid, Spain
Alarcón, E., ETSII-Universidad Politécnica de Madrid, Spain

Experimental Study on Burning Rate in a Full-Scale Train Model
Shaohua Mao, Yuanzhou Li, Haobo Wang, Shi Zhu, Ran Huo, University of Science and Technology of China, China,

Large-scale Commuter Train Fire Tests – Results from the METRO Project
Anders Lönnermark, Johan Lindström, Ying Zhen Li and Haukur Ingason, SP Technical Research Institute of Sweden, Sweden
Mia Kumm, Mälardalen University, Sweden

Full-scale Experiments for Heat Release Rate Measurements of Railcar Fires
George Hadjisophocleous, Carleton University, Canada
Duck Hee Lee and Won Hee Park, Korea Railroad Research Institute, Korea

RISK & COST BENEFIT ANALYSIS

On Bayesian Probabilistic Networks for Risk Analysis of Road Tunnels
Rune Brandt, HBI Haerter, Switzerland
Niels Peter Høj, HOJ Consulting, Switzerland
Matthias Schubert, Matrisk, Switzerland

Assessment model for the transport of dangerous goods through road tunnels
Mirjam Nelisse and Ton Vrouwenvelder, TNO, the Netherlands

Fire Ventilation Upgrades: Can a retrofit be detrimental to Fire Life Safety?
Sam Hoffman, Daniel McKinney and Bruce Dandie, AECOM Technical Services, Inc., USA

Risk Framework – Methodology for Tunnel
Jimmy Jönsson, Arup Fire, Spain
Peter Johnson, Arup Fire, Australia

Fixed Fire Fighting Systems for Tunnels – SOLIT2 Research Project
Max Lakkonen, FOGTEC Fire Protection, Germany

Effectiveness Analysis of a Fire Detection System Config-ured as a Multi-Function Portal Aimed at Protecting Railway Tunnels
Marco Cigolini, RFI spa, Italy
Risk-based Evaluation of Longitudinal Ventilation with Enhanced Safety Concept
Göran Nygren, Johan Lundin and Per-Olof Jönsson, WSP, Sweden

Assessing Fire Development Risk in Rail Vehicles and the Impacts on Tunnel Infrastructure
Jarrod Alston & Kurt Schebel, Arup, USA
Brian Meacham, Worcester Polytechnic Institute, USA
Andrew Coles, Sereca, Canada

Optimization of Measures Directed on the People Safety at Tunnel Fire by Means of Computational Methods
Karpov A.V., Khasanov I.R., Kopylov N.P., Ushakov D.V., All-Russian Research Institute For Fire Protection (VNIIPo), Russia

DECISION SUPPORT & OPERATION

Decision Support System for Emergencies in Road Tunnels
Jorge A. Capote, Daniel Alvear, Orlando Abreu, Arturo Cuesta, Virginia Alonso, University of Cantabria, Spain

Brisbane’s Busway Network – Twelve Years of Designing and Operating Safe Tunnels
Nick Agnew, Stacey Agnew Pty Ltd, Australia
Matthew Bilson, Parsons Brinckerhoff, Australia
Ray Donato, Donato Consultancy, Australia

The Use of Traffic Flow Predictions to Enhance Tunnel Safety
Tomas Julner, Swedish Transport Administration, Sweden

Safety in Swedish Railway Tunnels
Per Vedin and Peter Lundman, Swedish Transport Administration, Sweden

On the Power of Simulation and the Need for Experimental Validation
Marco Bettelini, Amberg Engineering Ltd., Switzerland
Max Wietek, VSH Hagerbach Test Gallery Ltd., Switzerland

DESIGN FIRES

New Concept for Design Fires in Tunnels
Haukur Ingason, Ying Zhen Li, SP Technical Research Institute of Sweden, Sweden

Fine Water Spray Tunnel Fire Protection from Fixed Installed Systems
Carsten Palle, VID Fire-Kill, Denmark

HUMAN BEHAVIOUR & EVACUATION

Taking Advantage of Theories and Models on Human Behaviour in the Fire Safety Design of Underground Transportation Systems
Karl Fridolf, Daniel Nilsson and Håkan Frantzich, Lund University, Sweden

Ways of Improvements in Quantitative Risk Analyses by Application of a Linear Evacuation Module and Interpolation Strategies
Christoph Forster, Bernhard Kohl, ILF Consulting Engineers, Austria
Topic E - ERRA A5: Evacuation of a complex underground facility
Maximilian Wietek, VSH Hagerbach Test Gallery Ltd., Switzerland
Jonatan Hugosson, SP Technical Research Institute of Sweden, Sweden
Frank Leismann, STUVA, Germany
Fabien Fouillen, INERIS, France

Design of Voice Alarm Systems for Traffic Tunnels: Optimisation of Speech Intelligibility
Evert Start, Duran Audio BV, The Netherlands

Emergency Escape and Evacuation Simulation in Rail Tunnels
Marco Bettelini & Samuel Rigert, Amberg Engineering Ltd., Switzerland

Experiment for Behavior Estimation in the Egress Using Electronic Devices in the SAVE ME Project
Stefano Marsella, Corpo Nazionale dei Vigili del Fuoco, Italy
Jan-Paul Leuteritz, University of Stuttgart, Germany
Francesco Tesauri, University of Modena and Reggio Emilia, Italy
Uberto Delprato, IES Solutions, Italy

French Initiative to Implement PIARC’s Recommendations Regarding HGV Driver Training in France
Marc Tesson, Véronique Aurand & Bertrand Perrin, CETU, France

PASSIVE FIRE PROTECTION

Quantification of Fire Damage of Concrete for Tunnel Applications
Joakim Albrektsson, Robert Jansson, Mathias Flansbjer, SP Technical Research Institute of Sweden, Sweden
Jan Erik Lindqvist, CBI Swedish Cement and Concrete Research Institute, Sweden

Submerged Floating Tunnels, a New Tunnel Concept, Creating New Challenges in Tunnel Safety and Security
Lidvard Skorpa, Norwegian Public Roads Administration, Norway

Mobile Furnace for Determining Spalling Sensitivity of Existing Concrete Tunnel Linings
Martin Vermeer, Arnoud Breunese & Leander Noordijk, Efectis Nederland BV, The Netherlands

Temperature Loads and Passive Protection in Structural Tunnels
Stefan Zmigrodzki, CIMA+ Consulting Engineers, Canada

Test Methods for Determining Fire Spalling of Concrete
Lars Boström, Robert Jansson, SP Technical Research Institute of Sweden, Sweden

Assessing the Fire Resistance in Existing Tunnels
Leander Noordijk, Tim van der Waart & George Scholten, Efectis Nederland BV, The Netherlands
Coen van der Vliet, ARCADIS Nederland BV, The Netherlands
POSTERS

Rockdrain – a Novel System for Water Drainage, Insulation and Fire Protection for Tunnels
Lars Boström, SP Technical Research Institute of Sweden, Sweden
Robert Melander, Cathrine Ewertson, CBI Swedish Cement and Research Institute, Sweden

Crossrail Fire Safety Designs
Iain Bowman, David Eckford & Holy Liang, Mott Macdonald Limited, United Kingdom

Automatic Fire Suppression in Tunnels with Stationary Compressed Air Foam Extinguishing Systems (CAFS)
Axel Jaeger, Thorsten Behnke & Franziska Freudenberger, One Seven of Germany GmbH, Germany

Concept of Cost Effective Modernization of Old Single-tube Road Tunnels
Case Study: Učka Tunnel
Miodrag Drakulić, Mladen Lozica, CTP PROJEKT Ltd. Croatia

Carmel Tunnels – Case Study and project profile
Fire alarm & voice evacuation system
Eliezer Ezra, G4S, Israel

Analysis of Tunnel Fires over Twenty Years
Peter Schenkenhofer, LISTEC GmbH, Germany

FFFS for Flammable Liquid Fires in Road Tunnels
Kenneth J. Harris & Bobby J. Melvin, Parsons Brinckerhoff, USA

Commissioning of Performance Based Fire Systems
Charles Kilfoil, USA

Prediction of the Temperature Evolution in a Tunnel Construction in Case of Fire, by Coupling the Temperature-Dependent Heat Transfer Mechanisms Inside the Structural Components and at their Surface
Christian Knaust, Andreas Rogge, BAM Federal Institute for Materials Research and Testing, Germany

Active Open-Area Smoke Imaging Detection
Ron Knox, Xtralis, Australia

Emergency Egress Corridor Evacuation Analysis –Virginia Elizabeth River Midtown Tunnel
Praveen Kumar & Norris Harvey, Parsons Brinckerhoff, USA

Continuous Emergency Egress Corridor Pressurization Along a Tunnel Ventilated by Jet Fans
Andrew Louie, Norris Harvey, Parsons Brinckerhoff, USA

Design Loads and Methods for Prestressed Open Cut Tunnels under Severe Accidental and Malicious Threats –Fire
Frank Lukasched, Ingo Müllers, Assad Nawabi; Schüßler-Plan Ingenieurgesellschaft mbH, Germany, BRS-Design, Germany
Markus Nöldgen, Cologne University of Applied Science, CUAS, Germany
Numerical Predictions of Blast Waves Caused by Accidental or Intentional Detonations of Gaseous and Condensed Explosives in 3D Complex Geometries.
Christophe Matignon, Jean-Yves Vinçon, CEA, DAM, DIF, France
Sébastien Eveillard, CEA, DAM, DIF, France, PNRI, France

Model Scale Fire Tests in a Highly Inclined Tunnel
Hans Nyman, Brandskyddslaget, Sweden
Haukur Ingason, SP Technical Research Institute of Sweden, Sweden

Challenges and Consequences in Designing for Underground Station Fire Events in the Post 9/11 World
Marc Morgan, & Ian Ong, Hatch Mott MacDonald, USA
Thomas Eng, Los Angeles County Metro, USA

Design, Simulations and Implementation of Ventilation System for Metro Line 12 at Mexico D.F.
Ana M. Ruiz-Jimenez & E. Barrio, TD&T S.L., Spain

Fire Resistance of Smoke Control Air Outlets in Tunnel Constructions
Nikolay D. Solntsev, Boris B. Serkov, Academy of the Ministry of the Russian Federation for Civil Defence, Emergency Management and Natural Disasters Response, Russia

Towards 1D/3D Coupling for Fire and Ventilation Modelling in Large Underground Infrastructures?
Benjamin Truchot, Stéphane Duplantier, INERIS, France
Security in action: a measured management approach

Martin Brown
Head of Health, Safety and Environment, Rail and Corporate,
Transport for London (TfL), London UK

ABSTRACT

Transport for London (TfL) has practical experience of security threats, from our past, now in the present, and as we prepare for the Olympics, looking into the future. Key to managing the security risk is creating the right culture, one that supports the deployment of a measured framework, the maintenance of a balanced but targeted approach, and one which ensure action is always driven by a proper understanding of the current risks. This paper provides an outline of such an integrated approach, building on a model put forward by Centre for the Protection of National Infrastructure (CPNI), the UK agency responsible for the security of our national critical infrastructure. Some real life examples are also included; these are not all from TfL, but are all things the author has been involved in.

Keywords: Security; Management; Risk.

Introduction

I am sure most people are aware of Isaac Newton’s 3rd Law: ‘The mutual forces of action and reaction between two bodies are equal, opposite and collinear’, often more simply put as: ‘to every action there is always opposed an equal reaction’. This law has great resonance to security today. If we are to manage security effectively we need to know the forces out there, and we need to know what is needed to combat them, in a measured and targeted way. What we do not need is an over-reaction, something that is counterproductive and expensive.

To be effective in managing security, we must understand the nature of the threats, the benefits of the counter measures, and have a systematic way in dealing with this. We prepare for the worst, even if in most cases we experience something significantly more positive. Managing security is extremely hard to get right; decisions on how much resource to devote and how it will be deployed are very challenging. It can be easy to get the resource balance wrong, to devote significant resources when the risks are in reality low; yet it genuinely only takes one person to breach the security framework and controls put in place for significant damage to be done. As with much in business life the approach is about the deployment of good management systems, lead at a senior level, with specialist support to ensure that as the threats change, so do the approaches are re-evaluated and redefined to maintain effect.

Security can too simply be thought of as referring to acts of terrorism, in particular with reference to transport systems, however I will consider security in a wider manner. Threats can occur at many levels; impacts on the electronic control systems, damage to physical assets, criminal activity such as fraud, identity theft, and the threat come from outside the organisation or from insiders, impacting not just the organisations we work in, but suppliers and others.

The context in which we operate is important too. Those who work around iconic targets, know security threats to these targets attract greater publicity, and in the transport sector this is made even more of a challenge as it is essentially an open access system. Transport for London (TfL) is the transport authority for London, UK. TfL is responsible for a wide range of transport modes, including the Buses, Underground and some of the Overground Rail systems, the major Road networks, river
services, private hire and taxis, cycle hire, special transport services for the disabled and walking schemes. Some of the services are directly delivered by TFL employees, some are delivered by private sector contractors. TFL employs about 25,000 people direct, and our contractors employ about the same number of staff. There are about 3.5 bn journeys made every year on the system. And during the Olympics and Para Olympics this year, some parts of our network will see passenger numbers rise by three times. By any measure this is a busy transport system, with the potential for security threats. TFL has suffered significant terrorist attacks, such as the bombings on 7th July 2005 [1], so we have relevant experience. We are well aware that others have seen even worse, but our experience has led to real changes in our approach. Much of what follows derives from that learning.

This paper draws much from guidance produced by the Centre for the Protection of the National Infrastructure (CPNI), which TFL has contributed to. The approach is based on an assessment of the risks, a disciplined framework for targeting measures against these risks, and ways of checking that the approaches are working. The deployment of the framework requires an effective, senior management lead organisational security culture. There will be differences in the way this approach can be applied in different countries, with different laws, approaches to civil liberty, different roles of the police and security services, and of course differences in the actual threats themselves, but the basic approach should be generally applicable.

What is CPNI?

CPNI is the UK organisation which provides security advice for the critical national infrastructure. It is the United Kingdom government authority that provides protective security advice to businesses and organisations across the UK national infrastructure. CPNI advice aims to reduce the vulnerability of the national infrastructure to terrorism and other threats, keeping the UK's essential services safer. It sponsors research and works in partnership with academia, government partners (including the UK Security Service, CESG - the Information Assurance arm of GCHQ - and departments responsible for national infrastructure sectors), research institutions and the private sector, to develop best practice guidance. CPNI also has special access to intelligence and information about threats to national security. It is involved in providing protective security advice for the London 2012 Olympics. In 2010 CPNI published a framework for managing the security space [2]. The framework is set out in Figure 1 below:
The guidance sets out a logical cycle, which reinforces good practice. While the focus is the terrorism threat, the guidance has relevance to all security issues. Each of the major components of the cycle are explained in the following text:

1) Information

The starting point for effective control of security risks is a clear understanding of these risks. We must understand what we are facing, how much of the risks may actually affect us, and how we can control them.

1a) Identify the threats

The starting point is to be very clear about what the threats that you face are. Identify existing and potential vulnerabilities and the impact of any security breaches. Analyse the direct threats to the business, understand who might want to harm the business, and why, and the situations where harm from indirect impact caused by other businesses, including events in other countries impacting supply, can damage you. The list is what defines your risks.

Help exists at local level through business networks and police; in the UK this means UK Counter Terrorism Security Advisors (CTSA), but there will be equivalents in other countries. Utilise contacts with local business groups/Chambers of Commerce. The CTSAs are part of the National Counter Terrorism Security Office (NaCTSO), a police unit co-located within CPNI. NaCTSO contributes to the UK government’s counter terrorism strategy (CONTEST) by supporting the Protect and Prepare strands of the strategy. NaCTSO counter terrorism and security work is divided into three areas:

- Protection of crowded places;
- Protection of hazardous sites and dangerous substances; and
- Assisting the CPNI to protect the Critical National Infrastructure.

The core role of all CTSAs is to identify and assess local critical sites within their force area, that may be vulnerable to terrorist or extremist attack, and to devise and develop appropriate protective security plans to minimise impact on that site and the surrounding community. They promote awareness of the terrorism threat and develop positive on-going relationships with the local business community, partner agencies and site owners to encourage a co-ordinated approach.
At a national level we use CPNI with whom we maintain regular contact, watching for the national (and in some cases international) level picture, the Royal United Services Institution an independent British think tank engaged in defence and security research. But the key is to seek help from all you can.

This is not a one off exercise, as things continually change. Examples of new challenges we have had to accommodate in the last couple of years include increasing impacts from software borne viruses, and problems across our transport network from metal theft.

1b) Determine the priorities for protection

The next step is to determine what the priorities for action are. It is not possible to cover everything, but it is vital to understand the key vulnerabilities, so resource decisions can be made. Your review should look at people, assets, information and processes. It is important to consider both the current set up and possible future ones. And also look back to the old ways of doing things, as old ways may cloak ingrained vulnerabilities.

Where new developments are taking place ensure that security requirements are considered right from the planning stage. This is particularly important where security needs to be looked at afresh, and where it can engage new players. It is of course also cheaper to do at the planning stage than to retrofit. When Heathrow Terminal 4 (and later with T5) was being planned, virtual reality models were developed so specialist contractors were able to view the proposed airport in operation, and assist in redesigns that optimised service provision and saved millions of £s. Decide which are the high value/unique or hard to replace assets, so these can be prioritised.

In the past, much of the work looking at security was the domain of security experts, and those with specialist knowledge do add greatly. Increasingly security is a more general management task, supported by experts and benefiting from involvement of those who actually do the day to day work. Involving staff reinforces the fact that you are taking them seriously.

As the security targets change and the threat alters, it is important to keep asking if the current approach is still good enough. As your operation changes, are the controls still proportionate? Work with your supply chain, are you and they clear where the threats may come from? Undertake such reviews periodically. Be honest.

1c) Risk Assessment

Once the priorities are clear, the next stage is to provide the sense of proportion that comes from conducting a risk assessment, highlighting which of the threats the organisation might actually face, what their likelihood is, and what the impacts/consequences will be. The nature of security threats means it is particularly important to look at the really high consequence events, some of which may be realised for the first time. This may give rise to new work that had not before been considered. Within TfL our regular reviews have led to major changes of approach and engineering work to combat possible threats. But not all threats are so major.

2) Protective security

Once it has become clear what the security threats are, the control systems currently in place to prevent and protect can be reviewed as to current effectiveness, and decisions made as to where additional measures need to be developed and deployed.

2a) Getting the physical controls and housekeeping basics right
The actual physical measures to be deployed will depend on the risk and the nature of the work, but the following gives a flavour of the list from which you might pick:

- Design security into buildings from the start; where buildings are older review how they can be improved;
- Where possible, control the parking of unauthorised vehicles, keeping them away from sensitive buildings, consider remote car parking;
- Periodic vehicle searches on site, and when entering and leaving do deter, but ensure they are thorough;
- Keep access points to a minimum and issue staff and visitors with passes - encourage staff to challenge those they do not know;
- Install appropriate measures such as boundary controls, intruder alarms, locks, alarms, CCTV and IR surveillance for personnel and vehicle detection; ensure they are properly used;
- Install complementary lighting and glazing protection; with particularly sensitive locations you may even consider blast protection;
- Ensure maintenance of site’s security systems as a priority;
- Control the issue of keys, decide which doors are to be secure, enforce this;
- Ensure storage areas at kept under surveillance, and that things can’t be hidden there;
- Decide what information is to be securely controlled, and who and what type of access is permitted to IT and IT control system;
- Consider appropriate mail-handling procedures, with clear rules for suspicious items;
- Have phone procedures for hoax calls.

Every one of these elements has been deployed in the working environment within TfL in the last few years. The list as written is more appropriate to fixed buildings such as our stations, depots and offices, but the same approach has been used to consider the interaction of our trains, trams and buses, and river craft with our infrastructure, including our tunnels.

The approach has shown success in deterring graffiti attacks, detecting unauthorised people working on our sites, preventing fly-tipping and theft. We have also utilised these controls during construction to ensure trespassers cannot enter our sites and steal or place any suspect devices. My father, a land surveyor, always maintained you could get anywhere with a clipboard and a roll of plans, and this still has a ring of truth. Creating the assumption of challenge is important. Periodically check that systems work, we do using anonymous tests.

Do not only think about the things that go wrong. Understand the things that go right. We have developed an approach that describes our security baseline, looking as much at what we have in place that works as what we may need to enhance. Having this balanced document gives confidence that we are achieving our goals, it prevents any complacency, and provides clear direction for appropriate enhancement. Emphasising the positive make the few additional elements seem simpler, and enables the necessary changes to be more easily embraced; had only the new work/negatives been highlighted, such changes could appear far more daunting.

2b) Information security

Information security has become increasingly important as our personal lives and business processes have become more reliant on digital systems. The number of digital technology touch points is considerable, and many of these have security implications. Where such systems have links to the internet the potential risk grows further. Information is a valuable asset and needs to be managed as any other asset. It has a value to those wishing to breach our security controls, and any loss of its integrity can be catastrophic. It is perhaps in this area of security threats where we still need to do the most work to join up the dots.
The hazards include introduction of Malware (often via e-mail and unchecked portable storage devices), Hacking by IT ‘experts’, Phishing through false official elements, Denial of Service events (such as recent protest against the proposed United States privacy laws), so called zombie attacks such as the Stuxnet virus; all things we have had to combat in TfL. Viruses may initially do no more than slow down information systems, but in time they can paralyse through data overload, and lead to shut down. The limited penetration we have experienced shows the success of our systems, but as the attacks become more sophisticated so must we.

There is a dilemma for us all in how we handle information, as it hinges on trust and transparency. Not everyone will realise the importance of the data we hold; we may not want everyone to know. But if they do not have sufficient knowledge to understand the importance of the rules, they may be less likely to be as careful as we wish. On the other hand, where the value of the data is made clear, there may be fears that this may give rise to possible criminal activity. With small, easy to hide storage devices able to hold so much data, it is easy to take data away. I am aware of one individual who has twice downloaded all the personnel records from the company that individual was working for, and made financial gains from selling the data to others. The first time it was hushed up, but after the second, legal action was taken.

Of course it is not just electronic data that we must take care of, we still rely in many cases on paper systems, which must also be controlled. Some of the material that businesses routinely throw away can be of use to a variety of groups including business competitors, identity thieves, criminals and terrorists. Staff names and addresses, telephone numbers, product information, technical specifications etc. can all be of value to such people. Be clear in defining the levels of security required and security-mark documents accordingly; keep defined sensitive data secure; remove papers off desks at the end of the day; deploy security shredding and confidential waste procedures; do not allowing secure documents to leave the workplace, so they cannot then be accidently lost; reduce access to personal data to reduce identity theft; check old IT equipment (obsolete laptops, old media disks, flash drives and so on) for data cleansing before disposal.

2c) Personnel security

Most security issues involve people, either as perpetrators or victims, so it is not surprising that personnel are a key part of the framework. The people threat may come from inside or outside the organisation, it may be the result of an error or a malicious act, it may have minor implications or major consequences, and of course people being hurt can be the result.

To maintain security as a core value, it must be emphasised from the outset of the employment process. Basic level checks on staff at recruitment are important. In UK we check that people have the right to work in the country (usually via a passport), we normally check past work history and work /employment background, in some cases we do police and financial checks. Sometimes checks on oversees employment are undertaken. We look for gaps in the employment records, especially where people have visited certain locations. If we use employment agencies for campaigns, we expect them to follow the same approaches.

In UK transport, our approach has been developed following a review into Airport Security, in particular looking at the insider threat [3]. We have evolved an approach based on the risks as related to the role. We look at the security impact the role can have, and the access that the role permits, and use this to decide the levels of checks needed. Once staff are employed, we look at their performance and any changes in their behaviour. When people are promoted, or move to more sensitive posts we look again.

Where an insider threat appears a possibility, dealing with this can be very sensitive. We had an employee who went on an extended break to an area of potential terrorist activity, and then submitted a request for further time out there. The employee held an important post, with access to potentially sensitive data about our transport system, and had remote access. The person was well liked and
colleagues did not believe there could be a problem. But the requests for more time included papers we believed to be forgeries, and questions were evaded about their return. The behaviour was challenged and in the end they handed in their notice.

We can struggle to believe that any of our colleagues could be a security threat, or that they would do anything to threaten security, or be threatened. Once I carried out a thorough search of one of the offices I worked in, and found restricted documentation on open desks, alcohol hidden in desks (we did not let any in our offices), digital storage devices lying around, personal credit cards, money, personal documents that would have provided enough for identification (ID) theft. I produced a report for my Managing Director, with recommendations on how we should tighten up the levels of security. He refused to believe any of the findings were a problem. He may have been right, in this case the risks were small, but getting the message across that security needs constant vigilance is a challenge for us all. Lead from the top, make it personal, and ensure that security concerns and breaches are properly followed up.

And finally beware of requests for data. There are many countries that have some form of freedom of information (FOI), allowing persons to obtain information on request, especially from public bodies. But we recently found we were being asked almost weekly under FOI for ever more detailed information about the signal and control systems of a new railway under construction, we became suspicious and stopped the flow, the requests stopped too.

3) Response planning

There will be situations where the controls have not worked fully, and there is some form of security incident. It is therefore important to have plans in place setting out how you will react.

3a) Plan and rehearse business continuity

Perhaps it is obvious, but planning how you get back into operation as soon as possible after an event, is a vital part of managing the risks. Again, this requires understanding of what the security risks are to your business, knowing who are the key people, what are the core processes, controls and equipment, and understanding which third parties and suppliers are critical. Triggers need to be in place to enable the operation to be back up running in say 24 hrs, 48 hrs, 5 days, so an understanding of the costs and logistics, how quickly responses can be rolled out, what systems need duplicating and to be backed up, where such back ups will be, and how people will be kept informed is what matters. All this needs to be practiced, with the key players being part of this. Over time the practices need to explore different scenarios. Business contracts may be needed to define recovery levels.

Some things will be new, and you won’t have anticipated them, and must make real time decisions. For example when the 7/7 bombings occurred in London, we occupied an office in the Canary Wharf area of London. Because of fears of further explosive devices, the area was in effect locked down. It looked like we could not get off the Wharf, and might have to stay the night there. But when we tried to find hotel rooms, we found that they had all gone, the banks had been far quicker off the mark than we had. In fact things eased, but this led subsequently to quite different contingency arrangements. During the same event we realised we did not know whether to keep the window blinds up or down in our office. This may seem minor, but became of the increasing concern of another device, we needed to consider was it better to provide some (albeit limited) blast protection in case of another device exploding nearby, or did leaving the blinds down scare people as they could not see out. In the end we raised them.

3b) Incident response

The nature of the response to incidents obviously depends on what has occurred, and includes short, medium and long term activities. At present UK railways are suffering from significant metal theft.
We are deploying immediate measures greater visual and physical security, we have medium term plans to change the legislative structure, and longer term we are looking to make the cable harder to remove and easier to detect when removed.

When dealing with more significant incidents, procedures will include specialist incident command structures, deployment of incident centres and help points, detailed communication systems, incident investigation and system recovery teams with links to security and emergency services. There is no perfect blueprint, and the way an incident is recovered will depend on the experience and competence of staff. But developing responses through table top simulations and other practice exercises makes a big difference. Such planning and practising is a significant part of the current Olympic preparations in London.

Not all security incidents will be major ones, and as we need to be able to deal with the full range, there are a number of elements we need to have in place. An obvious pre-requisite, though not always actually in place, is a culture that encourages reporting security related incidents, with an attached blame free assumption. With the major events, such reporting is well managed and detailed, there are high expectations of lessons being learned. With smaller security lapses this may not be the case. But this is a problem in the making; such small lapses may become regular behaviour, from which larger scale problems can occur.

Once an event has been reported, some form of follow up is needed to recover the normal operations. This will depend on the event. But perhaps more important is to conduct an investigation or review. This needs to be fact based, comparing what was supposed to happen with what did, looking to acknowledge what went well and provide suggestions for improvement. The challenge is to make this transparent. Often local managers don’t want to admit that lapses have occurred, for fear of personal criticism. Yet if there are to be lessons across the organisation open explanations must occur. Eventually senior management will also become engaged, but make this proportionate too; senior managers need assurance that improvement is taking place, engaging to emphasise the importance while enhancing trust.

3c) Communications plan

When incidents do occur there are likely to be communication difficulties and information gaps. With major security alerts it is possible that there will be rehearsed protocols put into place by the security services, including information and phone service lock down with no media response. This happened in London after 7/7, and meant there were real problems in communicating to families, staff and stakeholders for some time. The protocols we had in place had to be revised and a range of alternative methods used until the system returned.

In the new world of social media, information will often get round much quicker than it would have in the past. Some of the information will be useful, some will be wrong or ill informed, some will help, some hinder. But this means that the information that is disseminated from official sources must be even more accurate, or it will not be able to overcome the electronic spread of rumour. It can make sense to have prepared press releases and notes for a range of situations available, but in the end the facts will determine what is used.

In most cases there are no such technical barriers to communication. What connects both the minor lapses and major events is that no communication system can work unless the data is accurate and balanced. Facts must be collected, checked and only then passed on.

Maintaining an up to date contact list is important so everyone can be accounted for and relatives kept informed. Out of hours message cascades through management chains should be maintained up to date, and regularly tested.
Communication after more significant events to external stakeholders is important. These may include politicians, shareholders, emergency contacts and main utilities, and suppliers, contractors and families. The approach needs to be developed, and again rehearsed. The reactive demands can be high and allocating dedicated resource to managing can pay dividends. Different methods may be used for the different groups, and different management teams may be deployed for different types of incidents. The messages need to explain what has happened, what is happening now, and what will happen next.

4) Security culture

Although these three elements are placed at the end of the framework, they can be the most important. During the past decade or so, awareness of the importance of cultures within an organisation has grown. The role that safety culture plays has been developing for ten years or more, and now the understanding of the role a security culture plays is following suit.

4a) Staff awareness

As with most things that define the culture within an organisation, the role Senior Management plays does matter [4]. Building a security culture from the top, means that the Board must own the policies, plans and procedures, they must provide the framework to make this happen, and then consistently seek the assurance that the right things are being done. Although the IOD/HSE guidance ‘Leading Health and Safety at Work’ was written for Boards to help them improve their approach to assuring Safety Management Systems, if the word Safety is replaced by Security in the text, in particular the annex, this is a very useful guide [5]. Senior Managers must live the values, setting a personal example and ensuring resources are in place to back up the intent. Security is not just for specialist managers but an issue for all business leaders. Security must be built into senior manager job descriptions and appraisal processes.

Developing a security culture within an organisation is about encouraging staff to respect common values and standards towards security, whether they are inside or outside the workplace. The awareness of security amongst staff – their vigilance when conducting everyday routines, for example – is an essential layer of an organisation’s protection and staff training, regular drills and internal communications play an important part. But so does the manner in which a business reinforces its words through its actions.

If we want action we need to make it simple to do and clear [6]. Understanding how we achieve compliance by nudging people to comply, through simply making it easier to do the right thing, is gaining greater recognition. If we want clear desks to maintain controls on papers, we need to provide adequate lockable storage, ensure it is kept locked storage, and make repairing broken locks a priority. If we allow mobile storage devices, expect them to be virus checked before use, we have to provide the means to check. If an access pass must be prominently displayed, everyone must show them.

Staff with direct line management responsibilities, are in a prime position to influence attitudes amongst colleagues and address any behaviours of concern amongst their staff. Through their regular contact with staff it should be a part of their duties to ensure their teams are acting appropriately and ensuring that security standards are maintained – even with staff working in different locations. Include individual security behaviours in performance appraisal processes to ensure staff are assessed in a transparent and regular manner.

Employees who work in more sensitive positions may be asked to complete an annual security appraisal form to determine any changes in their personal and financial circumstances which may pose a risk to the organisation’s security. Where possible, an environment needs to be created in which employees can discuss problems in confidence and find out about where and when support can be provided (e.g. cases of illegal drug use or personal debt). If staff feel compelled to conceal their
concerns, it may encourage some to become disaffected with their employer and possibly more susceptible to manipulation.

In larger organisations a hotline or email account is sometimes offered for staff to report, anonymously or otherwise, any suspicions or actual incidents of illegal, unethical or improper conduct by their colleagues, such as bullying, failure to adhere to security procedures, fraud or theft. Providing a reporting hotline does raise a number of legal issues that need to be resolved, and organisations should seek legal advice first as the laws are different in different countries, but this can be a very useful approach.

4b) Staff surveys

Companies use a range of means to assess how their staff feel: looking to see how satisfied staff are, measuring staff attitudes to things such as health and safety, determining the engagement of staff within their business. Measuring the awareness and attitudes of staff to security is less common. Yet without knowing how people view security both generally and more specifically within the workplace an important element can and will be missed.

Monitoring compliance and attitudes to the policy can of course occur all the time: do people leave important company or personal papers on the desk at night; are things put away but the drawers left unlocked; are doors left open at night for contractors to get in, and in so doing allowing anyone else to get in; what happens when trespassers are found on site; can contractors access digital control system remotely with no virus checks on their data devices? These are all things we have experienced. But some form of formal assessment is sensible. CPNI has developed a security culture tool, which provides one approach [7].

The importance of security within an organisation should be emphasised through regular communications with staff. This might be in the form of posters, leaflets or the intranet, but it should also include face-to-face activities such as training programmes, management forums or programme of talks and workshops.

4c) Best practice

Constantly check that you are still meeting a level of security appropriate to the risks you face. Neither become obsessed and unrealistic, nor complacent. As the threats change, and common practice changes, you may need to change your approaches too. On a regular basis ask yourself whether what you do is still good enough. Many of the same sources that were used to assess the treats in the first place can be utilised again, the police, local business groups, and even competitors. Reward the good practice where it occurs, seek to understand when lapses do occur, and fix the problems on the basis of knowledge and risk.

Conclusions

This is a tunnels conference, but I have said little about tunnels. But, everything above can (and has been) applied to the tunnels that we operate through in TfL, the principles are applicable to all our workplaces: lead from the top in setting a strong security culture; have a proper understanding of the risks; maintain a proportionate response to them; deploy strong controls of the physical, personnel and procedural; make good security the way we do things round here.

As we go forward, we will all face new and different challenges. However by sticking with a disciplined approach we will be increasingly sure that we can continue to stay safe and secure. I hope what I have written will assist you. All I would ask is that you critically review what you do against the framework I have set out. Be honest, with yourself and make changes so they will endure, and do
it as soon as is practicable. As Sgt.Esterhaus used to say in Hill Street Blues, ‘Let’s be careful out there’.

References


[4] Although in a quite different context, the power of organisational culture, and the role of senior managers to shape behaviour, is illuminatingly set out in Andrew Ross Sorkin’s expose of Wall Street Finance ‘Too Big to Fail’ (London: Penguin Books, 2009)


Mitigation of Tunnel Fires

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ABSTRACT

Various systems are used or proposed for mitigation of fires in tunnels. Several of these are discussed in relation to the influences they actually have on fires in confined spaces. The differences between ‘suppression’, ‘protection’, ‘mitigation’ and ‘fire fighting’ are discussed. Water is shown to be an effective agent for mitigation of fires in tunnels. Its capabilities are discussed and some of the limitations of current systems are presented. In general it is shown that most current systems provide good fire protection in tunnels, but are not able to ensure fire suppression. A system of testing and classifying mitigation systems is proposed. Finally, the paper looks to the future and briefly speculates on the future of mitigation systems for fires in tunnels.

KEYWORDS: fire suppression, water mist systems, deluge systems, fire testing.

Note: Named commercial products are given as examples only, and should not be understood to be endorsements.

A PERSONAL INTRODUCTION

In 1999, a few months after the Mont Blanc and Tauern tunnel fire incidents, the author attended a conference on ‘Long Road and Rail Tunnels’ in Basel, Switzerland [1]. At that conference there was a heated debate following one presentation concerning the installation of a deluge system in the tunnels on the ‘Betuweroute’ – a freight-only railway in the Netherlands. During the debate, one delegate expressed the opinion that such a system, while it might protect the structure, would “kill the driver” of the freight train; about half the audience nodded in agreement.

This appears to have been the general opinion in the industry in the latter part of last century, based on statements in the National Fire Protection Association (NFPA) standards of the time and also in the World Road Association (PIARC) publications [2].

The tide of opinion in the industry shifted considerably in the first decade of this century, with a number of research projects, including the UPTUN [3] and SOLIT [4] projects, showing that fixed fire fighting systems (FFFS) could, in some circumstances, provide a measure of control over a fire in a tunnel, and increase the tenability of the environment to facilitate safe egress. By 2008, both NFPA and PIARC had changed their official stance and both tentatively permitted the use of FFFS as a life safety device [5,6].

In 2008, at the 3rd ISTSS conference in Stockholm, the author joined the debate by making a number of comments relating to the capabilities of FFFS in general, and water mist systems (WMS) in particular [7,8]. These comments were based on observations of published details of water mist tests, as discussed in more detail at the ‘3rd Tunnel Safety Forum for Road and Rail’ in Nice, in 2011 [9]. The main comments may be summarised as follows:

- WMS have only been demonstrated on a very limited range of fuels, we do not yet know if they can control real vehicle fires.
• WMS have only been demonstrated under a very limited range of ventilation conditions, we do not yet know if they will work at higher velocities.
• Fire has been observed to spread between vehicles during WMS activation, we do not yet know under what circumstances this will happen.
• A system which does not halt or reverse fire growth should not be referred to as a ‘suppression’ system. (‘FFFS’ is not necessarily a better phrase, for the same reasons.)

In an attempt to find answers to some of these questions, and hoping to keep an open mind, the author attended the SOLIT2 workshop in Gijon, Spain, in June 2011 [10]. During that event, the author got a chance to put on waterproofs and walk close to a very large ‘HGV trailer’ fire during water mist activation, see Figure 1.

Figure 1 The author standing in water mist, a few metres away from a 15MW fire. Photograph courtesy of STUVA and SOLIT/IFAB

The experience of walking close to a “15-20MW” fire during water mist activation certainly helps put the capabilities and limitations of WMS in context. Having read the reports, seen the videos and now felt the heat in the mist, I feel suitably knowledgeable and experienced to comment on mitigation of tunnel fires. But first, some basic fire science.

**TUNNEL FIRE SCIENCE “101”**

It is commonly held that in order to have a fire, three factors are required: fuel, oxygen and heat. This is often referred to as the ‘fire triangle’, see Figure 2(a). If you remove any of these factors, you extinguish the fire. If you can control any of these factors, you can control the fire. Thus, in general, mitigation of a fire involves some form of manipulation of these factors, often by introducing a cooling effect (e.g. water, which may be used to cool the flames or surfaces directly) or by reducing the flow (or concentration) of oxygen to the fire (e.g. by dilution of the local environment by CO$_2$ or steam generated by the application of water spray on a fire).

Fires in confined environments, including tunnels, are also controlled by other factors, including heat transfer to and from the surrounding structure, so the simple triangle paradigm cannot easily explain the complex network of interactions. Here we will consider the ‘tunnel fire pentagon’, see Figure 2(b),...
to summarise the processes involved. The pentagon represents the five main interchanges:

1. Heat transfer to the fuel; which results in fuel mass transfer to the fire
2. Heat and mass transfer to the smoke; which results in heat feedback from the smoke
3. Heat transfer to the tunnel structure; which results in heat feedback from the tunnel structure
4. Heat transfer to the potential fuel (that is, flammable materials nearby which are not on fire, but are being heated and may become involved in the fire in due course)
5. Oxygen mass transfer from the air

There are also secondary transfer processes, such as the interchange of heat and mass between the air and the smoke, and the exchange of heat between the smoke and the tunnel structure, but we will neglect these for now.

**Figure 2** Diagrams of (a) the conventional Fire Triangle and (b) the Tunnel Fire Pentagon.

As with the triangle concept, if you can control any of these interchanges, then you can have some degree of control over the fire and its effects. All means of mitigation of fires in tunnels interrupt one or more of these processes.

**MITIGATION, SUPPRESSION & FIRE-FIGHTING**

In this paper various systems intended to mitigate the effects of fires in tunnels will be discussed. In order not to prejudice the discussion, phrases like ‘suppression’ and ‘fire fighting system’ will not be used to describe active systems. To clarify the matter, it is appropriate to define these terms [11]:

- **Suppress:**
  - to put an end to; prohibit
  - to hold in check; restrain
  - to stop the activities of; crush
- **Mitigate:**
  - to lessen in force or intensity
  - to make less severe
- **Protect:**
  - to defend or guard from attack
- **Fire-fighting:**
  - activity directed at limiting the spread of fire and extinguishing it

Thus, if a system shields people or the tunnel structure from the effects of the fire, it is a protection...
If it interferes with the fire to such an effect that the fire severity is reduced or the fire growth is halted, then it may be described as a suppression system. If it extinguishes the fire it is certainly a fire-fighting system. Most generally, if it is able to influence the fire in a beneficial way (however slightly), or reduce the effects of the fire, it may be classified as a mitigation system.

It is also useful to make one further distinction, there is a difference between mitigation of the fire itself and mitigation of the effects of the fire. A system may mitigate the effects of a fire without mitigating the fire itself. For example, a passive fire protection system (e.g. a sprayed thermal barrier) will mitigate the effects of the fire – as far as the structure is concerned – but will have no mitigating effect on the fire itself, and cannot be considered a mitigating system with regard to other considerations, like life safety or vehicle protection. This paper will not discuss passive systems, but will instead focus on the various active fire systems in use and proposed for use in tunnels.

**ACTIVE SYSTEMS & MITIGATION MECHANISMS**

A number of different active systems for tunnel protection have been proposed over the years and several such systems are installed in vehicle tunnels around the world. Each will be considered in turn here and their mechanisms of fire mitigation will be discussed.

**Ventilation Systems**

Ventilation systems are the original tunnel fire safety system. Almost all tunnels of significant length have some form of mechanical ventilation system, used for temperature and pollution control in everyday use, and for smoke control in the event of a fire.

Forced longitudinal ventilation may interfere with several of the heat and mass transfer processes which govern the behaviour of the fire. If the ventilation is sufficiently strong, it may blow the smoke away from the fire location, breaking the heat feedback interchange between the smoke and the fire. The cool air will also have an influence on the hot tunnel structure, reducing that feedback interchange as well. However, longitudinal ventilation will increase the mass flow of oxygen to the fire and, by enflaming the fire and tilting the flames, may also enhance the heat transfer to the potential fuel. In general, it appears that the enflaming influence of ventilation on vehicle fires dominates the theoretical cooling influence, so longitudinal ventilation systems do not generally mitigate the fire itself [12]. However, longitudinal ventilation systems are able to mitigate the effects of the fire, at least as far as people and vehicles on the upstream side of the fire are concerned.

Other forms of ventilation systems are available and it is claimed that some are able to mitigate the fire to some degree by producing low flow conditions at the fire itself (i.e. less oxygen to feed the fire), with high smoke extract rates on either side of the fire (i.e. removal of smoke and heat) [e.g. 13].

**Sprinkler / deluge Systems with water**

Water based sprinkler systems have been routinely installed in road tunnels in Japan since 1963, and in Australia since 1992. There are a handful of other tunnels around the world with such systems. The terminology ‘deluge system’ is generally taken to imply that the water flow to the sprinkler heads is actuated by means of valves, rather than by means of frangible bulbs or equivalent, as in domestic sprinkler heads. However, confusingly, the terminology ‘sprinkler’ is often used to describe both types of system.

Conventional sprinkler heads produce a water spray with drops with diameters of the order of 1 mm. Such drops are too large to be evaporated by, or otherwise interact with, the flames of a fire and their primary means of effect are to cool the involved fuel, resulting in a considerable reduction in the mass flow of fuel into the fire. They also cool the potential fuel, to reduce the rate or likelihood of fire spread. The spray also cools the smoke and the tunnel structure, breaking both those heat feedback...
interchanges, and finally, the water vapour produced as the water spray evaporates tends to displace and dilute the incoming airflow, thus reducing the mass flow of oxygen to the fire. In addition to directly cooling the smoke and structure, the water spray also blocks a significant portion of the radiant heat from the fire, essentially providing some additional protection for the structure and any people or potential fuel in the locality.

However, such systems are not able to completely solve the tunnel fire problem as, in many cases, the vehicle itself may shield the fire location and so the water drops may not reach the involved (or potential) fuel in order to cool it directly. Other safety concerns have been raised regarding such systems, such as problems with steam production [2], but many of these have been dismissed following research [e.g. 14].

Sprinkler / deluge Systems with additives

Deluge systems with additives are less common, but are used in, for example, the Betuweroute in the Netherlands [15] and in the Mt Baker Ridge and Mercer Island road tunnels in the USA [2]. The principles of these systems are broadly the same as that of the deluge systems with water, but the additives (commonly ‘aqueous film forming foam’ (AFFF)) are included to deal with some of the secondary concerns, generally relating to issues with liquid fuel spillages and potential release of flammable vapours.

Water Mist Systems

A true water mist system generates a spray where 99% of the droplets (by volume) are smaller than 1 mm in diameter. The majority of droplets from commercial WMS are in the range from 50 to 250 μm in diameter. Such tiny droplets have a very high surface area to volume ratio and are readily evaporated by flames or hot gases. This means that water mist droplets are able to directly interact with the flames of a fire and can disrupt the chemical reactions in the gas phase. This also means that water mist droplets are not generally able to pass through the flames to cool the involved fuel directly. Water mist also has excellent radiation blocking properties and thus breaks or reduces the heat feedback processes between the fire and the smoke, the tunnel structure, and the potential fuel.

One of the principal reasons WMS are used in preference to conventional sprinkler/deluge systems is that WMS use considerably less water, thus use smaller pipes and reservoirs. However, it should be noted that by using smaller quantities (or flow rates) of water, the ability of such systems to cool surfaces, such as the tunnel walls and any potential fuel, is reduced, compared to conventional sprinkler systems. In practice, WMS for tunnel applications do not produce a uniform water mist, but rather a mixture of small and larger droplets.

Water mist systems have been installed in, for example, sections of the Madrid M30 ring road tunnels, the tunnel section of the A86 Paris ring road, the new Tyne crossing, and in sections of the Channel Tunnel. These systems are intended for several other tunnel projects, both new-build tunnels and refurbishments.

High-expansion foam systems

High-expansion foam systems have been proposed and tested for use in transport tunnels [16] and, as far as the author is aware, the Liefkenshoek freight railway tunnel in Belgium (currently under construction) is the only tunnel intended to be protected with such a system. The aim of a high-expansion foam system is generally to fill the entire protected volume with foam, so that there is no flow of oxygen to the fire, no flow of gas away from it, and that all heat transfer processes are blocked by the physical barrier of the foam. This makes it an excellent fire-fighting device, but problematic with regard to egress and life safety in that egress routes will be locked with foam and the atmosphere may not be breathable. High expansion foam systems are therefore not considered for situations where there are significant numbers of passengers. However, such have been proposed for freight-only rail
systems, where the train staff would be trained and responsible for their own safety, and probably also equipped with personal life-safety devices. Due to the nature of these systems, high expansion foam systems are not suitable for use in tunnels with significant longitudinal flows.

**Gas-based extinguishing systems**

Gas-based extinguishing systems have also been considered for use in tunnels although, as far as the author is aware, no transport tunnel has such a system as a fixture. Gas-based systems operate on the fire directly, either by diluting and replacing the fresh air such that the fire is suffocated, or by introducing a chemical agent which interrupts and inhibits the chemical reactions in the flames. By extinguishing the flames, the system reduces all heat transfer processes and prevents fire spread.

Such systems are generally only applied in enclosed spaces, so their use in open ended tunnels is problematic. However, for example, fixed hypoxic air systems [17] and mobile inert gas systems [18] have been proposed for protection of transport tunnels.

The FirePASS hypoxic air system has been proposed for tunnel applications [17]. Hypoxic ‘fire prevention’ systems work by maintaining a reduced oxygen environment within the protected space. At about 15% oxygen, people can still breathe but ignition of common fuels is generally not possible. However, the problems of maintaining a reduced oxygen environment in an operational tunnel make this system impractical. An alternative solution would be a hypoxic ‘fire suppression’ system which, once a fire was detected, would aim to flood all or part of the tunnel with inert gas, such that the oxygen content in the vicinity of the fire would be reduced to about 12%, this would extinguish fires involving the majority of fuels. However, the practicalities of compartmenting the tunnel or maintaining sufficient volumes of the hypoxic air mixture make this system nonviable in the majority of tunnel scenarios.

The Steamexfire system [18] is a fixed or mobile unit which burns liquid fuel in a controlled manner, adding water to produce a large volume of largely oxygen free steam. This gas is then used to fill the volume containing a fire, for example a mine or a warehouse. The system has been proposed for tunnel applications, and a prototype mobile unit appears to exist, yet this system has same problems of compartmenting the tunnel and preventing oxygen ingress as other gas based systems. Obviously, given that this system seeks to generate an oxygen free atmosphere, this system could not be deployed until all tunnel users had been evacuated to a place of safety.

**Tunnel compartmentation for suppression**

A number of different products have been proposed to introduce some form of compartmentation into tunnels in the event of a fire. The majority of such products seem to be inflatable ‘tunnel plugs’ which may be either tunnel fixtures or portable devices. Tunnel plugs have been used during construction and maintenance of some metro tunnels and have been tested in a fire safety context as part of the UPTUN project [19,20]. They do not perform well in situations where there are pressure differences across the plug, but may have application for directing smoke movement in some tunnel networks, such as metro stations.

Water ‘walls’ and ‘curtains’ have also been proposed and tested as a way to partially compartment tunnels in the event of a fire. Initial exploration of water mist systems for tunnel applications considered this type of installation [21], although research into this type of system for tunnels has largely been abandoned in favour of deluge type water mist research. It was found that water mist curtains were able to slightly improve visibility and tenability in tunnel fire scenarios, but as the system had no noticeable influence on the fire size, it is not particularly useful as a mitigation system.
MITIGATION SYSTEMS VS. EGRESS

One of the old objections to use of sprinklers in tunnels as a life safety device was that active water spray would ‘hinder egress’ (primarily by reducing visibility) and thus the sprinklers, if installed, should not be used until all tunnel users had been evacuated [2]. However, the practice in Australia appears to be to activate the deluge system as early as possible following fire detection, in order to keep fire size as small as possible, even if people are in the vicinity [22]. This strategy was employed during the 2007 Burnley Tunnel fire incident, and while some tunnel users did get wet, the early activation of the system does not appear to have noticeably hindered egress or unduly inconvenienced the tunnel users [23]. The evidence of studies like the recent SOLIT² project has also dispelled some of the myths about the lack of visibility during water mist operation [10].

However, the issue of when to activate a mitigation system following fire detection is still a matter of debate [24]. Of course, certain types of system (e.g. inert gas and high expansion foam systems) should not be deployed until all people are out of the tunnel in a place of safety, but activation of ventilation and water based systems during the egress phase appears to be becoming accepted as part of fire safety strategies.

WATER AS A FIRE MITIGATION AGENT

The majority of active mitigation systems used and considered for tunnel fire applications are water-based, so it is appropriate to focus on how water actually works as a mitigation agent. Water has many benefits as a mitigation agent in that it is inexpensive, plentiful, non-toxic, non-flammable, relatively easy to transport, liquid at ambient temperature (in most climates) and has a higher latent heat of vaporisation than almost other common chemicals which are liquid at ambient temperature.

One kilogram (that is, approximately one litre) of water requires 375 kJ of heat to raise it from ambient temperature (assumed here to be about 10°C) to boiling point. Water then requires a further 2260 kJ/kg of heat to vaporise it, see Figure 3. That is to say, if a water-based system delivered about a kilogram of water every second into a fire scenario, then that water could, in theory, absorb about 2.5 MW of heat from the fire.

Thus, for example, if a zone of nozzles in a tunnel deliver a total of 25 litres per second into the vicinity of the fire (this is reasonably typical for water mist systems), the heating and vaporisation of the water – assuming all water is vaporised – could absorb about 65MW of heat released by a fire. Of course, this type of calculation only provides a theoretical maximum upper value for the capabilities

![Figure 3 Heating and vaporisation of 1kg of water](image-url)
of the system as not all of the water will be vaporised, indeed, much of it may not interact with the fire at all.

For the most efficient cooling of the gas phase (i.e. smoke, the air around the fire and the flames themselves), the water droplets should be as small as possible. The rate of cooling is largely dependent on the total surface area of the drops. If one litre of drops was uniformly split into 1mm diameter droplets, the total surface area would be about 60m$^2$. If the same quantity was split into 100μm drops, the total surface area increases to about 600m$^2$. In other words, 1 litre of 100μm water mist has the same cooling surface as about 10 litres of 1mm sprinkler drops. Thus, the smaller the drops, the greater the surface area and, hence, the more efficient cooling.

Cooling of solid surfaces, on the other hand, depends more on layer formation than it does on droplet size, so for cooling of involved and potential solid fuels, as well as the walls, ceiling and roadway of the tunnel, greater mass of water is more important than smaller drop size.

One question which remains unresolved for tunnel fires is whether cooling of the gaseous environment is more important than cooling of the surfaces. Thus it is not currently possible to answer whether a fine water mist is preferable to a large quantity of water with larger drops.

Water is an excellent mitigation agent, provided it can be delivered to the fire location. Unlike most other domestic or commercial properties, mitigation systems in tunnels have to deliver the water to the fire, with an acceptable degree of accuracy, in the context of significant ventilation flows. The extent to which droplet trajectories are influenced by the ventilation depends on a number of factors including droplet size, initial droplet velocity at the nozzle, average ventilation velocity, and the amount of turbulence in the flow. Various experimental and numerical studies have been carried out to investigate these effects [8,14,25,26] and it is clear that there is a problem using water mist systems in conjunction with high longitudinal flows, see Figure 4.

![Figure 4](image)

*Figure 4  Predicted water mist droplet trajectories, for four droplet sizes at 3 and 10 ms$^{-1}$. Adapted from Rein et al. [8]*

From these studies it is clear that high ventilation velocities may blow the finest droplets several tens of metres (perhaps over 100 m) downstream, so, if possible, care should be taken to control ventilation during application of water spray on fires, to ensure that the droplets best able to act upon the flames and reduce temperatures are not blown far away from the fire location.

Having said that, some ventilation configurations may assist the mitigation action of water mist systems. However, this is only speculation at present and needs more research.
COMPARISON OF EXISTING SYSTEMS AND THEIR LIMITATIONS

Until recently, no direct comparison of traditional sprinkler systems and modern water mist systems had been carried out in a tunnel. However, a direct comparison has been carried out as part of the SOLIT² project, although details of the tests have yet to be formally published [27].

Tests were carried out using conventional deluge sprinkler heads, providing a spray coverage of 12.5 mm/min, and tests with similar fire loads were carried out using water mist with a flow rate equivalent to less than 4 mm/min. Both systems performed well in terms of temperature management, preventing fire spread and structural protection, in the initial stages of the test. Later in the test the water mist system was shown to provide better protection of the structure than the deluge system as the droplets from the deluge system fall rapidly and do not provide as much thermal barrier in the upper parts of the tunnel as the lighter water mist does [28].

Traditional deluge/sprinkler systems have been tested a number of times in tunnel environments over the past five decades, but no detailed test series has ever been carried out. The majority of tunnel fire sprinkler tests have been carried out in Japan and are only summarised in the western literature [29,30]. The largest non-Japanese investigation into the abilities of sprinklers on tunnel fires was carried out in the 2nd Benelux Tunnel in the Netherlands in 2002 [14]. Reports on these sprinkler tests have generally focussed on temperature management and prevention of fire spread rather than on suppression or fire fighting.

Water mist systems, on the other hand, have been subject to extensive testing in tunnels. Many of the fire tests have been carried out by the water mist companies themselves and details of the tests remain confidential. However, the results of some tests carried out as part of the UPTUN, SOLIT and SOLIT² projects are in the public domain [3,4,10] and the results of some of the tests carried out by the water mist companies have been presented at conferences, etc. [e.g. 31,32,33].

A survey of the published data [see, e.g. 9] shows that the performance criteria for water mist systems varies considerably between test series. For example, in one presented test the application of the water mist did little to slow the rate of growth, and the fire grew from about 10 MW to over 60 MW with the mist active, yet the system was considered to perform well as the fire did not spread to the downstream ‘target’ [31].

It is clear from the published data that water mist systems cannot suppress cargo fires with any reliability. If the cargo is covered by a tarpaulin or contains significant quantities of plastics, it appears that water mist can do little to halt or significantly slow fire growth [31,32]. It is generally claimed that in such tests water mist does manage to reduce the peak heat release rate, but this has never been demonstrated by direct comparison with an un-sprinklered, free burning test.

It is equally clear from the published data that water mists systems generally can protect the structure from the effects of fire. This has led to the current debate regarding whether the addition of water-based protection systems can be used to justify the removal of passive fire protection systems or the reduction in capacity of ventilation systems [34,35].

In most investigations of water mist performance where a ‘target’ has been placed in the locality of the fire (commonly 5m downstream), the water mist has been shown to prevent fire spread to the target object. However, it must also be noted that in at least one fire test using water mist, fire did spread between vehicles. A number of fire tests were carried out with various configurations of real cars at the Hagerbach facility in Switzerland to test the capabilities of the water mist system which was intended for (and is now installed in) the tunnel section of the A86 near Paris, France.

In one of the tests, referred to as ‘Test C’, three cars were arranged in a collision configuration and the engine compartment of one of the cars was set on fire [33]. Various other cars were positioned close to the incident cars. The water mist was operated very early and no fire spread to the adjoining
vehicles (i.e. those supposedly involved in the collision) was observed. 22 minutes after ignition the water mist system was switched off for 4 minutes. During this time the fire spread rapidly to both adjoining vehicles and the combined HRR of the vehicle fires grew sharply from about 2 MW to over 15 MW. After the water mist was switched on again the HRR peaked at about 21 MW before dropping to about 12 MW. However, after a few minutes and while the water mist was active, the fire was observed to spread to two of the adjacent (but non-incident) vehicles, causing the total HRR to grow to over 15 MW once again.

This single observation demonstrates that fire spread can occur during water mist operation, and shows that more research is needed to investigate the circumstances under which fire spread will happen during water mist action, in order to prevent such fire spread in real incidents.

Finally, and most importantly, it must be observed that both water mist and conventional sprinkler/deluge systems have been demonstrated to mitigate the effects of fires in tunnels, and generally make the environment in the locality of the fire considerably more tenable for egress. In situations where untenable conditions do arise, the time to untenable conditions is generally considerably extended by the action of a water mist or sprinkler system.

A QUESTION OF CLASSIFICATION

Given the observations above, the author is of the opinion that a new method of classification of mitigation systems for tunnels should be developed. A ‘reasonable worst case’ scenario should be defined and systems tested against it.

For example, the test data discussed above have shown that mitigation systems have problems dealing with solid fuel loads, containing plastics, with a cover over them. Given that we now know this, the benefit of continuing to test mitigation systems with uncovered piles of wooden pallets, or open pools of diesel fuel is unclear.

The author proposes a mixed cargo of various good containing a significant proportion of plastics. This should be contained within a rigid container, with solid walls at the front and rear, perhaps with a fibre glass roof and tarpaulin sides, as is common on our roads. This should be tested in a tunnel with a ventilation flow rate of at least 3 ms⁻¹, as is common in road tunnels.

If the system is demonstrated to be able to protect the structure – i.e. the temperature of the structure does not exceed a temperature of, say, 300°C during the test – then the system may be classified as a Fire Protection System.

If the system is demonstrated to be able to halt fire growth (within, say, 5 minutes after activation) then the system may be classified as a Fire Suppression System.

If the system is demonstrated to be able to reduce peak fire size (within 5 minutes) to an acceptably low level, then the system may be classified as a Fire Fighting System.

[The author acknowledges that the current edition of NFPA 502 (2011) uses different terminology; it uses the term ‘fire control’ where I have used ‘suppression’ and it uses ‘suppression’ where I have used ‘fire-fighting’. I am pedantically sticking to my own phraseology for the moment as the word ‘suppression’ does not necessarily imply reduction in severity and the word ‘control’ does not necessarily imply prevention of growth. However, this is a matter of terminology and doesn’t ultimately matter. In the end, consensus of usage will prevail.]

Systems specified for tunnels are generally decided on the basis of cost-benefit analysis and risk assessment. It may be that simpler Fire Protection Systems are all that is required in many tunnel situations, perhaps specified to a less onerous set of criteria than are currently the norm, while other
situations may require systems specified to a higher classification.

The above is intended to open a debate on this topic, not be a definitive solution. It is acknowledged that the performance of a system in one tunnel environment does not necessarily mean the same performance will be achieved in a tunnel of significantly different size or shape. Current models and methodologies are not able to extrapolate from experimental tests to predict performance in scenarios on a significantly larger or smaller scale.

CAN WE IMPROVE ON CURRENT TECHNOLOGY?

As we’ve seen, water is an excellent fire mitigation agent. The author is of the opinion that, if a fire mitigation system is to be installed in a tunnel, it should be a water based system unless there are particular and unusual hazards associated with the goods transported through the tunnel which might require specialist systems.

As the fire mitigation properties of water are already well established, the primary way that systems may be developed to give better performance is in the mechanism of delivery of the water to the fire location.

This requires faster detection systems, more accurate location systems and more controllable deployment systems. More research needs to be carried out into the interaction of current systems, like water mist, and ventilation systems.

One solution which may play more of a role in tunnels in the future is a system like water cannons (see, for example, the systems manufactured by Unifire AB in Sweden [36]) which are beginning to be installed in some industrial warehouse scenarios. These systems directly target the fire and do not waste water on locations distant from it.

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Regulating Road Tunnel Safety

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ABSTRACT

This paper identifies the various international road tunnel safety regulations, guidelines and recommendations currently in existence today. Descriptions of the authoritative stature of these documents are provided along with an up-to-date listing of their adoption status by various countries. This paper also provides background on the development of the European Directive 2004/54/EC and describes the development process for the National Fire Protection Association (NFPA) Standard 502. Significant differences in tunnel safety requirements between these documents and others are discussed and specific examples are provided. Future issues concerning road tunnel safety regulation development including the need for guidance in the application of performance-based assessments; and the need for development of strategies aimed at reducing the risk of fires that can be applied outside of a tunnel are also discussed.

KEYWORDS: road tunnel, fire protection, life safety requirements, standards, regulations.

INTRODUCTION

Over 30 countries have adopted regulations to establish requirements for fire protection, life safety and operational safety within their road tunnels. In addition to these regulations, there are several recognized standards and guidelines that have been published by organizations such as the United Nations Economic Commission for Europe (UNECE), World Road Association (PIARC), International Tunnelling Association (ITA), and the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) that are also specific to fire protection, life safety, and operational practices of road tunnels.

These existing international regulations, standards and guidelines often differ from each other in their requirements or recommended best practices. These differences are generally due, in part, to operational experience, local conditions, vehicle fleet mix, emergency response capability and/or technical philosophy. Recognizing that all of these documents have been developed based on differing ideas and perceptions, none are considered to be incorrect. However, this plethora of internationally developed documents is often compared and evaluated by those engaged in the ongoing development of safety regulations for road tunnels. While it is not reasonable, nor warranted, to expect a uniform international consensus on all requirements, those responsible for safety regulation development need to focus on establishing a more rationalized approach that will allow critical fire protection and life safety requirements to be independently established by identifying proven and validated engineering principles and methodologies.

It is necessary for tunnel operators, code enforcers, design engineers and others in the industry to understand the authoritative stature of each type of document. Typically, a legally empowered entity within a country or jurisdiction will either develop their own road tunnel fire protection and safety requirements, or may choose to adopt, in whole or in part, an existing document. In either case it is imperative that the governing document establishes safety requirements in an unambiguous and enforceable manner. This is particularly important when a performance-based approach is required or an equivalency approach is allowed.

Organizations with interest in road tunnel fire protection and life safety have developed an extensive data base of the most recently recognized international documents, and some have also performed thorough comparative studies that identify the similarities and differences between them.
ROAD TUNNEL SAFETY REGULATIONS, STANDARDS AND GUIDELINES

The numerous documents relating to road tunnel fire protection and life safety that exist today differ by their intended purpose and authoritative stature. In general, and as referenced in this paper, these documents can be classified and defined as follows:

**Regulation** - A document containing specific mandatory requirements adopted and enforced by a legal government entity.

**Standard** - A document containing mandatory language, usually produced by a technical entity such as an association or society. These documents by themselves have no legal standing, except where they have been adopted by or on behalf of a government agency by legislative action or other legal empowerment or authority.

**Guideline** - A document providing recommended practices in the design, construction, installation, and/or operation of life safety, security and/or fire protection systems for road tunnel applications. These documents are typically prepared by technical associations as well as by certain governmental agencies.

The following section describes a prominent example of each of these document types, including a brief synopsis of evolution:


Between 1999 and 2001 three catastrophic fires occurred within European road tunnels that collectively accounted for 62 fatalities, destroyed 91 vehicles, and caused serious damage to more than 2,100 meters (m) of tunnel structure. These significant fires which occurred in the Mont Blanc, Tauern and St. Gotthard Road Tunnels highlighted the fact that large scale fires in tunnels are not necessarily limited to hazardous or otherwise regulated cargos and, more importantly, that accepted fire protection and life safety design assumptions and practices in place at the time were not sufficient.

Prior to these fire events, substantial tunnel fire research programs had been carried out and many fire safety regulations, standards and guidelines had been developed and applied to road tunnels. But these fires demonstrated that it was not sufficient to simply require the installation of certain systems and features and assume that all road tunnels can be equally protected and safe for the users. Rather, it became obvious that the each road tunnel is a unique facility due to numerous variables, and that these variables must be taken into account in order to better understand the equally unique risk potential for that facility. Thus, an international resurgence in tunnel fire research programs ensued, along with an urgent need to develop harmonized requirements to improve fire protection and life safety in all road tunnels.

In the aftermath of these events, the European Union (EU) commissioned several research programs and thematic networks aimed at improving road tunnel safety. In 2004, EU issued Directive 2004/54/EC [1], establishing regulatory legislation for minimum operational and safety requirements to be adopted by all member states with tunnels longer than 500m on the Trans European Road Network; affecting more than 500 road tunnels. The EU Directive is primarily structured around the respected road tunnel fire safety guidelines developed by the transport division of the United Nations Economic and Social Council (ECOSOC) entitled “Recommendations of the Group of Experts on Safety in Road Tunnels” [2] and various tunnel safety guidelines published by PIARC. The EU Directive also introduces mandatory requirements for establishing a tunnel facility management structure that clearly identifies roles and responsibilities in the operation of each tunnel facility and institutes and maintains procedural best practices consistent throughout the network.
Standard - NFPA 502

The National Fire Protection Association (NFPA) issues codes, standards, recommended practices and guides which are developed through a consensus process approved by the American National Standards Institute (ANSI). The document development process is transparent and allows public participation during technical proposal cycles. Individual “Technical Committees” consisting of volunteers representing varied viewpoints and interests within the industry are established to achieve consensus on the adoption of proposals and content for each document.

NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways [3] establishes minimum fire protection and life safety requirements for road tunnels, bridges and other roadways where access by emergency responders is physically limited. NFPA 502 is issued as a “standard”, and thus has no legal standing until adopted by or on behalf of a government agency by legislative action or other legal empowerment or authority. NFPA 502 has been generally adopted throughout North America by jurisdictional authorities concerned with road tunnels.

The Technical Committee for NFPA 502 currently consists of 31 appointed members (24 voting) representing eight (8) different countries including Australia, Canada, Germany, Netherlands, Singapore, Sweden, UK and US. In order to ensure that the document establishes requirements through an achieved consensus, the Technical Committee is balanced among various interests. The current Technical Committee is comprised of the following:

- Special Experts - 33%
- Manufacturers - 24%
- Users - 14%
- Research/Testing - 14%
- Enforcement - 10%
- Consumers - 5%

Prior to being issued as an official NFPA Standard, NFPA 502 existed only as a “Tentative Standard” which was woefully inadequate for several new road tunnel projects being planned in the US during the 1980s. NFPA reconvened a new Technical Committee and eventually published NFPA 502 as a “Recommended Practice”, which is the technical equivalent of a guideline. Finally, the document was further developed to a level of completeness and acceptance enabling the NFPA to release it as a Standard. The following is a full chronology of the development of NFPA 502.

- 1980 – Rewritten as Recommended Practice with additional requirements for air-rights structures.
- 1987 – Revised to include water supply and fire apparatus requirements.
- 1992 – Recommended Practice reconfirmed and re-issued.
- 1996 – Revisions to chapters on tunnels and air-rights structures and some correlating provisions.
- 1998 – Title changed to Standard for Road Tunnels, Bridges, and Other Limited Access Highways and issued as an NFPA Standard. Complete document revision with most significant changes to the chapter on Tunnel Emergency Ventilation.
- 2001 – Significant editorial rewrite and reorganization of the document. Changes made to clarify the application of the standard based on tunnel length. Technical changes regarding emergency communication, emergency egress, emergency lighting, and emergency ventilation.
- 2004 – New requirements for structural fire resistance of tunnels and air-rights structures. Revised requirements for emergency lighting levels and clarification for travel distance to emergency exits. Updated Annex A material on potential fire heat release rates.
• 2008 – Significant revision to categorization of road tunnels and broad reconsideration of the requirements and recommendations for application of fixed fire suppression systems, protection of structure, tenable environment, and transport of regulated and unregulated cargo.

• 2011 – Significant revisions, modifications and updates throughout the document including risk factors for protection of life and facility, several new requirements for bridges and elevated roadways, new application requirements for fixed water-based fire suppression systems, emergency egress assessment, cabling requirements and testing standards for emergency electrical systems, and new requirements for facility commissioning and periodic testing of life safety systems.

NFPA 502 follows a three-year cycle. This means that every three years the Technical Committee must reconvene to guide the document through the public proposal process, and develop revisions for the next edition. During the first five-month period of each cycle, the public is allowed to submit proposals affecting the document. The Technical Committee is then required to review and act on all proposals received – accepting, accepting in part or principle, or rejecting. During this period of proposal review, the Technical Committee may also put forth proposals that they develop through a process of internal consensus. The final actions of the Technical Committee in regard to all proposals are then published for final public review and acceptance/debate over another five-month period. The Technical Committee then issues a final record of all finalized proposals to the NFPA Standards Council for publication in the next edition. NFPA 502 entered into a new cycle in July 2011, beginning the process for issuance of the 2014 edition in August of 2013.

Guideline - World Road Association (PIARC) "Fire and Smoke Control in Road Tunnels"

PIARC is an international association assembled to encourage the exchange of knowledge on roads and road transport policy and practices within an integrated context. PIARC exists to provide an international forum for analysis and discussion of the full spectrum of transport issues related to roads and road transport by allowing its members to identify, develop and disseminate best practices and give better access to international information.

The Technical Committee on Road Tunnel Operation (C4) of PIARC develops and disseminates information and recommendations for road tunnel safety and operations. More than 30 publications in the following categories have been issued:

• Operations and Training
• Human Factors of Safety
• Pollution, Ventilation, Environment
• Communication Systems
• Dangerous Goods Transport
• Fire and Smoke Control
• Risk Analysis
• Emergency Team Planning and Preparedness.

In 1999 PIARC published a technical guideline entitled "Fire and Smoke Control in Road Tunnels" [4] in conjunction with the XXIst World Road Congress in Kuala Lumpur. This guideline was prepared by the PIARC Technical Committee in an effort to present a “state-of-the-art” assessment of the issues and methodologies for evaluating fire and smoke control in road tunnels. It was intended for those interested in road tunnel planning, design, construction, operation and safety, including owners, consultants, operators, researchers, regulators and emergency responders. The publication provides an overview of the key issues related to fire emergencies in road tunnels, and offers background information, current practices and recommendations on generally accepted means and methods for protecting against fire and smoke in road tunnels. For each subject addressed, references for obtaining further technical detail are provided.
COMPARISON OF ROAD TUNNEL SAFETY REGULATIONS, STANDARDS AND GUIDELINES

The sample regulation, standard, and guideline documents described above have been compared for their individual requirements for certain critical fire protection and life safety features including Water Supply, Fire Detection, Emergency Egress, Hydrants/Hose Connections, Emergency Ventilation, Portable Fire Extinguishers, and Fixed Fire Fighting Systems, yielding the following findings:

Water Supply:

- **EU Directive**: Required in all tunnels longer than 500 m. No capacity provided.
- **NFPA 502**: Required in all tunnels longer than 90 m. 1,920 L/min for 1 hour.
- **PIARC 1999**: Recommended. 1,000 L/min at 0.5 mPa.

Fire Detection:

- **EU Directive**: Required in all tunnels longer than 500 m. Incident detection systems may be used in place of fire detection devices.
- **NFPA 502**: Two means required (one manual) in all tunnels longer than 300 m.
- **PIARC 1999**: Recommends either automatic detection or operator surveillance.

Emergency Egress:

- **EU Directive**: Required in all tunnels longer than 500 m with tunnel traffic greater than 2,000 vehicles per lane (v/l). Spacing not to exceed 500 m.
- **NFPA 502**: Required in all tunnels longer than 300 m. Spacing not to exceed 300 m. Cross passageways spaced at 200 m allowed in lieu of emergency exits.
- **PIARC 1999**: Recommended. Spacing should be 100 to 200 m.

Hydrant/Hose Connections:

- **EU Directive**: Required in all tunnels longer than 500 m. Spacing not to exceed 250 m.
- **NFPA 502**: Required in all tunnels longer than 90 m. Spacing not to exceed 85 m. No location on the protected roadway to be more than 45 m from the hose connection.
- **PIARC 1999**: Recommended. Spacing should be 100 to 200 m.

Emergency Ventilation:

- **EU Directive**: Required when tunnel length is 1,000 m or greater and tunnel traffic is greater than 2000 vehicles per lane (v/l).
- **NFPA 502**: Required in all tunnels 300 m or longer (240 m when the maximum distance from any point within the tunnel to a point of safety exceeds 120 m).
- **PIARC 1999**: Recommended with no specific application criteria given.

Portable Fire Extinguishers:

- **EU Directive**: Required in all tunnels longer than 500 m. Spacing not to exceed 250 m in existing tunnels and 150 m in new tunnels.
- **NFPA 502**: Required in all tunnels longer than 300 m. Spacing not to exceed 90 m.
- **PIARC 1999**: Recommended. Spacing should be 100 m to 200 m.
Fixed Fire Fighting Systems:

- NFPA 502: Must be considered for tunnels 1,000 m or longer.
- PIARC 1999: Neutral.

Variations in road tunnel regulations, standards and guidelines are best exemplified by starting with the basic fact that most of these documents identify minimum fire protection and life safety requirements based on tunnel length. For example, comparison of existing regulations and standards reveals the variation in minimum tunnel length before invoking minimum safety requirements as: 90 m (US), 100 m (Japan and Sweden), 150 m (UK), 300 m (France) and 500 m (Norway and EU). Other countries such as Australia, Germany and Korea do not set a minimum tunnel length value, but instead rely on an assessment of danger potential and/or analysis of risk.

In the report entitled “Comparison and Review of Safety Design Guidelines for Road Tunnels” [6], SP Technical Research Institute of Sweden provides a thorough comparison of the most recognized published road tunnel safety documents including regulations, standards, guidelines and directives that have been adopted by various countries. The report compares the requirements for 38 fire protection and life safety features as defined by 13 different documents (affecting 25 different countries), and presents a clear illustration of how the specific requirements differ significantly from one document to another. The report also highlights the variation in use of prescriptive- and performance-based requirements, and discusses the significance of the various differences for each individual system.

INVENTORY OF ROAD TUNNEL SAFETY REGULATIONS, STANDARDS AND GUIDELINES

In 2005, the International Tunneling Association (ITA) established its Committee on Operational Safety of Underground Facilities (COSUF) to facilitate collaboration, cooperation, and the exchange of knowledge on all initiatives concerning operational safety and security in road tunnels on an international basis. In 2011, ITA-COSUF updated and re-issued their report entitled “Survey of Existing Regulations and Recognised Recommendations (Operation and Safety of Road Tunnels)” [7].

This comprehensive report, which was first issued in 2008, provides a listing of countries and their current governing road tunnel safety regulations, and provides a full commentary on their status. A separate listing provides an up-to-date status on each EU Member State’s mandated transposition (adoption) of the EU Directive 2004/54/EC. The report also includes the latest recognized guidelines and provides a full listing of current publications from organizations such as ITA, PIARC and ASHRAE.

A current listing of all prominent international road tunnel safety regulations, standards, and guidance documents is shown on Table 1. This table has been extracted from Chapter 10 of the National Cooperative Highway Research Program Synthesis 415, Design Fires in Road Tunnels [8]which also provides detailed discussion on the differences between international regulations as they pertain to commonly required fire protection and life safety systems and features. The table is included here primarily for reference and to emphasize the quantity and variety of documents used internationally to govern road tunnel safety.
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<td>ASHRAE</td>
<td>Handbook</td>
<td>2011 (every 4 years)</td>
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<td>UN</td>
<td>Recommendations of the Group of Experts 0/1 Safety in Road Tunnels</td>
<td>UN TRANS/AC.7.9</td>
<td>Report</td>
<td>Economic and Social Council, Inland Transport Committee (2001)</td>
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<td>Fire Safety Guideline for Road Tunnels</td>
<td>AFAC</td>
<td>Guideline</td>
<td>Australian Fire Authority Council (2001)</td>
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<td>Austria</td>
<td>Guidelines &amp; Regulations for Road Tunnel Design</td>
<td>RVS, IBS</td>
<td>Guideline</td>
<td>Transportation &amp; Road Research Association (2001)</td>
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<td>Law No. 2002-3 of 3 January 2002 relative to safety of infrastructures and transport systems, etc.</td>
<td>Law 2002-12</td>
<td>Law</td>
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<td>Guidelines for Equipment and Operation of Road Tunnels</td>
<td>RABT,DMT, SOU To STUV A, VdS, VFDB</td>
<td>Guidelines</td>
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<td>Functional and Geometrical Standard for Construction of Roads</td>
<td>Ministry of infrastructure and Transport</td>
<td>Ministerial decree</td>
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<td>Safety Standards</td>
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<td>Korea</td>
<td>National Fire Safety Codes</td>
<td>NFSC</td>
<td>Code (Regulation)</td>
<td>Korea National Emergency Management Agency</td>
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<tr>
<td>Korea</td>
<td>Guideline for Installation of Safety Facility in Road Tunnels</td>
<td>GIST</td>
<td>Guideline</td>
<td>Ministry of Construction &amp; Transportation (2004)</td>
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<td>Technical Standards for the Provisions &amp; Installations RWS Curves</td>
<td>Rijkswaterstaat TNO (UPTUN)</td>
<td>Guideline</td>
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<td>27</td>
<td>Russia</td>
<td>Construction Rules &amp; Regulations (SNIP) #32-04-97 &quot;Railway &amp; Road Tunnels&quot;</td>
<td>SNIP</td>
<td>Guideline State Construction Committee (GOSTROI)</td>
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<td>IC</td>
<td>Norma 3.1 Dec. 1999</td>
</tr>
<tr>
<td>30</td>
<td>Spain</td>
<td>Road Instruction, Norm, Vertical signals</td>
<td>IC</td>
<td>Norma 8.1 Dec. 1999</td>
</tr>
<tr>
<td>34</td>
<td>Switzerland</td>
<td>Guidelines for the Design of Road Tunnels</td>
<td>ASTRA (Swiss Federal Roads Office)</td>
<td>Guidelines by the Federal Roads Office 2005 (updated)</td>
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<td>38</td>
<td>EU</td>
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<td>UPTUN; L-SURF</td>
<td>Recommendation <a href="http://www.uptun.net">www.uptun.net</a>; <a href="http://www.lsurf.org">www.lsurf.org</a></td>
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<td>39</td>
<td>PIARC</td>
<td>Fire and Smoke Control in Road Tunnels 05.05.B</td>
<td>PIARC</td>
<td>Recommendation PIARC (1999)</td>
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<td>43</td>
<td>NVF</td>
<td>Ventilation av Vagtunnelar (Ventilation of Road Tunnels)</td>
<td>Nordic Road Technical Association</td>
<td>Report of a Nordic working group NYF 1993</td>
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<tr>
<td>45</td>
<td>PWRI/Japan</td>
<td>Road Tunnel Technology in Japan PWRI no. 3023</td>
<td>Public Works Research Institute</td>
<td>Technical Memorandum Ministry of Construction, 1991</td>
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<td>48</td>
<td>European Thermal Network</td>
<td>Fire in Tunnels</td>
<td>FIT</td>
<td>Technical Report Thermal Network FIT supported by European Community GIRT-CT-2001-05017</td>
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DISCUSSION

The following sections discuss two specific topics that this author believes require immediate consideration by regulators of road tunnel safety:

**Prescriptive- and Performance-Based Requirements**

As previously mentioned, many road tunnel guidelines, standards and regulations establish prescriptive fire protection and safety requirements based on tunnel length or on a combination of tunnel length and traffic volume (i.e., annual average daily traffic). While this can be considered a reasonable method for establishing “minimum” fire protection and life safety feature requirements, other parameters that can ultimately influence these requirements include the location of the tunnel, the tunnel’s geometry (cross section and profile), the anticipated traffic type and risk of congestion, planned monitoring and supervision capabilities, and estimated response time of emergency services. As a reference, NFPA 502 contains a paragraph identifying 19 different factors that should be considered regardless of a tunnel’s length.

There is a need to allow for a rationalized approach in establishing road tunnel fire protection and life safety related requirements that is based on the critical parameters, risks and mitigations which are unique and specific to a facility. Design parameters such as fire size to be used for establishing emergency ventilation capacities, fire growth rate to be used for determining time of tenability and required emergency exit spacing, and appropriate time-temperature curve for establishing structural fire protection requirements are unique for every road tunnel, have significant cost impacts, and cannot be prescribed as “one size fits all”. However, it is not enough for these regulations to simply require a “risk assessment” or an “engineering analysis” without establishing precise variables and specific parameters to be considered and identifying the appropriate means and acceptable methodologies for performing such studies. Establishing these “performance criteria” is necessary to ensure a uniform and validated approach for designers and to provide a measurable level of compliance and certainty for enforcement authorities.

Establishing prescriptive requirements is still considered the more favourable approach for certain fire protection and life safety features like the minimum spacing between and locations of safety-related devices such as emergency phones, fire extinguishers and standpipe hose valves, and for provision of critical life safety systems such as emergency power and emergency lighting.

**Regulating Beyond the Portals**

One commonality amongst existing road tunnel regulations, standards and guidelines is that they are all primarily focused on provisions for reacting to a tunnel fire emergency. There are currently no specific requirements focused on preventative measures that could effectively serve to alleviate incident potential and fire risk.

It is typical, particularly in urban environments, for road tunnels to act as a traffic choke point. This occurs due to a myriad of reasons such as multiple open lanes being suddenly reduced to two or three lanes through the tunnel, multiple roadways combining and leading to a single tunnel entrance, or tunnel toll facilities that throttle multiple lanes of traffic in close proximity to the tunnel entrance, thus creating full congestion. Likewise, similar highway or roadway layouts beyond a tunnel’s exit portal can prevent the free flow of traffic to the extent where traffic queues back into the tunnel. Many road tunnel fires occur as a result of collision, over-heated engines, and over-heated brakes, most of which result, in part, from high volume or congested traffic. Motorists also become anxious and agitated in congested traffic conditions and are more apt to take risks that they normally would not take under normal driving conditions.

Requirements for traffic control strategies upstream and downstream of high-volume tunnel facilities needs to be developed to reduce and/or control traffic volumes, mitigate congestion inside the tunnel,
and maintain a balanced flow of traffic into and out of the tunnel. Civil design standards for roadways or highways leading to or leaving from tunnels need to be advanced to include specific guidelines that address elements such as alignment, profile, lane configuration, traffic speed, metering, tolling, etc., so that traffic flow into, through, and out of the tunnel is uniform. The use of traffic monitoring and control systems to measure traffic conditions and mitigate adverse conditions needs to become as much of tunnel fire and life-safety requirements as the ventilation and suppression systems are today.

CONCLUSION

This paper has focused on the significant number of standards and guidelines for road tunnel safety that exist today, their authoritative stature, their adoption and areas which need improvement. In a general sense, these documents are similar only by the fire protection and life safety elements they cover, but vary significantly in what they prescribe for those elements. This variability creates confusion, particularly among the regulatory community that needs to define an enforcement document. By better defining the basis of the prescriptive requirements, regulators can then make informed decisions on how to develop the appropriate document for their situation.

In addition to the prescriptive language variability, there is often little guidance on performance-based approaches. Definition for what criteria performance-based standards should meet needs to be provided so enforcers have the ability to judge whether or not a particular assessment meets the requirements.

Finally, while most of the attention has been focused on what happens inside the tunnel, conditions outside the portals need to be addressed as many incidents occur because of the transitions to and from the tunnel.

REFERENCES


Risk Reduction for Today's Critical Infrastructure

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US Department of Homeland Security
Transportation Security Administration
Highway and Motor Carrier Division

Introduction

The United States Department of Homeland Security (DHS), Transportation Security Administration (TSA)’s Highway and Motor Carrier (HMC) Division utilizes risk reduction initiatives to secure the nation’s critical highway infrastructure. HMC’s vision is to lead the national effort to maintain the capability to move freely and facilitate commerce in all conditions, and to continuously set the standard for excellence in highway transportation security through our people, processes, and technology. This paper will offer a concise review of TSA’s National Highway Bridge Strategy, as well as two current risk reduction programs being implemented by HMC to secure the nation’s highway bridges and tunnels. The first program to be reviewed is the TSA/US Army Corps of Engineers (USACE) bridge and tunnel assessment program. The second program to be reviewed will be the Baseline Assessment for Security Enhancement (BASE) program.

Highway Motor Carrier Organization

Risk identification and mitigation are at the forefront of HMC initiatives. HMC has recently reorganized into four branches to efficiently address risk. The four branches are the Risk Analysis and Measures Branch, the Policy and Plans Branch, the Regulatory and Field Integration Branch, and the Programs and Initiatives Branch. These four branches work together to implement risk based strategies and programs.

Risk Based Strategies

HMC defines Risk as a function of likelihood (probability) multiplied by the consequences (direct and indirect). The likelihood of attack may be viewed as threat (capability + intent) and vulnerability (exposure, susceptibility, survivability). HMC utilizes risk-based strategies to secure U.S. transportation systems, working closely with highway stakeholders, as well as the partners in the law enforcement and intelligence community. The U.S. Economy is dependent on its infrastructure. No one entity owns or operates the entire highway infrastructure in the nation. In the U.S. roads, bridges and tunnels are owned and operated by states, local governments and private entities. Thus, it is vital for HMC to work in partnership with these stakeholders.
Highway Infrastructure Landscape

The following statistics provide an overview of the key infrastructure comprising the US Highway system, which includes:

- 46,934 miles of Interstate highway
- 116,813 miles of other National Highway System roads
- 3,884,777 miles of other roads
- 599,766 bridges over 20 feet of span
- 366 U.S. highway tunnels over 100 meters in length

National Strategy for Highway Bridge Security

Signed into policy during 2008 by former TSA Administrator Kip Hawley, the National Strategy for Highway Bridge Security, created by TSA/Federal Highway Administration/DHS Policy working groups, defines short, middle and long-range strategies for the security of highway bridges in America.

- **Phase One** of the strategy calls for the identification of significant highway bridges, risk assessment, and where possible, implementation of short-term measures to mitigate risk. During this phase, the branch identified many significant national highway bridges and categorized them into two priority tiers using existing TSA and other federal data. Initial tier ratings incorporated threat information based on criteria such as construction, traffic volume, collocation with other infrastructure, amount of time needed to rebuild, iconic value, existing vulnerability data, and the impact of loss on the local, regional, and national economy.

- **Phase Two** of the strategy lays a foundation for sharing DHS and Department of Transportation information and recommendations to Tier 1 and Tier 2 bridge owners regarding federal resource sharing supporting our collective bridge infrastructure risk mitigation strategy. This phase also supported and encouraged scientific research required to improve long-term design technologies and assessment methodologies.

- **Phase Three** focuses on implementing layered security measures at significant national highway structures with the development and implementation of new design and retrofit measures for risk mitigation. During this phase, federal agency subject matter experts are encouraged to establish program authority in offices charged with standards, methodology, protective strategy and technology oversight and stakeholder collaboration.

Transportation Security Administration/United States Army Corps of Engineers Bridge and Tunnel Assessments

Consistent with each phase of the strategy, HMC collaborated with USACE, public and private sector bridge owners, affiliated federal and local highway administrations, law enforcement and other public safety teams to acquire detailed insight into structure vulnerability via field assessments. With the overarching national strategy guiding the team, the branch administered 36 bridge assessments and two tunnel assessments since 2010 and provided the impetus needed to organize public and private sector organizations planning to address this infrastructure vulnerability. Although these assessments are conducted in support of the 9/11 Act, stakeholder participation in
these assessments is voluntary. The *Implementing Recommendations of the 9/11 Commission Act of 2007* (Public Law 110-53-AUG. 3, 2007), 121 STAT. 374, Section 1002 (“9/11 Act”), Risk Assessments and Report, indicates risk assessments on critical infrastructure and key resources of the United States must be conducted. According to the 9/11 Act, a report shall also be prepared on the comprehensive assessments conducted of the critical infrastructure and key resources of the United States, evaluating threat, vulnerability, and consequence.

The assessments utilize USACE’s risk-based methodology to facilitate prioritization of terrorist threat mitigation strategies on individual structures. This methodology is unique in that it is specifically designed to focus on a single structure and the risk associated with each of its many individual structural components. Security engineers at the PDC execute comprehensive on-site physical security surveys to determine threats and vulnerabilities for critical facilities and individual assets. The information gathered during these surveys is used to develop a set of protective measures designed to mitigate specific aggressor threats. These protective designs use a proven security engineering approach which incorporates elements of construction, equipment, procedures, and manpower. Assessment teams prepare a cost-efficient, structure-specific report detailing potential protective design strategies, implementation plans and estimated costs of mitigation strategies, to include existing structure estimated replacement cost, as appropriate per structure. Owners of the structures will have access to the reports.

USACE has developed and is refining a **tunnel assessment methodology** to support TSA’s assessment efforts. USACE plans to deliver a technical presentation on this methodology at the Transportation Research Board (TRB)’s Annual Meeting in Washington, DC in January 2012. The presentation will be delivered at the Bridge and Tunnel Safety and Security Session. USACE also plans to discuss this tunnel methodology at the Tunnels and Underground Structures Committee meeting, which is part of the TRB Annual Meeting. In addition, USACE plans to host a separate meeting to obtain expert technical guidance (expert elicitation) to insure the methodology meet users needs. This meeting will take place at USACE headquarters in Washington, DC in January 2012. In support of tunnel assessment efforts, USACE is also developing a **tunnel security checklist for TSA**. The USACE and HMC are partnering to pilot TSA’s Bridge Security Checklist as part of this assessment program. Once the pilot is completed, the process will generate an observational security preparedness survey which can be used by state highway bridge inspectors during mandatory biennial safety inspections. While full vulnerability assessments are reserved for bridges designated as “significant” to national and regional economies, these abbreviated security assessments provide fresh insight into vulnerability pertaining to the hundreds of locally and regionally-valuable structures across the country.

**Baseline Assessment for Security Enhancements (BASE) Program**

In the past, HMC staff conducted Corporate Security Reviews (CSRs). CSRs were conducted with organizations engaged in transportation by motor vehicle and those that maintained or operated key physical assets within the highway transportation community. They served to evaluate and collect physical and operational preparedness information, critical assets and key point-of-contact lists, review emergency procedures and domain awareness training, and provided an opportunity to share industry best practices. Beginning in 2010 and continuing throughout mid 2011, HMC began development of a program designed to assess and ultimately elevate the level of security across all transportation modes in the Highway sector, including trucking, motorcoach, school bus and infrastructure. The program was based in part on the BASE program successfully being used in TSA’s mass transit sector. The goal of the program, aptly named Highway Baseline Assessment for
Security Enhancements (HWY BASE) was to take the assessment process to all highway sectors, an audience many times larger than that seen in the mass transit program.

The first step necessary to bring the HWY BASE to realization was applying a risk based review and analysis to all of the assets across all of the highway modes to identify a manageable list of those infrastructure partners best suited for participation. By applying appropriately identified risk factors for each of our transportation sub-modes, lists of potential partners including infrastructure sites were developed that represented the largest portion of their respective industries. Specifically, asset lists for infrastructure (bridges and tunnels) sites were developed.

The next step in development of the HWY BASE was development of a single, comprehensive list of appropriate questions designed to elicit the best results in assessing the level of security across all highway transportation modes. Twenty-three (23) specific security areas (“Security Action Items”) were identified using all security-practice resources available from across all modes. Scouring all of the available resources resulted in the development of security “checklists” that were unique for each mode.

Each company or facility identified would be visited by a TSA representative who would assess each security item. The stakeholder would receive a detailed summary report that includes security strengths, security weaknesses and a security “score.” Participating stakeholders would receive a “report card” type analysis, in which all 23 SAI’s were scored and then combined for their “Overall Performance Score” ranging from 0% thru 100%. Those scoring 90% or more would be recognized for earning TSA’s “Security Gold Standard” and would receive a certificate commending their security efforts.

The final step needed to make the program operational across all areas of the U.S. was to identify and train TSA personnel assigned to the field that could be deployed as a force-multiplier. TSNM/HMC partnered with the Surface Transportation Security Inspection Program (STSIP) Office and identified approximately 300 Transportation Security Inspectors-Surface (TSI-S) assigned to the Office of Security Services (OSO) located at various TSA offices across the country as the appropriate personnel to administer the HWY BASE program. HMC developed a training program designed to instruct these inspectors on how to conduct HWY BASE assessments and administered the training over a two month period. The final of four training sessions was completed in October 2011 and the HWY BASE program became fully operational in November. TSA Surface Inspectors have been tasked with conducting HWY BASE reviews at all of the highway transportation companies/facilities/sites identified for inclusion in this program by HMC. Inspectors will also be expected to provide assistance to stakeholders in developing security plans and conducting risk assessments as needed. Toward that goal, HMC is also developing tools for assisting stakeholders in need of security planning guidance by providing a simplified security plan template adaptable to all modes, as well as a step-by-step guide to conducting an effective, site-specific risk assessment for any location.

As HWY BASE reports are received from field personnel, HMC will analyze the data collected to begin assessing the overall posture of each of the highway sub-modes. Industry-wide strengths and weaknesses will be identified in an effort to better plan and implement mitigation strategies. The HMC BASE program also calls for revisits to all stakeholders within one-to-three years (depending on the company’s Overall Performance Score) in order to track developing highway security trends. It must be noted that stakeholder participation in this program is also voluntary.
Summary

HMC has adopted successful strategies and programs to reduce risk for today’s critical infrastructure, including highway bridges and tunnels. Reducing risk for critical infrastructure is everyone’s responsibility. It must be noted that HMC does not have regulations for the highway infrastructure community. Also, HMC does not have funds available for assisting stakeholders to implement the security recommendations made by HMC. The success of HMC’s programs is dependent on its effective partnerships with its stakeholder community. HMC does not operate independently and welcomes stakeholder input and participation. The two programs reviewed in this paper are voluntary, thus their success is dependent on stakeholder participation.

Thank you for your dedication to secure our transportation systems infrastructure through the sharing of your expertise with the Transportation Security Administration.

REMEMBER WORKING TOGETHER WE WILL MAKE A DIFFERENCE!
Fire Safety Engineering – A Tool in Tunnel Design

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ABSTRACT

Tunnels are becoming an increasing part of our transport infrastructure for both roads and railways. At the same time, the development of fire safety engineering and risk analysis has allowed a performance based approach to become much more popular for tunnel design. This has led to more flexibility in design and more cost effective construction. Codes and standards are also reflecting this concept of fire safety engineering as a tool of choice in tunnel design. Key engineering developments in understanding the design of tunnel structures, emergency ventilation and water based suppression have certainly contributed to new design solutions for tunnels. At the same time, there is a need for more research in 1D/3D modelling, fire systems availability and human behaviour during evacuation. This can only enhance further our fire safety engineering and risk analysis and provide even better tunnel design solutions and improved public safety into the future.

KEYWORDS: Performance based design, fire safety engineering, risk analysis, tunnel design,

INTRODUCTION

Given the trend towards urbanisation and larger cities, tunnels for road and rail infrastructure have increasingly become popular as a means of preserving streetscapes and creating minimal disturbance to city layouts. At the same time, major highway construction and new railways including long distance, high speed rail projects are employing more tunnels to eliminate steep grades, provide transport under mountain ranges and sub-sea, and minimise the impact on communities and the environment.

Tunnels for water, sewage, electrical services and other utility functions are also becoming ever more popular.

Sitting beside this growth in tunnels has been a global trend towards performance based fire safety design. This is increasingly supported by more sophisticated fire engineering and modelling tools which can be used in order to develop cost effective designs and satisfy approval authorities. This performance based fire safety engineering in turn is a key element and contribution to assessment to risk assessment often Quantitative Risk Assessment (QRA) that is required as part of a broader safety case for tunnel design approval. Fire engineering and risk assessment may also assist tunnel proponents with cost benefit analysis of design options in relation to critical tunnel elements.

This paper looks at the evolving field of fire safety engineering as a key tool in tunnel design. This is also a key to proper documentation for the approvals authority and safety case acceptance which are always significant project risks that must be well managed if tunnels are to be delivered on time and on budget.

TUNNEL DESIGN

Fire safety design has an influence on many aspects of tunnel design, especially for road and rail tunnels. A number of these fire safety aspects affect space proofing and civil engineering works. The
role of the fire safety engineer can therefore make a crucial contribution to the early development of a tunnel concept design, and provide significant input to the understanding of costs and construction risks.

These crucial design aspects that relate to fire engineering include:

- Tunnel lining and structures – stability and separation
- Cross passage spacing and egress passage locations
- Longitudinal versus transverse or semi – transverse emergency ventilation and if required, exhaust/smoke duct size
- Vent stations size and location above and below ground and real estate considerations
- Tunnel walkways and their width and grade to suit mobility impaired
- Intervention shafts for fire brigade access and/or occupant egress
- Power, communications and water supply services routes in tunnels or in-ground
- Suppression or not, and issues of drainage and water treatment.

Early decisions on these fire safety issues can impact or be impacted by overall tunnel design decisions on:

- Construction methods: Bored tunnel, mined tunnel or cut and cover
- Immersed tube (IMT) verses TBM (tunnel boring machine) for sub-sea tunnels
- Single versus twin tube tunnels
- The need or otherwise for a service or escape/rescue tunnel or a third bore.
- Space proofing for vehicle envelope, passages and all structures and services
- Availability of emergency services for incident response
- Operations and maintenance regimes

It is recognised by experienced fire safety engineers working in tunnel design that, for example, cross passages in TBM tunnels represent a considerable construction risk. There is therefore a desire to space cross passages as far apart as possible consistent with safety requirements, i.e. it is a balance of risks.

At the same time, the issue of emergency lanes or not in road tunnels, and their impact on likelihood and consequence of accidents, some of which may lead to fires, is a significant issue for road tunnel design. The width and height of walkways is another issue that like emergency lanes, can have significant impact on tunnel diameter, TBM design and overall project cost.

A key issue that the fire safety engineer also needs to be aware of in design is the impact of design decisions, on longer term operations and maintenance. For example, if sprayed fire protection is applied to structural elements in a road tunnel it often absorbs dirt from traffic operations, is very difficult to clean, becomes black and absorbs light, adds to recurrent electrical costs, and detracts from tunnel appearance and potentially safety. Equally if a semi-transverse Ventilation system is employed rather than a simple longitudinal ventilation system then such systems can be complex and require higher levels of maintenance and therefore cost, with attendant issues of reliability.

Many of these design and operational issues can be solved more cost effectively with performance based fire safety engineering and risk analysis rather than simply following generic prescriptive rules.

**FIRE SAFETY ENGINEERING**

The traditional approach to fire safety design for buildings and transport infrastructure was to follow a set of prescriptive rules which were generic. These rules were often set out in codes and standards and were required to be followed, almost regardless of whether the application of the rules was sensible or cost effective or even offered a reasonable level of fire safety.
From the 1980’s and 1990’s onwards, a significant number of countries moved to performance based building codes. This meant that key fire safety objectives and Performance Requirements were set in the code, but the designers had the freedom and flexibility to develop any reasonable design solution, provided it met the Performance Requirements and could be justified technically.

One important reason why performance based fire safety engineering advanced strongly was that fire science and research had delivered a much better understanding of fire development and people behaviour in building fires. This was encapsulated in guidance documents, research papers, and fire, smoke and people evacuation models which enabled real fire safety engineering to be undertaken with much greater confidence.

At the same time owners, developers, architects and many other design professionals realised the clear advantages of a performance based approach. The benefits included:

- Better, focused and specific design, not generic
- More flexible, innovative designs
- Better aesthetic outcomes
- More cost effective construction
- Equal or better fire safety

This same science and engineering and the attractive benefits of the performance based approach, has flowed through to the design for fire and life safety of tunnels, albeit a little more slowly. However, it is still the case for many tunnel projects that the peak design fire size for tunnel ventilation, the fire resistance of the tunnel lining, the distance between tunnel exit doors are all specified by a client or in a required standard for design.

Nevertheless, changes are occurring and the greater use of performance based fire safety engineering, with design solutions supported by fire modelling and analysis and quantitative risk assessment is reflected in recent issues of internationally recognised codes and standards.

INTERNATIONAL CODES AND STANDARDS
Rail tunnels in the European Union are designed in accordance with the Safety in Railway Tunnels Technical Specification for Interoperability (SRT TSI) [1]. This document facilitates performance based fire engineering in its consideration of:

- Tunnel length. For example, clause 1.1.2 states that “tunnels of more than 20 km in length require a special safety investigation that may lead to the specification of additional safety measures not included in this TSI in order to admit interoperable trains (trains complying with the relevant TSIs) in an acceptable fire safety environment.”
- The facilities which are required for a self-rescue as well as evacuation and rescue in the event of an incident. In this regard clause 4.2.2.6.5 states that “alternative technical solutions providing a safe area with a minimum equivalent safety level are permitted. A technical study shall be undertaken to justify the alternative solution which must be agreed by the Relevant National Authority.”

In North America NFPA 130 [2] also facilities a performance based approach to the design of rail tunnel systems. Chapter 1 of NFPA 130 introduces the concept in terms of ‘equivalency’ and in Appendix A the explanation is provided that “the equivalency clause in 1.4.3 permits the use of alternative systems, methods, or devices to meet the intent of the prescribed provisions of a standard where approved as being equivalent. Equivalency provides an opportunity for a performance-based design approach. Through the rigor of a performance-based design, it can be demonstrated whether a station, guideway, or vehicle design is satisfactory and complies with the implicit or explicit intent of the applicable requirement provided by a standard.”
A similar approach is taken by NFPA 502 [3] which relates to design of road tunnels. Again it facilitates the application of performance based design through a concept of ‘equivalency’ which is detailed in section 1.5 of the standard.

Australian requirements for both road and rail tunnels are defined by AS4825 [4]. The approach of this standard is to provide guidance on typical provisions which would be common in various types of tunnels, but ultimately the standard is performance based. It notes in its preface that “the committee decided that the most appropriate format [was] to facilitate the current Australian practice of adopting a performance-based approach to fire safety in tunnels. Such an approach is reliant on fire safety engineering methodologies similar to those described in the International Fire Safety Engineering Guidelines which is extensively used in Australia for performance-based design for fire safety in building.’

The other significant reference standard for road tunnel design is the PIARC guidance, and the PIARC 2007 guidelines on Systems and Equipment for Fire and Smoke Control in Road Tunnels [5]. This document provides general design guidance which is very much performance based. As an example, the section 5.4.1 requirement for emergency exits states the following: “the type of ventilation system – natural or mechanical – determines if and how road users will be affected by smoke. Ventilation must keep escape routes free of smoke, at least for a certain period of time. Escape routes in unventilated tunnels should be shorter than in tunnels with mechanical ventilation.”

**FIRE SAFETY DESIGN PROCESS**
The process of fire safety engineering and performance based design fits very well as part of the overall tunnel design process and the project approval process although the names given to each stage of design and construction may vary between countries. These processes are illustrated in Figure 1 below.
Figure 1 reflects the fact that as general tunnel design progresses, so does fire safety engineering, with the fire safety design progressing from a concept and schematic design, supported by qualitative statements, and later design development supported by detailed fire modelling and quantitative analysis. This process of fire safety design is as outlined in the International Fire Engineering Guidelines [6], SFPE Fire Protection Engineering Guidelines [7] and other international equivalents. This process of fire safety design also sits within a project design context that as the design develops, the uncertainties in design and costs are being reduced, and there are reducing opportunities for design changes as the design proceeds towards a fixed budget cost.

Another important principle of design is to remember that while some design solutions may look attractive in terms of capital cost, there may be severe long term operating or maintenance cost implications. For example, in many PPP projects (build, own and operate tunnel contracts over 30 years) the capital cost is only one third of the overall project cost, and electric power costs may be the largest cost over the life of the project, and excessive tunnel ventilation and power costs are to be avoided in design if possible.

This illustrates how important fire safety engineering is as a design tool and a key part of the tunnel design process.
**FIRE SCENARIOS**

Fire safety engineering is scenario driven. This means it fits neatly with quantitative risk assessment in terms of probability and consequences of potential fire events. The outputs from fire scenario analysis serve well as inputs to the QRA / safety case.

Previous work by Johnson, Gildersleeve and Boverman [8] has shown the benefits of dividing all tunnel fire scenarios into three groups or categories as set out in Figure 2 below.

![Design Fire Scenarios Development Framework](image)

*Figure 2 – Design Fire Scenarios Development Framework*

The great advantage of this approach has been illustrated in recent major tunnel projects such as the Fehmarnbelt Fixed Link between Denmark and Germany and a recent major tunnel project is Brisbane, Australia. This fire scenario development and methodology for design scenarios and design fires provides a clear, objective definition of design fires for much improved stakeholder consultation including:

- A basis for establishing probabilities or return periods for each fire scenario
- A method for incorporating failure of fire protection systems into the high challenge fires as part of sensitivity analysis and,
- A basis for discussion of extreme events which cannot be design cases but for which other measures such as tunnel traffic entry controls, security systems and other mitigation measures can be properly evaluated.

Once the fire safety engineer, design team, fire authorities and other stakeholders have agreed on these fire scenarios and resultant design fires and the potential tunnel occupants expected to be exposed to fire conditions, then the typical Available Safe Egress Time (ASET) versus Required Safety Egress Time (RSET) analysis can be done for fire and life safety evaluation for each scenario.

**RECENT AREAS OF DEVELOPMENT**

The research and engineering communities have developed some new approaches to fire safety engineering in selected areas which have led to more innovation and more cost effective design and operation of tunnels, both road and rail.
Tunnel Structure
The prescriptive approach to fire protection design of tunnel linings is often as follows:

- For road tunnels, the tunnel linings and all associated structures shall have 2 or 3 hr fire resistance to the HC inc time-temperature curve.
- For rail tunnels, the lining of the tunnels shall have a 4 hr fire resistance to the IS0834 time – temperature curve.

This does not properly account for the specific design of the tunnel lining elements, the loading on these segments, the effect of spalling, the provision or not of a suppression system, or the risk associated with a range of different types of fire hazards, except in a very general and generic sense.

Recently Gildersleeve and the design team for an Australian road tunnel have taken a performance based fire safety engineering approach to tunnel lining design [9]. This approach has utilised the risk based assessment methodology now included in the new performance based Australian tunnel fire safety standard AS4825 [4]. The methodology considers a range of design fire scenarios assuming tunnel systems operate as intended and a series of high challenge fire scenarios associated with operator error or fire safety system failures, such a deluge suppression failure.

They have shown that for non-critical sections of a tunnel such as cut and cover structures where the consequence of a localised collapse is tolerable, structures can be designed to meet a short duration hydrocarbon time-temperature curve, based on real tunnel single heavy goods vehicle fire data rather than the traditional building type 4 hr ISO fire resistance. For more critical areas of a tunnel where local collapse would impact adversely on surface structures or cause flooding of the tunnel, a longer duration hydrocarbon fire curve is used representing a multiple vehicle fire.

The approach lends itself well to tunnels with a suppression system that will significantly reduce the frequency of more severe fire incidents and their consequences, and supports the use of fire resisting concrete in a variety of tunnel construction methods including precast segmental tubes, insitu cast and shotcrete arches, and precast, prestressed cut and cover structures. Fire resisting concrete contains selected low expansion aggregate and monofilament polypropylene fibre additives and can result in cost effective construction substantially removing the need for thermal insulation spray or cladding, while also creating valuable time savings and OH&S benefits.

Tunnel Ventilation
The prescriptive approach in standards such NFPA502 [3], AS4825 [4] and the Japanese code for road tunnels [10] suggests that the risk and therefore the extent of prescriptive fire safety provisions increases with:

- Tunnel length
- Traffic volume

There is no doubt that, given all these provisions being equal, that increasing the tunnel length and traffic volume creates the potential for more tunnel accidents and more fire incidents. That is, a major 10km urban tunnel with 100,000 vehicles/ day is likely to have a greater rate of accidents and fires than in a 2 km rural tunnel with traffic volumes of 10,000 vehicles/ day.

However, does the risk increase with tunnel length mean the fire safety provisions need to be stepped up with greater tunnel length? For example, if a road tunnel is increased from 2 to 5 km in length, is there a need to change from a longitudinal ventilation system with jet fans for smoke control to a semi-transverse or transverse ducted exhaust system with all the complexity, cost, maintenance and potential reliability issues that comes with such systems. Especially for lower traffic volumes, if a safety case can be made for a longitudinal system and it works for 2, 3, 4, or 5km, why can it not work for 15 or 20 km? In some cases performance based fire safety engineering and risk analysis can provide the basis for such justification.
**Fire Suppression**
A major decision for road tunnel construction now dominates global design practice. It is whether to install a suppression system or not, and if so, what type?

While the prescriptive provisions of codes and guidelines such as NFPA502 [3] and PIARC guidance [5] were previously against water based suppression systems in road tunnels, they now at least suggest consideration. In part this has been because of the experience of damaging fires and deaths in tunnels without suppression, and the success of suppression in tunnels in Japan and Australia in controlling potentially major fire incidents.

It can well be argued the use of performance based fire engineering, risk analysis and cost benefit analysis has shown the clear benefits of suppression in tunnel design [11] in terms of:

- Life safety of tunnel users and staff
- Asset protection, including for buildings and infrastructure above the tunnels
- Fire fighting and access for emergency services personnel
- Operational continuity of the tunnel and the surrounding transport network

Zone deluge systems are also either installed or proposed in at least two rail tunnels in Europe which are carrying dangerous goods, and the use of water mist in rolling stock for the Madrid Metro, which largely runs underground, supports the idea of consideration of suppression for rail infrastructure.

**Evacuation**
In rail tunnels and in road tunnels, prescriptive guidance in standards or in project specifications has exits or cross passages with spacings ranging from 100m to 500m or more, depending upon the code, standard or country.

Given the importance of exits and cross passages for life and life safety, but equally the risks and costs in their construction in many tunnels, there must be a better way than following simple generic guidance. And there is. In recent years, distances along tunnels to exits or cross passages have been subjected to fire safety engineering evaluation and risk analysis to arrive at sensible design solutions that have been granted authority approvals.

**Fire Brigade Access**
Access for the fire brigade is a very important aspect of tunnel design, be it via the portals, via intervention shafts or via emergency stations. The use of fire engineering methodologies for fire brigade intervention as part of an overall safety concept have helped many designs come to sensible conclusions about these fire brigade access points.

In particular, fire engineering and risk analysis have enabled all stakeholders including the tunnel owner and operator, design team, and emergency services to arrive at cost effective solutions instead of following generic rules. For example, if access for emergency services can be provided at 2 - 3 kms intervals along a rail tunnel from an adjacent road tunnel or via surface intervention shafts, there is no need for special third tunnel bore and/or emergency station access. On the other hand for long sub-sea rail tunnels or under high mountain ranges, emergency station access or third bore solutions may be appropriate.

**FURTHER DEVELOPMENTS AND RESEARCH**
The further development of fire safety engineering and risk analysis as tools in tunnel design will combine to drive greater safety and more cost effective construction in all form of tunnels. Some of the key questions of tunnel design continue to be:

- Is it better to have cross passages and exits at 125m or 250m, rather than 500m, or alternatively add a suppression system to a road tunnel?
• If a deluge or water mist system is installed in a road tunnel, can the peak design fire size for ventilation design be reduced from 50MW to 25MW?
• How does the rail tunnel design have to change if there is a desire to carry freight or dangerous goods in the tunnel?
• For which elements of tunnel structures is collapse acceptable, and at what time after the incident?

In order to best understand these questions and optimize designs, we need continuing research in a number of key areas. These areas include:

• Fire scenarios – Lönnermark, Ingason and others at SP [12] continue to provide valuable data on design fires for road and rail vehicles. Their current work with Lund University and others for Stockholm Metro [13] on full scale fire tests for rail rolling stock in tunnels will provide valuable data for testing simulation models which Coles, Yii, Paveley and others have been developing [14].
• Suppression – The work in Europe though the UPTUN [15] and SOLIT [16] programs have provided extensive data on the performance of water mist which can feed into fire modelling and fire engineering analysis. However, there is little similar published work on zoned deluge suppression systems, despite their extensive use in Japan and Australia. This has held back their acceptance in some countries.
• Human Behaviour – A critical element of tunnel evacuation strategies in fire engineering analysis is how do people in rail and road vehicles behave in developing fire incidents in tunnels? For example, what is a reasonable assumption about the pre movement time between the start of a fire incident and people leaving their vehicles and moving away towards an exit in a road tunnel? There is only limited research by Tesson [17] and a few others, but more investigation of this is required.
• Availability - In risk analysis for each scenario developed and evaluated, an estimate needs to be made on the probability of fire protection systems operating correctly upon demand. Data on availability of systems such as suppression, emergency ventilation, heat detection, VAID, emergency lighting, and exit doors is very limited, especially for tunnels where piston effect pressures, vibration, corrosion and dirt accumulation can make tunnels a very harsh environment in which fire safety systems need to operate. The risk analysis should consider the possibility of human error of the tunnel operator and the limitation of resources and training available to the operator.
• CFD Models - For long tunnels, there is a desire to use three dimensional (3D) CFD models to understand fire behaviour in the area relatively close to the fire. On the other hand, the wind and pressure effects at portals, and other impacts of tunnel linings on airflow in long tunnels suggests a one dimensional (1D) model may be only way to practically deal with these effects. Work by Colella, Borchiellini, and others from Edinburgh University [18] has shown that 3D modelling close to the fire linked to 1D modelling in the far field may be an ideal way to account for all tunnel variables affecting airflow and fire performance in emergency ventilation.
CONCLUSIONS

Greater use is being made of tunnels in transport infrastructure globally, especially in the case of road and rail tunnels. At the same time, performance based fire safety engineering and risk analysis have developed to the point that they are often the most appropriate approach to tunnel fire safety design.

There are a range of tunnel design issues for which fire safety engineering is now the tool of choice of designers, and there is a growing use of the performance based approach and risk analysis in international codes and standards for tunnels.

Fire safety engineering has been shown to be useful in helping to solve key tunnel design issues such as suppression, emergency ventilation and fire brigade access. Nevertheless, further research in areas such as human behaviour and egress, design fires and system availability data, and fire modelling will enable even better use of fire safety engineering as a key design tool for tunnels into the future.

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REFERENCES


Human Behaviour in Tunnels
What further steps to take?

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ABSTRACT

Tunnel safety, especially in case of fires, has received a lot of attention due to heavy disasters. However, much attention is paid to controlling and extinguishing the fire, and not so much on the role of human behaviour. In this case, human behaviour includes the behaviour of road users, rail passengers, tunnel operators and emergency rescue services. Increasing the safety of tunnels starts with a proper design. The less chance of small accidents and incidents, the less chance of larger incidents or fires. Good design starts with proper lighting, signalling, enough lateral space and proper transitions from outside to inside the tunnel. In case of an accident or even a fire, in case of accidents or incidents in tunnels, the tunnel user has to understand what is going on in order to be able to show the right behavior. However, the question is whether knowing what is going on is sufficient, since people often underestimate a fire. The first period of a fire is very important, since there is no time to be lost. In case of fires, significant time can be lost from the moment the fire starts until people understand that they are in mortal danger and start of the actual the evacuation process. When this period is long, the possibility for loss of lives increases. Proper unambiguous signs should be provided (e.g. playing a fire alarm sound and specific instructions of a tunnel operator) and the same messages should be repeated via various channels. Information needs to be ‘over-complete’, with if possible a repetition of additional messages. Also, people with visible official status should be sent inside the tunnel to reinforce public address announcements and issue instructions to help people make the right decisions. Tunnel operators should inform the public and should stress that this is not a general message but that this is actually applying to them. Professional truck drivers should be trained to show the right behavior and stimulate others to evacuate. Many training and practice is required for operators and emergency personnel, where joint training exercises are of utmost importance.

KEYWORDS: Human behaviour, road users, tunnel design, evacuation, operator, emergency services.

INTRODUCTION

Tunnel safety has received quite some attention due to large accidents, leading to fatalities, human casualties and a lot of economic damage. In the field of tunnel safety, the human factor plays an important role. To a large extent, tunnel safety is determined by human behavior, where the probability of accidents, the severity of the accidents and their consequences depend to a great extent on the design and operation of the tunnel system as a whole.

But why do we even speak about tunnels as a separate road category? What makes driving in tunnels any different from driving on open roads? In the ideal situation, the level of traffic safety on the road should not diminish in and near tunnels. Tunnels should be designed in such a way that the level of
Safety in and near tunnels is in the basis about the same as on other parts of the road network. Therefore it is important to identify the reasons for the low safety level in and near tunnels.

WHY IS A TUNNEL SO DIFFERENT?

In itself, tunnels are not crash prone but accident severity is somewhat higher in tunnels than on the national road network in general (e.g. [1], [2]). Analysis of the crash types showed that the proportions of frontal, single vehicle and other type crashes in tunnels are similar to those on road network as a whole. Rear-end collisions, however were twice as common in road tunnels as on the open roads. The distribution of tunnel and road crashes is shown in Table 1.

<table>
<thead>
<tr>
<th>CRASH TYPE</th>
<th>INSIDE TUNNEL</th>
<th>ROADS OUTSIDE TUNNEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same direction</td>
<td>43.3%</td>
<td>22.2%</td>
</tr>
<tr>
<td>Opposing directions</td>
<td>17.2%</td>
<td>14.3%</td>
</tr>
<tr>
<td>Crossing and turning</td>
<td>1.6%</td>
<td>23.7%</td>
</tr>
<tr>
<td>Pedestrian involved</td>
<td>1.6%</td>
<td>8.1%</td>
</tr>
<tr>
<td>Vehicle leaving road</td>
<td>29.8%</td>
<td>26.3%</td>
</tr>
<tr>
<td>Other accident types</td>
<td>6.5%</td>
<td>5.4%</td>
</tr>
<tr>
<td>Sum of accidents</td>
<td>372</td>
<td>4917</td>
</tr>
</tbody>
</table>

Crash rates decline with increasing tunnel length, which is in accordance with the fact that entrance zone crash rates are higher than those for the mid-zones. This means that especially at the transition from outside to the inside or vice versa, changes in risk occur. However, there are differences between tunnels. The crash frequencies in the entrance zones were higher for shorter than for longer tunnels. Narrow tunnels (smaller number of lanes) had higher crash rate than wider ones. It was found that there is a concentration of crashes just outside tunnel openings on roads with one-way traffic. In such cases rear-end collisions predominate. These are often related to high traffic volumes and are sometimes exacerbated by blinding sunlight and closely spaced traffic signals [1]. Besides the transitions and changes in lay-out, another major difference to driving on open roads is that if an accident happens, the consequences are far more serious in case of a tunnel compared to the open road (e.g. in case of fire and smoke). This is illustrated in Figure 1.

![Figure 1](image)

The number of people killed and seriously injured per accident in the different tunnel zones [3]

The purpose of this study is to identify some important human behavioral aspects related to design and organizational issues. We will focus on normal and critical situations, and we will focus on various aspects of human behavior, that is the behavior of the tunnel user, behavior of the tunnel operator and the behavior of emergency services. Each of above stakeholders has a specific role in the operation of the tunnel. These roles are interdependent. Bad coordination of these roles and mutual misunderstandings can contribute to errors and eventually to accidents.
NORMAL DRIVING CONDITIONS

Lighting
When entering a tunnel, a rather large reduction in ambient luminance may cause problems in perceiving crucial visual information inside the tunnel. Due to this limitation in perception, crucial information may be missed and dangerous situations might result. A slow adaptation process of the visual system occurs when luminance levels decrease. The eyes need some time to get adapted to the lower luminance level, and in this period of time only objects with a luminance not far below the adaptation level outside the tunnel can be perceived. When approaching a tunnel, perception is also limited due to the amount of straylight in the eye of the driver. Straylight is a constant veil that results from the light that gets scattered in the eye media, in the atmosphere and on the windshield of automobiles. This straylight forms a luminous veil that reduces the visibility of objects in the entrance of tunnels [4], [5]. This plays an important role especially at tunnel entrances, since the presence of high ambient luminance levels near a dark tunnel entrance emphasizes the relative difference and reduces the contrast of objects in the tunnel. Before entering the tunnel, the driver’s fovea is adapted to the sum of the luminance of the surrounding area and the amount of straylight in the eye of the driver [6]. As a consequence, visibility problems inside a tunnel are likely to occur, unless the luminance level inside a tunnel is high enough. Due to the slow adaptation process and the presence of straylight, the luminance level inside the tunnel may appear to be extra low and, consequently, the tunnel appears as a black hole, in which no details can be perceived. Due to a lack of anticipation, the risk of rear-end collisions increases, and due to limited visual guidance, lane keeping might be difficult.

Therefore, large differences or transitions between the luminance level outside and inside a tunnel should be avoided in order to avoid adaptation and perceptibility problems. Improved lighting and tunnel entrance design have contributed positively to a significant reduction in tunnel transition zone accidents (see for an example Figure 2).

![Accident frequency per billion vehicle kilometers travelled within the different tunnel zones](image)

Figure 2 Accident frequency per billion vehicle kilometers travelled within the different tunnel zones [3]

Luminance differences can be minimized by increasing luminance inside and decreasing luminance outside the tunnel. Here the absolute luminance level inside the tunnel is not of utmost importance, but rather the difference between the luminance level inside and outside the tunnel and whether this
transition in luminance level is a gradual one. The luminance level inside a tunnel should allow for sufficient anticipation of objects and the road lay-out.

**Proximity of tunnel wall and lateral clearance**
Due to financial and technical constraints, the lateral clearance in tunnels is often minimized to a degree that is generally considered unacceptable on open roads. The proximity of the tunnel wall to the lane has an effect on perceived narrowness of the tunnel, and consequently on driving behavior.

Already decades ago, it was found that while driving on the right lane, road users drove more to the centerline marking at the beginning of the wall, where the emergency lane was interrupted. This could be an indication of fear to hit the wall with sometimes more than 30 cm change in lateral position even before the tunnel entrance. The lateral position changed again to the old position of the open road after some adaptation to the decreased available lateral space (a.o. [7], [8]). Also, steering frequency increases, indicating strenuous steering, and speed is reduced [9], [10], and [8]. A narrow tube requires better lane keeping, which is facilitated by a reduction in driving speed. On the other hand, the speed reduction can also be the result of the high amount of stimulation in the visual periphery. Research shows that too much stimulation in the visual periphery (about 30 degrees left and right of the fovea), is considered very unpleasant [11]. If the value of 2 rad/s of angular velocity is exceeded, drivers adapt their position and speed to avoid disturbing effects [12]. This speed reduction increases the risk of interruptions in the traffic flow and collisions.

In conclusion, large reductions and rather abrupt changes in lateral clearance should be avoided in order to avoid large or sudden changes in driving behavior and increase the risk of an accident. Reductions may result in increased steering activity, lateral displacement and reductions in driving speed, factors that may negatively affect driving safety since drivers may respond in different ways. In order to avoid reductions in homogeneity, and head-on and rear-end collisions, sufficient lateral manoeuvring space should be provided. A smooth transition should be provided between the standard open road, the road part approaching the tunnel and the tunnel entrance, without any sudden narrowing. Anticipation of the road lay-out seems necessary to prevent uncertainty about the available manoeuvring space and lane width should be sufficient to avoid interfering actions from passing cars and to improve the driving conditions for heavy vehicles. Although higher costs are involved, continuing the emergency lane inside a tunnel does not only guarantee a continuous amount of available lateral space, but also permits clearing the road in case of a car break-down, thereby increasing objective and subjective safety.

**Tunnel length**
Driving through tunnels may in itself lead to increased uncertainty and fear. This fear is partly the result of the experienced threat of getting stuck inside the tunnel in case of traffic accidents or calamities, because of experienced vulnerability and doubts on physical safety inside tunnels in these cases. Drivers mention that tunnel fear is the result of fear of hitting anything, like an object, the tunnel wall or other vehicles, and fear of problems to escape from dangerous situations, for instance in case of a fire or if a tunnel collapses. Due to this latter fear, tunnels that underpass water are considered more fearful than other tunnels, as well as longer tunnels [13], [14].

Although no objective investigations of the effect of tunnel length on driving behavior are available, one can state that extremely long tunnels should be avoided if possible. Also, information should be provided at considerable distance so that drivers can still decide to take the exit road and not enter the tunnel. In extreme cases, drivers may stop just before the tunnel entrance, leading to a large accident risk. It is also important since over-height vehicles have to stop at the tunnel portal or may enter and cause damage to the tunnel structure or system. Also, it provides a final means of forewarning the drivers of hazardous loads that there is a tunnel ahead. Providing some information about the total length of the tunnel or its remaining length may also reduce fear, since this reduces the experienced uncertainty. In some countries, information on tunnel depth is also provided, but this may also increase tunnel fear and is therefore not recommended.
Longitudinal profile
The amount of curvature in a road can have major implications for the possibility to anticipate the longitudinal profile. This applies especially to tunnels, where sight is overall more restricted than on open roads due to the presence of a tunnel tube. The tighter the curve, the more problems will occur with anticipating upcoming situations or responding to preceding traffic. Besides sight distance, tight curves will also affect the amount of effort put into the driving task. There will be more problems with lane keeping, which can either affect driving behavior directly, or indirectly by affecting driver uncertainty. Rising and falling gradients inside tunnels are also important in this respect, since they decrease the possibility to look through the tunnel, reduce sight distances, and limit anticipation. Note that also in tunnel fires, the gradients are important since they may function as a chimney. Besides this, gradients affect driving speed via characteristics of the car, with rising gradients leading to lower speeds and falling gradients to higher speeds. The combination leads to rather large variation in driving speed. Speed differences lead to reductions in traffic homogeneity and affect driving safety in that respect too. It is important to choose a speed limit that is in accordance with the driving and stopping distances, but indicating a speed limit alone does not guarantee that this is also the actual driving speed. The presence of an incident management system, that indicates when a lane cannot be used once a non-moving vehicle is detected, may to some extent make up for short viewing distances [15]. This way, auxiliary information compensates for a reduction of the anticipation distance that drivers normally need. But whenever possible, driving sight and stopping sight should be sufficient for every particular driving situation per se, without any concessions.

Road signs and signals
In general, roads have a large number of road signs to indicate destinations, bottlenecks, road numbers, rest areas, and tunnels. Sufficient information should be provided in order to let drivers reach their destination in an efficient and safe manner, although this should not lead to an overload of information. Research has shown that road users focus their attention on the tunnel entrance about 150 to 200 meters before actually entering the tunnel [16, [17]]. Attention is focused on the tunnel entrance, which means that the environment in front of the tunnel should not ask for special attention. If there is too much information in the area close to the tunnel entrance, information will either not be noticed or attention, normally paid to the tunnel entrance, will be distracted. Therefore, a proper treatment of lateral areas near the tunnel is very important. It should provide a calm and comprehensible picture to drivers in order to allow them to focus their attention to the tunnel entrance. The use of road signs near tunnel entrances should be reduced to a minimum and they should not be erected immediately (150-200 m) in front of a tunnel. Besides general road signs, incident management can be used inside tunnels to inform the driver. In case of a problem, traffic may be guided and lane use can be controlled. A signal, indicating the tunnel is safe by using green arrows, would be useful in reducing drivers’ anxiety. In case of closing a tunnel, there are still drivers that enter a tunnel. At the Tauern tunnel, many drivers simply passed the red lights and continued into the tunnel. A similar test was made some months later at another tunnel for a TV report and it also showed lots and lots of cars ignoring the traffic lights. Traffic lights present no physical obstacle, and also do not say why entry to the tunnel is not allowed. Without additional information, a prolonged red light may simply be taken for a malfunction, and once the first drivers ignore it, others will follow. It is important that a tunnel operator can actually physically close a tunnel.

DRIVING IN CRITICAL CONDITIONS
In the press and at conferences, much attention is being paid to large tunnel fires. After the large tunnel fires in for example Mont Blanc (1999), Tauern (1999), Kaprun (2000) and Gotthart (2001), everyone hoped that such large tunnel fires with human casualties would be history. However, large fire accidents continue and continue. To only mention some, we can mention the London Underground (2002), Burnley Tunnel Fire (2007), Channel tunnel fire (2008), and more recently Oslofjord (2011) and the M4 motorway tunnel (2011) and unfortunately many more. The interesting part here is however that the primary focus is on the fire rescue, whereas there are many stages before that offer part of the solution of fighting the problem. If we can limit the number of accidents, we can limit the chances of fire. And if we improve behavior in traffic jams, accidents or car breakdowns, we
can also limit the chance of additional accidents and fire. The first step to be taken in limiting the impact of a tunnel fire is to limit the chances of a fire, and step two is limiting the consequences of a fire.

Traffic jam
When the traffic intensity approaches the road capacity (or the network capacity) both the driving speed and the distance between vehicles decrease. Sometimes, traffic may even come to a complete standstill for some minutes. This might happen in tunnels on interurban roads as well as in urban tunnels. The risk here is twofold: On the one hand, the risk for head-tail collisions increases, and on the other hand, if traffic drives close together or even comes to a complete stop, the risk is large in case of a fire that the fire will spread quickly. Also, focusing on behaviour in traffic jams in tunnels is important since drivers who are further away from a fire may think they are in a traffic jam, since they will encounter heavy traffic (e.g. [18]). Therefore all precautions need to be taken to improve this behaviour.

One solution is to ask drivers in tunnels to maintain a larger distance between the vehicles. However practice and research have shown that this is almost impossible as well as impractical. Even though many tunnels have signs that indicate to keep a certain distance, people almost never do. In that sense people behave as they would also behave in a traffic jam outside a tunnel, and that is to drive closely together and not keep much distance in case of a standstill. Even in a driving simulator, with road users reading a specific tunnel leaflet just for entering the tunnel that indicated to keep larger distance in case of traffic jam, with road users knowing they are being monitored, drivers did not keep sufficient distance to the lead vehicle when getting in a traffic jam situations [18]. Also, in case of high speed accidents under low traffic volumes, there is hardly any sufficient distance one can keep in order to prevent additional crashes. Various traffic accidents in tunnels are recorded on video, and show that these situations are hard to avoid. The only remedy here is to have strict speed limits, to enforce these limits and to protect accidents or car breakdowns by means of traffic signals warning upcoming traffic.

Vehicle breakdown or accident
The same discussion for traffic jams also holds for breakdowns or small accidents. The absence of an emergency lane does not only affect the proximity of the tunnel wall, with an indirect effect on traffic safety as was already described, but may also have direct effects on traffic safety. In case of emergencies, such as a car breakdown, not enough room may be available to clear the driving lanes. To prevent dangerous situations, to decrease the subjective uncertainty of drivers, and to reduce fear, it is important to have enough opportunity to stop inside a tunnel and good evacuation and escape possibilities, irrespective of whether this is realised by means of an emergency lane or other facilities. Emergency lay-bys facilitate safe parking off the road, and can also be used to work on technical installations. When using emergency lay-bys instead of emergency lanes, some attention should be paid to the overview from this lay-by on the driving lanes. If a car has to leave the emergency lay-by, enough sight distance should be available to judge whether it is safe to merge into the traffic stream. In this respect, an emergency lane is much safer, since they may be used to accelerate in order to perform safer merging behavior. Also, an emergency lane offers extra space in order to avoid collisions. Many videos are available showing how an emergency lane actually helped avoid additional collisions, since drivers were able to steer to the right if the approached still-standing traffic with too high speeds. Besides providing emergency facilities for off the road parking in case of a car breakdown, a sufficient amount of evacuation facilities, for instance turning niches, should be provided for emergency evacuation of the tunnel.

Tunnel fires and evacuation
In case of an actual tunnel fire, it is very important that people behave correctly in order to limit the casualties and injuries. However, there are many studies that show that this behavior is not always the way we hoped it would be.
The Caldecott Tunnel fire (USA, 1982) killed seven people in a road tunnel, involving cargo with gasoline. This tunnel fire also started with an ordinary accident. Shortly after midnight a driver drifted out of lane and the car struck the tunnel wall. The driver brought the car to rest in the left-hand (fast) lane and got out to inspect the damage. The car was almost half-way through the tunnel. The initial accident created a bottleneck for traffic coming up behind. Probably due to the late hour of the accident and a low traffic density, other drivers did not expect a traffic jam. A double tanker carrying gasoline hit the car, and a bus behind the tanker also hit the car and/or the tanker. The bus driver was killed and the tanker driver ran downhill and made it safely out of the exit portal of the tunnel after he saw the first small fires. The natural draught in the tunnel acted as a chimney encouraging the smoke to flow uphill towards the oncoming vehicles and out of the entrance portal. The tunnel ventilation system remained off throughout the event except for a brief period when the level of carbon monoxide exceeded the trigger level. Approximately 20 vehicles entered the tunnel in the next few minutes and most drivers managed to reverse out, prompted by the smoke moving towards them. Four vehicles were trapped behind the burning tanker, some started to reverse out of the tunnel but soon left the car and walked back uphill to warn other drivers. Five minutes after the crash, one pedestrian called for help from an emergency phone but was overcome by smoke. The occupants of another truck responded too late and were also overcome by smoke close to the truck. An elderly couple remained in their vehicle and died. Some people even passed by tunnel escape doors without noticing them. In all, two people died in the initial crash(es), five were killed by the smoke and fire and two were hospitalized for smoke inhalation. All others escaped unharmed. Unknown to the people fleeing east in the tunnel there were safe passages between the two bores at intervals; these might have enabled some to escape from the fire and smoke, but none of the unlocked doors available was used.

What can we learn from human behavior here? That the guy from the gasoline truck was a hero for realizing the danger and bringing himself in safety? That he was a coward for leaving other people in their car and not helping them? Was it a stupid decision that he did not try and extinguish the fire, or was he smart not to lose valuable evacuation time by trying to extinguish a non-extinguishable fire? Were the people who walked uphill stupid since going downhill would have brought them into safety muck quicker? Or were they brave in trying to warn other drivers? Was the person trying to use the emergency phone a hero or again stupid since this action eventually lead to his death? It is always easy to put the blame on people afterwards, after knowing all details, but a fact is that people do what they do, since this seemed to be the best decision at that time. Installing emergency exits is simply not sufficient, and providing drivers with general information at one or several points in their driving career is also not enough. Every tunnel is different, every situation is different and every road user is different, making it difficult to educate drivers on how to behave in general.

In tunnel fires and human factors research, various stages of human response are described. The first of these has been called the interpretation stage. The ambiguity of potential disasters in their early stages, the rarity of such events and the tendency of people to interpret their surroundings in relation to the expectations of normal use, results in the initial cues being ignored or misinterpreted. People see what is going on around them and try to interpret and make sense of it. If they do not realize that there is a fire or that they need to escape, they will most likely underestimate the danger. Only after the fire is noticed, behavior enters the second stage, where people decide what to do next. Any additional information which can be given to people will make effective action more likely. If people are not convinced of the seriousness of the event, they will make the wrong decision, e.g. to wait or see what will happen next. In this stage, people have shown to greatly differ in the number of cues necessary to alert them to the likelihood that something unusual is happening. The recognition of a single cue, such as smoke, was often followed by a search for other cues before people decide what is going on in and what they should do. As emergencies are rare, such a probabilistic model is by definition likely to lead to a misinterpretation. The final stage is where people attempt to deal with the emergency, either by tackling the fire, interacting with other people, or escaping. One important aspect of this stage is that people are unlikely to produce acts under emergencies that they would or could not produce under normal circumstances. These three stages are often called the Recognition, Response and Movement times phases, with the Response stage including all actions other than movement to the exit. The Recognition and Response stages are often collectively referred to as “pre-
movement time” although this is slightly misleading as movement may not occur in the end. The movement is not directed to evacuation only, but also to other activities.

Stage 1: Recognition time
The time taken for individuals to recognize the existence of a fire is a complex function of many parameters. Some of these refer to the individual, their degree of alertness, the extent to which they are committed to their current course of action. During the process of evaluating cues, a person is very perceptive to the overt actions and communications of others, and may choose to mimic these rather than react independently [19]. Although the activities of other people are potentially important, they may also easily be misinterpreted [20]. Separated individuals respond rapidly but family groups wait until clear sign of fire threat. However, if there are many people witnessing any event they may all tend to assume that it is "someone else's problem". The information content of the cues reaching them is therefore of great significance. Whereas in buildings, a fire always starts with a fire alarm, a tunnel fire never starts with this simple and well-known signal. This is a very intriguing issue. Since this alarm is an international alarm (despite differences in sound and pattern, it is internationally recognized by many people), it will at least be a very good first step to understand what is going on. The alarm always sounds when evacuation is in place in buildings. This means that people can be warned without the need to see the fire for themselves. Adding the fire alarm may be a very valuable first step in information and alarming tunnel users and preparing them for evacuation.

Stage 2: Response time, non-egress behavior
Based upon experimental studies as well as on realistically contrived evacuation tests and exercises it has been shown that people may need up to 5 to 15 minutes to decide whether they should do anything at all and finally what to do. In this, the phase of the fire and magnitude of the fire and distance to the fire plays an important role here. Other studies of earlier stages of evacuation show typical behavior patterns characterized by uncertainty, confusion and inefficiency [21], [22]. In the Caldecott accident, the gasoline truck driver probably realized the danger from a professional viewpoint and therefore acted quickly.

The problem with fires is that one may underreact, not realizing the seriousness of the event. People are not very good at predicting the actual growth rates [23]. When the fire is small people do not feel threatened because they do not realize how fast the fire will develop. On the other hand, they may overreact. During anxiety a person’s focus becomes very narrow – only allowing processing of the most obvious elements of the environment. This is confirmed by [24], who reported about actual behavior during the fires in the Mont Blanc and Tauern tunnels in 1999. The main conclusions are that people will stay in their cars as long as they do not recognize the threat of the fire. This is concluded based on the fact that in the Mont Blanc tunnel fire many victims were found inside or near their vehicles. This means that they did not start evacuating in time. In the Tauern tunnel fire, most of the people had the sense to flee on foot. Only three people stayed in their cars and died. Not to forget, a lot of people got out at an early stage, saving their life. The victims of the Gotthard tunnel fire "died because of their false appreciation of the situation and their incorrect behavior as they waited or tried to turn their vehicles, instead of proceeding immediately to emergency exits" [25]. Analyses of the Kings Cross fire in November 1997 [26] came to the conclusion that human behavior depends on the role of a person. For example a commuter who travels every day with the same goal is likely to follow the same pattern as usually even during an emergency. The Summerland fire (1977) showed that deaths were statistically most likely to occur amongst people who were in groups when first alerted. People already in groups started to move later than individuals separated from other group members, and moved more slowly as a group. At least three-quarters of the people interviewed escaped with at least one other group member. However, this may also be turned into efficient behavior if one person starts to show the right behavior, and others may follow. However, it depends on who that person is. If it is the head of a family, the family may follow. However if it is the 14 year old son, the parents may not be convinced that this is the right behavior. Therefore it is extremely important to provide different cues that all provide the same behavior and offer as much official and unambiguous cues.
A driving simulator study [18] found that even directly after reading a leaflet about what to do in various critical situations in tunnels, drivers were not very effective in applying the information. About 60% of the drivers switched off the engine spontaneously, after reading the leaflet this increased to 70%, only with the help of the operator this number rose to 100%. Not too many people used the radio to get additional information, not even after reading the leaflet (in which this was recommended). Some people wanted to use the radio but mentioned they had forgotten the frequency indicated in the leaflet. The most crucial action: getting out of the vehicle (or stating one would), was highly affected by the statement of the operator. Whereas 65% of the people indicated they would want or try to leave the vehicle, with 75% of the people who read the leaflet, this number increases to 94% after the operator announcement. So reading the leaflet already improves the situation somewhat compared to not getting any additional information. However, with the help of an operator voice, performance improves even more. This leads to more people doing the right thing, but also to getting into action more quickly. Even though participants already had passed the tunnel 3 times before and had a chance to see the exits inside the tunnel on ride 4 as well, some people still indicated wanting to use the tunnel entry to leave the tunnel. In the last group, in which it is specifically mentioned by the operator, no-one mentioned this. What was striking was that quite some people indicated they did not have an idea of how to handle the given situation (even in the condition with leaflet and operator). This means that there is a lot of uncertainty in the case of accidents or incidents in tunnels, even though there is an operator voice, and even though people read the leaflet.

Stage 3: Egress time, movement
When people finally are threatened from the fire it can be too late because of the smoke and the heat. Also, because tunnels are enclosed spaces, fires that occur result in poor visibility and the spread of smoke and toxic gases along the tunnel, the rapid development of high temperatures and a reduction in the level of oxygen in the air. Also from human behavior in fires in buildings we can learn a lot. Research has demonstrated a remarkable consistency in people's behavior during emergencies in an apparently wide variety of settings [27], [23], [28], [29]. Much effort has gone into measurements connected with the movement stage of evacuation, although it is now appreciated that this stage may not be the main determinant of the overall evacuation time.

The tendency of people to stick to the routes they know may be overcome to some extent by the provision of guidance systems (e.g. signs). Good direction signs on the other hand speed up evacuation [30]. The fact that in tunnel fires, many people try to drive or walk out of the tunnel entrance or exit, irrespective of the presence of emergency doors shows this as well. Since people know that there is open air at that entrance or exit, they prefer to choose the secure option, even allowing them to stay in their car. Reversing out of the tunnel in case that turning is not possible is also an option that is seen as safe and secure. Leaving your car and going through a door one does not know is not a very attractive option if one thinks one has an alternative.

Using fire extinguishers
Even though there is a lot of debate on whether we want ordinary drivers or train passengers to try to use fire extinguishing equipment, there is at least sufficient evidence that they do not sufficiently know how to use them. On the bus in the Huegenot tunnel, the co-driver attempted to smother the flames with clothing which promptly caught fire. No one even thought of using the fire extinguisher onboard the bus, or any of those available in the tunnel, being only 50 meters away. In the Mont Blanc tunnel, the Belgian lorry driver survived, warned by the flashing headlights of oncoming vehicles, but said not to have time to use his fire extinguisher. In Tauern tunnel fire, the first extinguisher was taken out of its housing 5 minutes after the crash. Following the Taegu fire, the newspapers stated that the passengers could not do anything except panic with no one attempting to use the fire extinguishers placed under the seat. In a safety drill, following the tragic incident, it took people as long as 33 seconds to find them even if they were aware of the location. The blaze on the subway car in Taegu was raging in less than 10 seconds. Only 38% said they knew how to operate the extinguishers. In many countries, learning how to use a fire extinguisher is not part of any normal training.
Fear to leave the car
In the unpublished car simulation tests carried out for Eurotunnel, people were presented with cosmetic smoke from a car at the front of the wagon, while seated in their cars. People in the cars behind the "fire" were observed to sit and watch developments, in some cases they just closed their windows to keep the smoke out of their own car. They only evacuated the car and the wagon when they heard an instruction to do so, or saw others leaving. This corresponds to the simulated fires in two driving simulator studies for the UPTUN project [18], where drivers also closed the windows and put off the fan in order to keep the smoke out of their vehicle, and in case of trucks, truck drivers tried to pass the fire and drive out of the tunnel.

Witnesses from the Tauern tunnel reported how some drivers refused to leave their cars, despite the chaos around them. Others even tried to maneuver their vehicles in the middle of the smoky inferno and drive in the opposite direction. In the St Gotthard tunnel, it was estimated there were about 200 vehicles inside at the time of the fire. About 100 cars turned around and left the single-bore, two-lane tunnel. Once the cars were cleared, a bus full of passengers managed to reverse out of the tunnel, as did about 15 trucks. Some drivers stayed in their vehicles and tried to telephone for help. Of the 11 (eventual) fatalities, six of the bodies were found on the tarmac as people tried to reach safety, while the remaining four were in their cars. There were fewer vehicles in the Mont Blanc tunnel, but these were not able to get out. Most of the drivers, both in trucks and in passenger vehicles, stayed inside or near their vehicle. Of the 10 passenger vehicles, 4 had started to make U-turns, but were stopped practically at their point of departure. 27 of the victims were found in their own vehicle, 2 in other vehicles, and 9 elsewhere in the tunnel or refuges.

These observations receive support from a recent truck fire incident in the 7.3 km subsea tunnel in Norway on the 23rd of June 2011. A truckload of wastepaper on the lower end of the 3km long and 7% downhill slope caught fire due to engine failure. 34 people were caught downstream in the smoke. Some tried to back out in reverse their car, while others tried to turn around and drive out. Some succeeded, but some crashed with the tunnel wall and other drivers collided with other vehicles. One person was struck and injured by a car as he fumbled along the tunnel wall. Of those who left their vehicle, 7 were found huddled together in emergency phone booths, some tried to enter the cabin of a truck standing 200m from the fire, and one climbed through an inspection hatch for geologists and found refuge and fresh air in the 0.5-1m wide space between the rock face and the lining. The rest were sitting in their cars when rescued by the fire brigade just in time to avoid fatalities. Altogether, 33 people trapped in the smoke. Of the 33 people trapped in the smoke, 28 were sent to hospital with (serious) smoke damage. One of the drivers who stayed in his vehicle was rescued unharmed by the smoke. He had a new car, relatively air tight with a pollution sensor triggering automatic shift to recirculation of air in the vehicle.

Moving in smoke
The following situations illustrate that even for people who want to evacuate, this is not an easy job if too much time is lost before they come into action:
- Zarifa (Baku Metro): “It was pitch black and we couldn't see each other anymore… We groped along, somehow managing to hold onto each other and find our way out.”
- Un-named lorry driver (St Gotthard): "The smoke got thicker and thicker and it got to the point where I couldn't see any more. I felt my way down from my cab pressing my hands against the wall and reached a door through which I was able to gain access to the service tunnel."
- Marco Frischnecht, Swiss lorry driver (St Gotthard): "Luckily, I drove there every day and I know where all the emergency exits are," he said. "It was dark. You couldn't see a thing, not even the lights along the edge of the tunnel."

Large numbers of those questioned after the fire in the Zurich metro were moving through smoke from the very beginning. One person said "the air was so filled with smoke and it was so dark that I could not see the ground, or my own feet, or people standing next to me." In the Zurich fire, the smoke irritated eyes and respiratory systems almost immediately. In spite of a normal walking speed, people were exhausted after advancing only a few hundred meters. The last passengers left the tunnel roughly 20 minutes after the burning train came to a standstill. The longest escape out of the tunnel
was about 700m. The length people can move in smoke depends on the proper use of ventilation, the toxicity of the smoke (depending on the material that is burning), the temperatures, the slope of the tunnel and their physical condition. This clearly shows there are limits to self-rescue through smoke.

ROLE OF TUNNEL OPERATORS

Even though there is a lot of attention to tunnel user behavior, there is also a large role for the tunnel and train operator behavior in case of tunnel fires. The tunnel operator needs to detect incidents and accidents and communicate to the tunnel users by means of loudspeakers, the emergency phones or by activating tunnel signals and closing the tunnel.

The tunnel operator tasks are:
- Monitoring the traffic flow and situation in the tunnel (and vicinity) using cameras, sensor readings and communication equipment. A bottleneck here is that constant vigilance is required, which is a difficult job since under normal conditions not much happens.
- Preparation for effect reduction in case of accidents.
- Fast and correct detection of any event or disturbance likely to escalate into an incident.
- Closing the tunnel; switching equipment to 'emergency mode' (lights, ventilation, speed limits, escape doors, etc.).
- Alerting other operators (where applicable), rescue services and tunnel users (instructing them for escape if necessary).
- Communicating with tunnel users to help them escape and to help them help others or correct the situation (for example: putting out a small fire).
- From the control room, assisting the rescue services in their rescue operation.
- Evaluating and registering the incident for the purpose of improvement.

In the operator task, bottlenecks may be cognitive load, education, training and experience. Since tunnel accidents and fires do not happen very often, the amount of exercise on the job is extremely limited. Therefore sufficient training and exercise with road users and rescue services is extremely important.

However, the behavior of the tunnel operator is not always perfect. The cognitive load model ([31], [32]) distinguishes three load factors that have a substantial effect on task performance and mental effort of a tunnel operator. The first factor is the percentage of available time that the operator is occupied with his or her tasks. The higher this percentage, the higher the cognitive load. The second is the level of information processing, which relates to the complexity of tasks, with experienced tasks demanding the least cognitive effort and new tasks ask the most. The third one is the number of task-set switches, which refers to the number of switches the operator has to make between different task-sets. The more switches, the higher the cognitive load.

Combination of these factors yields an indication of the operator’s cognitive load, which is represented in Figure 3.
Cognitive overload (red area) can occur when the operator does not have enough time to finish the tasks, the operator tasks are too complicated or the operator has to perform too many tasks at the same time (or a combination of any of these elements). On the other hand, if all three elements are “low”, cognitive underload can occur (orange area). Cognitive underload, just as overload, may lead to suboptimal performance. Ideally, the task load matches the operator’s mental capacity in a certain task setting (green area). Other identified bottlenecks (although this list does not include all bottlenecks identified) were:
- Vigilance problems during long periods of normal operation (related to underload).
- Unclear allocation of responsibilities and authority to personnel.
- Insufficient skills due to lack of practice exercises, especially with the rescue services.
- Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.
- Too many incoming signals, not all of which are relevant at this time (related to overload).
- Absence of or insufficient coordinated procedures between operators and rescue services.
- Absence of adequate incident evaluating and registration procedures.
- Mistake in incident is not evaluated or registered due to fear for career consequences.

After the tasks and bottlenecks were identified, the next step was to find solutions for the most important bottlenecks and designing an improvement strategy. Using a prioritized list of bottlenecks and general methods for influencing operator behavior generates possible solutions for the most important bottlenecks. Possible solutions can be found in terms of:
- recruitment (assess the proper criteria),
- training and exercise (to improve skills, but also to test the effectivity of procedures),
- personnel and organization (number of people present, working method with time schedules and organizational culture),
- task support (such as procedures and guidelines), and
- control room and interface design (technical tools, such as one button to indicate a major accident, good tools to instruct the tunnel users).

Proper training and clear appointments of responsibility and operating procedures in case of incidents are the most crucial element of tunnel operator behavior

**ROLE OF EMERGENCY SERVICES AND TRAIN OPERATOR**

Directions given by people in “authority” are clearly a strong influence, as evidenced by Kings Cross (directions given by British Transport Police; London Underground staff and members of the public were not viewed as “authority” and thus were often ignored), St Gotthard (instructions to back up given by truck drivers, and later police), Zurich (directions to the portal given by the train drivers), San Francisco BART (directions from the train driver; cross-passages to the adjacent tunnel were spaced every 100m), etc.
In the Zurich metro [33], passengers on the first train were warned. Although the tone of voice from the loudspeakers seemed uncertain and nervous, the passengers heeded this advice (to wait until told to leave). Those who tried to disembark were held back by fellow passengers. Passengers on the second train remained seated, but knew that something was wrong when the conductor ran through the train declaring that there was a fire in the tunnel. There were different moods on the various exit platforms of the second train. Several people were unsure if they could have made it without presence of rescuers. It is of utmost importance to provide clear directions and instructions.

Research evidence from Kings Cross and other disasters can be used to propose certain principles to be followed in design, management and training. Information should be given rapidly, should be informative, early action should be emphasized and messages should be repeated in various forms and by various means. The need to persuade passengers to act appropriately is a key focus of emergency response; they must be provided with the maximum amount of information. Much of the delay frequently seen in evacuation is associated with people seeking confirmation before starting to act "abnormally".

One member of the Huguenot tunnel operating staff had driven into the tunnel. His vehicle was immersed in dense smoke and therefore he drove his way out again, feeling his way along the reflective studs in the centre line of the tunnel, all the time calling out to anybody still in the tunnel. Fortunately there were no people overcome by fumes lying in the road were they could be run over by his vehicle while he was doing this. (At Tauern, firefighters walked in front of their vehicle to prevent accidents like this). During the Bethnal Green incident London Underground staff, and those from the emergency services, were moving in the opposite direction and impeding the flow of passengers. This was really only a problem due to the narrow tunnel and the large number of people attempting to evacuate.

In some of the worst disasters (Baku, Kaprun, Taegu), the train doors were not opened, either because a power failure made this impossible, or the staff neglected their duty. The latter reason was suspected in Taegu, where the driver of the second train allegedly fled the scene without opening the doors, taking the master key with him, and leaving passengers trapped in their compartments. It took almost 2 minutes for a student taking part in the drill on the Seoul subway system to get out of the train by manually opening the doors. Victims of the Taegu fire would have had about 57 seconds to get the doors open before being smothered by the flames and smoke. About half of the 50 subway passengers interviewed in Seoul said they know how to operate the emergency equipment inside the trains that are used to open the doors manually.

Members of staff will usually behave in accordance with their training, but mistakes can be made. The two recovery staff who first arrived at the incident site in the Hong Kong Cross-Harbour tunnel had not fully complied with the standard emergency procedures. They did not wear smoke masks when entering the scene. They used a fire extinguisher instead of a fire hose to control the fire. One member of the staff left the scene to help with the evacuation, but should have stayed to work as a team. Both members of the staff should have stayed at the scene to hand over the operation to the fire officers on their arrival. According to the report from the rescue staff, as they did not wear smoke masks, they felt uncomfortable because of the heavy smoke and could not stay at the scene. Both staff proceeded to conduct evacuation. Failure to follow standard procedures may put the staff at risk.

The fire brigade is not immune from mistakes either. The fire brigade in the Huguenot tunnel fire scrambled immediately, but did not follow all the laid down procedures and therefore some of their operations were delayed. At Kings Cross, most fire-fighters returned to street level to collect hose and breathing apparatus; however three officers remained in the ticketing hall to supervise the evacuation of passengers. One of these three (the senior officer), Station Officer Colin Townsley, subsequently died after trying to rescue a woman passenger. At Mont Blanc, Chief Tosello of the Chamonix fire department died because there were insufficient BA kits, so he was sharing with one of his men. He had a heart attack following smoke inhalation while sheltering in a refuge with 4 other firemen.
Once rescue teams (police, firemen and medical services) are informed about tunnel accidents, they have to act in order to reduce possible consequences. By collecting data from different countries, it was possible to analysis the rescue team tasks. The main important issue in the case of rescue teams seems to be ‘what needs to be done’ (functions) and ‘who does it’ (actors).

The recent Norwegian fire disaster showed that additional measures such as rescue by ATV and IR camera greatly improves finding people and maneuvering between stranded and crashed vehicles. Also, quickly providing oxygen masks to people who escaped is very important to control the consequences.

Training and full scale exercises should always be done with all parties involved. Current training objective are often too general and evaluation sessions with rescue teams and the identified bottlenecks in the current way of training provides the opportunity to optimize training sessions. The structure of the training course should be based on the fact that the team members learn things at several levels, which they can use or apply while carrying out their job in the team.

CONCLUSIONS

The human response is a very important factor in case of tunnel accidents. As we have seen there are a lot of factors that can prevent the human being from doing the right thing. If road users do not know how to behave properly, they may wait too long in their cars. If tunnel operators are not properly selected, trained or supported they may make the wrong decision and all different parties involved from the rescue services may falsely expect the other partner to respond or may not receive the right information.

Avoiding tunnel fires starts with avoiding accidents in tunnels and limiting the consequences by a proper design, enforcing the right behavior, and using signals to inform traffic about appropriate speed limits, the closures of lanes or traffic jams. This is the first step in tunnel safety. This can be done with the proper lighting, allowing smooth transitions from outside to inside the tunnel, by avoiding sudden changes in lateral clearance of the tunnel, preferably having an emergency exit inside a tunnel, by having one-directional tunnels only, by having traffic signals above the lanes being able to dynamically control lane access and speeds.

However, in case that something happens, the tunnel user should be provided with accurate, specific and timely information. Since people underestimate the development and consequences of a fire, a lot of effort should be put into having people understand that a) there is a fire and b) it is serious and c) they need to evacuate. The first and second part can be activated by sounding a fire alarm inside a tunnel. But this is not sufficient. Information needs to be ‘over-complete’, with if possible a repetition of additional messages. Also, people with visible official status should be sent inside the tunnel to reinforce public address announcements and issue instructions to help people make the right decisions. Tunnel operators should inform the public and should stress that this is not a general message but that this is actually applying to them.

The presence of other people affects the individual and results in group behavior. As soon as someone reacts in a way that other people note, the behavior spreads among a group. Unfortunately, this also holds for negative behavior, such as staying in your car. It is therefore very important to stimulate the right behavior, e.g. by educating a specific group of drivers such as professional drivers (truck and bus drivers) by educating it is their responsibility to show the right behavior and instruct others to evacuate.

Critical attention should be paid to the communication procedures and facilities between the tunnel user, operator and the emergency rescue services. Only by proper co-operation can we limit the consequences of disasters. Tunnel operators and emergency rescue team members should be properly selected, trained and supported and bottlenecks should be identified in order to solve them. For rescue teams, standard operating procedures should be made and specific emphasis should be put on
knowing the responsibilities and training with all parties involved. Only by focusing on all three human groups in tunnels, tunnel safety can be improved.

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Advantages of Electronically Controlled Sprinklers (ECS) for fire protection of tunnels

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ABSTRACT

A new concept of smart and flexible electronically controlled sprinkler activation and the associated equipment recently developed at Gefest Ltd. (St.-Petersburg, Russia) are presented. The concept combines features of conventional activating sprinklers in statically assigned sections and of individual sprinkler activation due to passive warming of the thermal link. Dissimilar to the conventional methodologies, the proposed concept offers opportunity of dynamic adaptation to fire development and uses electronically enforced sprinkler activation. The expected advantages of it as compared to the conventional sprinkler-based systems are outlined.

INTRODUCTION

Vehicle tunnels exhibit high risk of fires [1]. Indeed, past events show that road accidents in tunnels (including those located in an urban area) are often accompanied by fires. According to recent Russian statistics [2], probability of fire to develop as a consequence of an accident in a tunnel is statistically 1.4 times higher than that in a highway.

Fire hazard in tunnels is aggravated due to a number of reasons listed below.

- High traffic intensity, significant amount of combustibles carried by vehicles, space confinement.
- High speed of fire growth which results in critical values of smoke concentrations, temperatures, oxygen depletion, and probability of disintegration of structures being achieved very rapidly.
- Restricted access of fire brigade, impossibility of quick evacuation of occupants. This was a reason of numerous casualties in catastrophic tunnel fires in the Mont Blanc tunnel, (France, Italy, 1999), the Tauern tunnel (Austria, 1999), the Gotthard tunnel (Switzerland, 2001), and the Frejus tunnel (France-Italy, 2005).
- Insufficient water and/or power supply, restricted capabilities of automatic fire suppression systems.

Fire protection systems currently installed in road tunnels fall in one of three categories.

1. Drencher-type systems in which protected area is divided by a number of sections. The sections are protected by the spray curtains with characteristic size of water droplets in a range of 200 to 300μ (FOGTEC being an example). According to recommendation by SOLIT [3] such a fire suppression system should be activated in 3 min, the length of the section should be of 25 to 40 m, and the
operating time should depend on the tunnel length (30 min for tunnels up to 500 m and 60 min otherwise).

High efficiency of the drencher-type systems is provided by the water supply to the entire section having area which is considerably greater than that engulfed in fire. If properly operated, such a system can quickly extinguish fire and prevent fire spread. However, for such a system an excessively high amount of water may be required, which, in turn, implies high power pumps to be installed. In some circumstances, excessive water supply may cause additional and unjustified damage. Also, if fire occurs at the boundary of two sections, wrong decision could be made by the fire detection system on which section should be activated.

2. Sprinkler-based systems which make it possible to supply water locally, depending on local temperature rise. Non-burning area is therefore not affected, and the water supply rate is reduced accordingly. The drawback of such an approach is thermal inertia of the sprinklers and high sensitivity of the activation time to the ceiling height and to the heat release rate in fire. Therefore, the area covered by activated sprinklers may not expand as rapidly as required to suppress horizontally propagating fire.

3. Mobile fire suppression systems capable of moving along the water pipe. Such a system is designed to get connected to the water supply at a location nearest to the fire origin. The example of such a system is that produced by the Engineering Centre of Fire Robots Technology (http://firerobots.ru/).

Note that high activation inertia is a potential drawback of each of the above systems.

To achieve optimum performance, we suggest combining advantages of the drencher-type and the sprinkler-based system in a single one. Operating principles of such a hybrid system are as follows. Sprinklers are activated by breaking the thermal link up when its temperature approaches critical value and/or by any other signal from smoke or heat detectors. Activated sprinklers indicate location of fire origin. Once a fire origin is localized, a number of adjacent sprinklers is activated to cover a confined area surrounding the fire origin. The key point here is to keep the wetted area as small as possible yet ensuring fire suppression. As such, a number of sprinklers simultaneously activated as a group should be in a range of 6 to 10 items. Automatic collection of the information on the status (active or inactive) for every sprinkler is required.

To the author’s opinion, the above principles make it possible to design new generation of the automatic fire suppression systems which rely on a variety of activation algorithms flexibly adapted to a particular fire scenario. Key component of such a system is a sprinkler with enforced activation. As described below, its activation mechanism (traditionally based of a breakup of the thermal link) is complemented by the additional option of controlled activation.

The purpose of this work is to introduce new concept of smart and flexible electronically controlled sprinkler activation and the associated equipment recently developed at Gefest Ltd. (St.-Petersburg, Russia). The expected advantages of it as compared to the conventional sprinkler-based systems are outlined in the paper.

**DESCRIPTION OF THE SYSTEM**

Here we introduce the Aqua Gefest sprinklers designed and produced at Gefest Ltd. (St.-Petersburg, Russia), which are activated by the electric resistor placed directly on the thermal link (bulb). The resistor warms up by electric current thereby breaking the link up more rapidly than that in case of “passive” heating (Fig. 1).
This sprinkler design provides option of full control over the sprinkler status thereby increasing reliability of the entire system. Automatic detection of sprinkler activation individually for every sprinkler is capable to adopt control algorithms of any complexity.

Controlled activation of the sprinkler could be done in one of three regimes: (1) automatic, by electric signal sent by the fire detection system; (2) automatic, by electric signal sent by the activated sprinkler(s) and/or water flow sensor; (3) manual, be electric signal sent by an operator (from either remote control center or local console). Note that the console must be secured from the unauthorized access. Manual activation is recommended to create spray curtains, in all the other cases automatic activation is a matter of choice.

Within the above concept, every sprinkler has its unique address, and the entire system represents the address field. The structure of the address field is designed to reflect the expected direction of fire spread in the most probable fire scenario. At this stage, every sprinkler is surrounded by a group of associated (satellite) sprinklers which will be activated as soon as the “main” sprinkler is activated. Configuration and composition of groups assigned to different sprinklers could be different; the number of groups is equal to the number of sprinklers. Thus, at the design stage the following decisions are made.

1. Type of fire load and most probable direction of fire spread.
2. The minimum size of the area corresponding to a single satellite sprinkler group.
3. Composition and shape of the satellite sprinkler group.

The example is illustrated in Fig. 2 which shows the compartment area protected by the array of sprinklers, each located in the corner of a rectangular. Two groups with 9 sprinklers are highlighted. Group 1 in Fig. 2 represents sprinkler location remote of the walls. If the central sprinkler is activated (shown red in Fig. 2), then the entire Group 1 is activated as well (“if-then” algorithm). Alternatively, Group 2 is located in the corner. In the latter case, the entire Group 2 is activated when not just “main” but any sprinkler within the group is activated (“if-or-then” algorithm). It can be seen that activation of any sprinkler triggers protection of a certain confined section, which makes this system similar to the drencher-type one. Note, however, that in the proposed system, protected section is determined dynamically, depending on the rate of fire growth and direction of fire propagation.
To manage the system, special control equipment “Olimp” has been designed and produced by Gefest Ltd. (St.-Petersburg, Russia). Olimp is capable of processing a large number of sprinkler addresses and generating signals to activate sprinklers according to the algorithms adopted. Worth noticing that currently available fire automatics equipment appeared to be not suitable for this task, which inspired development of Olimp to manage electronically controlled sprinklers Aqua Gefest. When applied for tunnel fire protection, appropriate activation algorithms (including number and addresses of sprinklers, configurations of satellite sprinkler groups) could be dynamically loaded in Olimp depending on the current traffic in the tunnel, e.g. on availability and speed of heavy good vehicles, vehicles carrying oil products etc.

ADVANTAGES OF ELECTRONICALLY CONTROLLED SPRINKLERS (ECS) FOR TUNNEL FIRE PROTECTION

The expected differences in operation of the conventional sprinkler-based system with subsequent activation and new group-based system developed in this work are illustrated in Fig. 3. Potential advantages of electronically controlled sprinklers (ECS) for tunnel fire protection can be summarized as follows.

1. In automatic activation regime, electronically enforced sprinkler activation above the protected area makes it possible to suppress or localise fire more quickly than that without the electric enforcing. This is expected to be particularly important for tall compartments of 8-10 m ceiling height with high fire load.

2. Manual activation regime provides an option of better managing the occupant evacuation and firefighter intervention by direct protection of the appropriate pathways. Manual operating of the system may require CCTV monitoring.

3. There is an opportunity to exactly determine location of fire origin. If the fire propagates in different directions, signals received from the activated sprinklers make it possible to introduce corrections to the pre-planned evacuation pathways in accordance to the actual fire development.

4. Opportunity of automatic connection of the sprinkler activation system to the alarm system to manage occupant evacuation.
WORK IN PROGRESS: FULL SCALE TESTS AND FIRE MODELING

Ongoing field tests, which have already shown reliability of Olymp system and Aqua Gefest sprinklers, are currently performed to quantitatively assess the efficiency of the entire methodology as compared to more conventional sprinklers with “passive” activation. The important issue that may have a considerable effect on the efficiency of fire suppression system developed in this work is the effect of ceiling height. Indeed, in case of conventional sprinkler activation by heating the thermal link up, higher sprinkler locations may result in delayed sprinkler activation, and the appropriate activation algorithm should be elaborated for the newly developed methodology.

To investigate this effect numerically, the following scenario is considered. Sprinklers are located just below the ceiling of the large compartment (ceiling height varies) in the nodes of rectangular mesh, each sprinkler covers area of 12 m$^2$. Thermal inertia of the sprinklers is quantified by RTI = 140 (m·s)$^{1/2}$ and the activation temperature of 67ºC. Water flow rate through a single sprinkler corresponds to the water flow rate per unit of protected area equal to 0.08 l/(m$^2$·s). Initial median volumetric diameter is set to 200μ.
Combustible material is located in the center of the compartment. After fuel is ignited in the selected point, flame spreads horizontally at a speed of 0.01 m/s. Fuel burns at a rate corresponding to 300 kW/m$^2$ (heat release rate per unit surface area). All the other settings are chosen as default values in FDS-5 [4].

For numerical studies of fire suppression, three computational tools are exploited: the in-house model and software tool Fire3D (for example, see [5]), FireFOAM solver [6], and Fire Dynamics Simulator [4]. FDS simulations shown in Fig. 4 illustrate the effect of ceiling height in a large compartment and demonstrate that fewer sprinklers have been activated for ceiling height of 10 m than for ceiling height of 5 m (after the same time period after ignition). Further simulations and experimental studies are required to identify fire scenarios in which expected advantages of the proposed system are most pronounced.

REFERENCES
3. SOLIT (Safety of Life In Tunnels), http://solit.info
ABSTRACT

The extreme temperatures possible in a tunnel fire can do extensive damage to a tunnel’s structural elements. This is recognized in the latest edition of NFPA 502, Standard for Road Tunnels, Bridges and Other Limited Access Highways, which now requires that both surface and reinforcing steel not exceed specified temperatures. Unless otherwise stipulated, the default input temperatures are described by the Rijkswaterstaat Curve (RWS). This requirement is quite rigorous and generally results in the need for some form of temperature mitigation, often the installation of a thermal protective board. It can be shown that a fixed fire fighting system (FFFS), commonly known as a sprinkler system, can offer significant protection to tunnel structure and system components from the extreme temperatures possible in tunnel fires. In many cases the temperature reduction is sufficient to eliminate the need for other mitigation measures. This paper explores both the reduction in maximum temperature and the shorter duration of fire to be expected with the application of FFFS’s on tunnel fires.

Computational fluid dynamic simulations using the Fire Dynamic Simulator (FDS) program are presented showing typical temperatures with and without a FFFS. Relative temperature performance of the various types of FFFS’s such as high pressure mist and traditional deluge sprinklers are also reviewed. The ability of FFFS’s to prevent spread of fire from an initial incident vehicle to other vehicles and fuel sources is explored and an assessment is made as to how this affects the potential duration of a tunnel fire. The summary temperature and duration limitations are applied to the formulation of a modified time-temperature curve to be used when a FFFS is employed. This is then compared to the RWS curve.

Heat transfer analyses are presented showing expected concrete temperature gradients at various depths within tunnel structure, with and without a FFFS. The Summary temperature gradients are then compared to surface and reinforcing steel temperature criteria as established in the standard. The extent of tunnel structure potentially exposed to elevated temperatures is presented, with and without a FFFS.

OVERVIEW

In the past considerable damage to tunnel structures has been experienced due to fires, prompting research into how fire damages tunnels and what measures best protect tunnel structure from fire. While no tunnel collapse has occurred, the resulting damage in some cases has been extensive, resulting in significant closures and loss of service. Examples of the potential scale of these fires and resulting economic impacts are highlighted in Table 1. Although structural failure has not resulted in tunnel collapse or loss of life the potential for this has come to the attention of tunnel life safety authorities and regulatory officials. In response, the National Fire Protection Association (NFPA) Standard 502, Standard for Road Tunnels, Bridges and Other Limited Access Highways, 2008 Edition (1) now stipulates in Article 7.3.1 that all primary structural concrete shall be protected to maintain
life safety, provide a tenable environment, mitigate structural damage and prevent progressive structural collapse.

The primary purpose of this paper is to provide information as to the temperatures likely to be seen in a large tunnel fire and in particular an example of the degree of temperature reduction offered by FFFS’s and resulting temperatures within concrete structure. It does not address whether or not these temperature exposures will cause damage to the concrete structure or as to the resulting economic cost of the damage.

The range of temperatures possible in a tunnel fire will depend on many factors including anticipated fire load, ventilation conditions, tunnel geometry, type of FFFS etc. Each tunnel and fire scenario must to be evaluated for its’ unique characteristics.

<table>
<thead>
<tr>
<th>Tunnel Accident</th>
<th>Location</th>
<th>Year</th>
<th>Vehicle Type</th>
<th>Duration (hrs)</th>
<th>Fatalities</th>
<th>Time Out of Service</th>
<th>Repair Cost</th>
<th>Economic Impact</th>
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</thead>
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<tr>
<td>Bernley</td>
<td>Australia</td>
<td>2008</td>
<td>2 HGV, 1 Car</td>
<td>1 hr</td>
<td>-</td>
<td>3 days</td>
<td>&lt;0.1*</td>
<td>NA</td>
</tr>
<tr>
<td>Newhall</td>
<td>LA, CA, USA</td>
<td>2007</td>
<td>15 HGV</td>
<td>18-24</td>
<td>3</td>
<td>1 ½ Months</td>
<td>$11.8M</td>
<td>NA</td>
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<td>Frejus</td>
<td>Modane, France</td>
<td>2005</td>
<td>4 HGV, 3 Fire Trucks</td>
<td>5-6</td>
<td>2</td>
<td>1 Year</td>
<td>$3.38M</td>
<td>$5.06M</td>
</tr>
<tr>
<td>St Gotthard</td>
<td>Uri, Switzerland</td>
<td>2001</td>
<td>13 HGV, 10 cars</td>
<td>3-4</td>
<td>11</td>
<td>2 Months</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Mont Blanc</td>
<td>Chamonix, France</td>
<td>1999</td>
<td>15 HGV’s, 9 cars</td>
<td>24</td>
<td>39</td>
<td>3 Years</td>
<td>$381M</td>
<td>$1,100M</td>
</tr>
<tr>
<td>Tauern</td>
<td>Salzburg, Austria</td>
<td>1999</td>
<td>16 HGV, 24 cars</td>
<td>7-10</td>
<td>12</td>
<td>3 Months</td>
<td>$17.1M</td>
<td>$40.3M</td>
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<tr>
<td>Caldecott Tunnel</td>
<td>Oakland, CA, USA</td>
<td>1982</td>
<td>Tanker, Cars, bus</td>
<td>2-3</td>
<td>7</td>
<td>6 Weeks</td>
<td>$4.96M</td>
<td>NA</td>
</tr>
<tr>
<td>Nihonzaka Tunnel</td>
<td>Shizuoka, Japan</td>
<td>1979</td>
<td>46 cars, 127 HGV</td>
<td>48-72</td>
<td>7</td>
<td>Abandoned</td>
<td>Abandoned</td>
<td>NA</td>
</tr>
</tbody>
</table>

*Fire controlled by sprinkler deluge system

Table 1, Major Road Tunnel Fire Incidents

Temperature loading in NFPA 502 is stipulated in Article 7.3.2 to be the Rijkswaterstaat (RWS) curve or other curve that is acceptable to the Authority Having Jurisdiction (AHJ). It allows the AHJ to accept another curve if it finds it acceptable. The prescriptive criteria (Article 7.3.3) to be satisfied after 120 minutes of fire exposure is that cast-in-situ concrete structural elements shall be protected such that the temperature of the concrete surface does not exceed 380° (716°F) and the temperature of the steel reinforcement (rebar) in the concrete does not exceed 250°C (572°F). Requirements for structural fire protection material are also included.

These requirements were included after a series of fire tests performed in the Runehamar Tunnel (2) in Norway in September 2003, conducted as part of the European UPTUN Program in association with the SP Technical Research Institute of Sweden and the Norwegian Fire Research Laboratory. The program was notable for having generated extremely large fires and intense temperatures. Thermal insulating board was installed around the test fire platform to protect the tunnels’ structure. The program did not include the potential influence of a FFFS to protect structure. FFFS’s have been shown in both test programs and actual tunnel fires to provide significant reduction in fire heat release rates, fire duration, and the temperature to which structures can be exposed. The question presented in this paper is, can these systems provide sufficient temperature protection to tunnel structure to allow the reduction or elimination of other structure protection mechanisms? In order to address this question, several factors are considered. What is the expected effect of water spray on the time-temperature curve described above? To what degree can tunnel temperature at ceiling be considered to be reduced? What would be the resultant temperature of concrete at surface and at depth of
reinforcement? To provide a sense of the potential of FFFS’s to mitigate concrete temperature in fires, a large fire scenario in a typical road tunnel is simulated and a methodology is employed to address temperature mitigation. This is done by taking advantage of the two primary affects of a FFFS, the decrease in ceiling temperatures and the reduction in duration of a fire incident by prevention of spread to other vehicles. Having established a theoretical maximum temperature and fire duration, a modified time-temperature curve is developed for use in determining resulting temperature gradients within the concrete structure. A comparison is then made with a tunnel not protected by a FFFS.

FIXED FIRE FIGHTING SYSTEMS

The increase in both the number of urban road tunnels and of general congestion of urban roadways has resulted in an increased number of serious tunnel fire incidents. The greater length and congestion of modern road tunnels further make fire fighting and rescue operations from fire services more difficult. In response to the increased threat of catastrophic fires, there has been an increase in the number of road tunnels equipped with FFFS’s, more familiarly known as deluge sprinkler systems or just sprinkler systems. While the majority of tunnels worldwide are not equipped with these systems, this has begun to change as their acceptance has grown. Australia and Japan currently require the installation of FFFS’s in most newly constructed road tunnels, particularly those in urban areas and with heavy traffic flows. Though not required in U.S. or European countries, more and more new tunnels are being equipped with these systems.

FFFS deliver water, usually under pressure provided by a local utility, to a designated coverage area via a piping network. Water is delivered through sprinkler heads or nozzles, either ceiling or wall mounted. There is significant variety in the types and performance of sprinkler systems. The most important variable is the amount of water delivered per unit of coverage area, referred to as design density or water application rate and the mean droplet diameter. Traditional deluge sprinkler systems deliver water under relatively low pressure, 1.5 to 4 Bar. Mean droplet diameter ranges between 700 to 900 microns. These systems are similar to those commonly found in buildings with the exception that water is delivered to a fixed number of open spray nozzles in pre-designated zones. High pressure mist systems are similar to deluge sprinkler systems with the exception that water is delivered under much higher pressure resulting in much smaller mean droplet diameter, 30 to 100 microns. The small droplet size purportedly allows the mist to penetrate deep into the seat of a fire by becoming entrained into the combustion air stream.

There have been numerous studies to determine the effectiveness of FFFS’s. The majority of recent full-scale test programs have been undertaken to prove the capability of mist systems. These have shown performance similar to traditional systems in many respects. Several studies have been undertaken to compare the systems. Both types have shown to be effective in controlling temperature in fires and in preventing spread of fire. A study by Melvin (3) showed that mist and traditional deluge systems performed comparably for shielded fires, those where water spray cannot contact the fire directly, and that traditional deluge systems performed better for unshielded fires, those where the water spray directly impinges onto the fire. A more recent study by Arvidson (4) showed similar results, with traditional systems much more effective at extinguishment of unshielded fires and at reducing FHRR in shielded fires. For the purpose of this paper, only traditional deluge sprinkler systems will be considered.

Water application rates in sprinkler systems for tunnel applications generally fall in a range between 6.0 mm/min and 10.0 mm/min. In Australia for example 10 mm/min is commonly used and in Japan 6 mm/min. Several tunnel projects currently underway in the U.S. where deluge sprinkler systems will be installed are being designed to 8 mm/min. Studies conducted by Harris (5) and Arvidson et al (4) have shown density in this range to be effective. Simulations performed for this paper will use 8mm/min as the design density.
IMPACT OF FFFS’S ON CEILING TEMPERATURE

Data from large scale test programs describing maximum temperature reduction due to FFFS’s in very large tunnel fires is not readily available. Most testing has been done with relatively small fuel loads over a limited area. Though results have been impressive, they do not provide sufficient useful input for this study. To provide additional temperature reduction data, a series of computational fluid dynamic simulations was performed using NIST’s Fire Dynamic Simulator (FDS) program. FDS uses a form of the Navier-Stokes equations to numerically solve fire-driven fluid flow. It has the capability of modeling life-like fire scenarios in three-dimensional space for many common building materials and fuel sources. It produces three-dimensional simulations of the development of fires, including movement of heat, thermal radiation, products of combustion, gas currents, and the effects of fire suppression. In addition, it produces spreadsheet-type data files describing these phenomena quantitatively. Validation work for the Fire Dynamic Simulator is summarized in the FDS Technical Reference Guide.

The measurement of the reduction in temperature and radiated heat levels due to suppression was modeled for this study using a constant heat release rate fire source and observing temperature reduction after application of suppression water. Suppression for these type models has no effect on FHRR, only on the resulting tunnel conditions. For the simulations, the fire was modeled using a function in FDS that simulates a fire burning as a constant heat source producing convective and radiative heat and products of combustion as specified in the input files. A deluge sprinkler array is located directly above a simulated truck cargo bed and is activated after some time is allowed for the fire to develop and conditions to reach a relatively steady state. Simulated instrumentation was located throughout the tunnel to measure temperature, see Figure 1.

Figure 1, Model Arrangement for FDS Simulations

Figure 2 presents plan-view temperature slices taken 250 mm below ceiling height for three conditions, 200MW fire without suppression, 100MW without suppression and 100MW with suppression. The top figure is a tunnel plan showing orientation of vehicles and location of thermocouples referenced in discussion of results. Measurement points where temperatures were substantially lower than those shown or where tunnel symmetry gave similar data are not presented for clarity. In the simulations, fire is allowed to burn for a period of time sufficient to reach a relatively steady state after which time, as applicable, the sprinkler system is activated. It is then allowed to burn at the constant heat release rate specified until temperature again reaches steady state.

From the figures, the most notable changes are the overall reduction of temperature and the extent over which severely elevated temperatures are reduced. While temperature remains relatively high at certain limited points near the ceiling and immediately adjacent to the fire, the overall effect is dramatic reduction in temperature over a wide area near and distant to the fire source. Figure 3 graphically presents temperature data at points along side and beyond the fire source. For clarity, temperature peaks and valleys have been normalized.
Partial Plan, HGV, Thermocouple and Sprinkler Array Prior to Fire

Temperature Below Ceiling, 200MW Fire, No Suppression

Temperature Below Ceiling, 100MW Fire, No Suppression

Temperature Below Ceiling, 100MW Fire, With Suppression

Figure 2, FDS ceiling temperature slices after 300 s exposure. Dark shading = temp > 800 °C.

As proposed by Ingason et al (6), for very large tunnel fires and relatively low ceiling height, flame and un-combusted gasses propagate along the ceiling where combustion continues for some distance. Maximum temperature reaches a relative peak and is widely distributed. From the graph, temperatures in the range of 1000°C are widespread. The graph lines are clustered in a narrow range.

Figure 3, Near Fire Temperature Measurements

The highest sustained average temperature of 1020°C is noted at T4, corresponding to a point five meters down tunnel of the fire. The highest peak temperature was approximately 1100°C. After suppression this point is reduced to average 650°C. It is also apparent that highest temperature measured before suppression activation is below the value reached in the Runehamar and other test programs. This may partially be due to the lower FHRR but also because a roof is modeled above the fire load to prevent direct suppression of the fire. This results in lower measured ceiling temperatures as reported by Ingasson (6). After activation of suppression, temperature at measurement points varies over a considerably greater range with just one point above 750°C. The point of highest temperature has moved from the down-tunnel location to just adjacent to the fire. It is proposed that
the average temperature value across the corresponding area of highest temperature be used in the assessment of compliance with prescriptive requirements of NFPA 502. The affect of a single point of somewhat higher temperature is evaluated as a localized event. The ultimate determination will be left to the structural engineer. The highest temperature points are those immediately adjacent to the fire. These are T2 (725°C), T6 (829°C) and T9 (733°C). The average of these three is 762°C. This will be applied in the modified time-temperature curve to be used in assessment of concrete temperature per NFPA 502.

THE MODIFIED TIME-TEMPERATURE CURVE

The RWS curve discussed earlier describes a fire that burns with extreme intensity at over 1200°C for a period of almost two hours. The fire itself will by necessity have burned for well over two hours assuming a reasonable rate of decay is included. A review of the time-temperature curves generated for the largest fires produced in the Runehamar test program indicate that temperatures of this magnitude were only maintained for a period of approximately 20 minutes. This would be typical for a single heavy goods vehicle (HGV) generating the magnitude of FHRR produced in the tests. This implies that multiple HGV’s would be required to maintain a fire of duration similar to the RWS curve. Because the geometry of a tunnel confines the heat and combustion products generated in a fire and prevents easy dispersal, high convective and radiative heat fluxes do allow fires to spread easily from vehicle to vehicle.

Recognizing that fire spread is essential for generating the fire duration mandated in the RWS curve, it can be assumed that the prevention of spread will reduce the length of time a large fire can be sustained. It is widely accepted that properly designed FFFSs are effective at controlling the temperature, ultimate heat release rate and spread of fire and thus reduces the potential duration of the fire. Quantifying the benefit for road tunnel applications has been an area of active research. There have been numerous full-scale tunnel fire suppression test programs conducted worldwide both for traditional deluge sprinkler systems and for high pressure mist systems. A summary of the data is presented in Table 2. As shown, in the cases where tested, fire spread was prevented. An in-depth computational fluid dynamic (CFD) study was conducted by Harris (5) on the effectiveness of various sprinkler system configurations in suppressing fire and preventing spread. It showed by theory and computational modeling that relatively light water application rates can be successful in preventing the spread of fire from the original incident. Water application rates were equal to or less than those used in the industry.

<table>
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<th>Shielding</th>
<th>Potential FHRR</th>
<th>% Reduction FHRR</th>
<th>Spread Prevented</th>
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</table>

*Estimated from comparison of FHRR graphs for free burn and Test 2S(10). Note that FFFS was activated very late. Total fuel load consumed was half of free burn value up to 30 minutes.

Table 2, Tunnel Fire Suppression System Test Programs

It can be reasonably concluded then that a properly designed FFFS will prevent the spread of fire. Therefore, a single HGV fuel load will be considered the appropriate design condition for a tunnel
equipped with a FFFS. The RWS time-temperature curve may then be modified to reflect the realistic fuel load and maximum duration with which the fire can be expected to be sustained.

The form of the modified time-temperature curve will reflect the maximum temperature determined earlier with duration calculated based on fuel load available for combustion from a single HGV. Using the largest fuel load tested in the Runehamar program as the typical basis, the expected duration can be derived based on the effect of sprinkler spray on the FHRR. Figure 4, shows the Time-FHRR curve generated in the largest Runehamar test, Test #1. The area under the curve represents the total energy available. Using a very conservative assumption, that all fuel is consumed, when the height of the curve (FHRR) is reduced in magnitude then the time to consume, length of curve, must be increased to equalize the energy consumption. Calculating the area under the curve in units of MW’s burned gives the total available energy. This value determines the maximum area of the modified curve. The energy calculated for Runehamar Test #1 is 4150MW-minutes or 249GJ. This is in agreement with the reported energy load in the Runehamar test report (2) of 242GJ. Any reduction in FHRR by the FFFS will therefore extend the incident duration in order to allow complete combustion of available fuel.

![Runehamar Program FHRR](image)

**Figure 4, Runehamar Test #1 & Modified Duration Curve**

The reduction in FHRR to be expected from a FFFS has also been an area of considerable study. Numerous scale test programs have been undertaken to quantify the degree to which water spray can affect FHRR. For the purpose of this study only shielded fires are considered since a well designed FFFS will generally extinguish or severely reduce the size of an unshielded fire. Again referring to Table 2, FHRR was reduced by at least fifty percent in all of the test programs dealing with deluge sprinkler systems. Therefore a fifty percent reduction in FHRR will be assumed in determination of the modified time-temperature curve. Whereas maximum FHRR in Runehamar Test #1 was approximately 200MW, the modified curve will peak at 100MW. The authors note that while this value is in common usage, it is considered very conservative for tunnels with FFFS’s. As proposed by Carvel (12) and Melvin (13), the geometry of a tunnel will have a significant effect on the ultimate FHRR in a tunnel fire. The Runehamar tunnel width is near the ideal for generating very large fires. In a wider tunnel such as modeled above, a smaller fire would be expected. This coupled with the effect of sprinkler spray would result in a significantly lower FHRR. However, to address the concerns of designers using the current FHRR, 100MW is used. With the peak FHRR established, the growth and decay phases are added to produce the modified FHRR curve as shown in Figure 4.

In the Runehamar curve, duration of fire with FHRR in excess of 100MW was 22 minutes. To equalize area under the curves, a fire with suppression would need to burn for 36 minutes. The modified time-temperature curve should therefore be characterized by a growth period, a sustained period of combustion at maximum temperature for 36 minutes followed by a decay period. Because the temperature growth and decay period is typically rapid, it is assumed to add only several minutes to the curve. Averaging the growth and decay, the total duration used will be 45 minutes. The form of the modified time-temperature curve will reflect the maximum temperature determined earlier with
duration calculated based on fuel load available for combustion from a single HGV. Incorporating the 
maximum average ceiling temperature for the tunnel after activation of suppression as determined 
earlier of 762°C, the modified curve will appear as shown in Figure 5. In comparison to the RWS 
curve, the modified curve is much shorter in duration and at significantly lower temperature. This 
curve will be used in the evaluation of resultant concrete temperatures.

![Modified Time-Temperature Curve]

**Figure 5, RWS and Modified Time-Temperature Curves**

**HEAT TRANSFER TO TUNNEL STRUCTURE**

An analysis of temperatures in concrete and rebar was made to determine the relative effects of fixed 
fire fighting system water spray in reducing concrete temperature. Results of the calculations are 
compared to NFPA 502 temperature criteria (380°C at concrete surface and 250°C at rebar depth) 
using the modified time-temperature curve developed in the previous section. The calculation uses 
transient heat conduction theory to establish temperatures at the key depths for exposure over given 
duration. For real world applications involving complex system interactions, the use of a 3D heat 
transfer and fluid modeling software package such as one of the various finite difference programs 
currently available should be considered. For practicality, a simplified approach is taken in this paper.

The tunnel ceiling is modeled as a semi-infinite solid with air flow at the stipulated temperatures. The 
expressions defining the temperature difference between the initial condition (ambient) and that at 
some distance from the surface (x) and time (t) for turbulent flow are given in Equation 1 (16).

\[
T_x = T_i + (T_{air} - T_i) \cdot \left[ \text{erfc} \left( \frac{x}{2\sqrt{\alpha t}} \right) - \exp \left[ \frac{hc^2}{k} + \frac{hc^2\alpha t}{k^2} \right] \cdot \text{erf} \left( \frac{x}{2\sqrt{\alpha t}} + \frac{hc\sqrt{\alpha t}}{k} \right) \right]
\]

(1)

The constants are defined as follows

\[
\alpha_{base} = \frac{k}{\rho \cdot C_{\rho}} \\
\text{Res} := \frac{Th}{k_1}
\]

Where:

- \( T_i \) Initial temperature
- \( T_{air} \) Smoke plume temperature
- \( t \) Time at calculated temperature
- \( x \) Depth at calculated temperature
- \( hc \) Convective heat transfer coefficient
- \( \alpha \) Diffusivity
- \( k \) Conductivity
- \( C_{\rho}c_p \) Specific heat
- \( \rho \) Density
- \( Th \) Thickness of ceiling material
- \( \text{Res} \) Material thermal resistance

The calculations assume fire grows immediately to the ultimate peak temperature in the modified 
curve and continues at that level for the full duration noted. The tunnel ceiling is concrete with rebar 
located at 50 mm depth. Properties of concrete and air (15) are shown in Table 3.
The determination of near-field convective heat transfer coefficients for large tunnel fires is very challenging. High ventilation flow rates coupled with strong buoyant and turbulent flame effects as well as velocities induced by superheating gasses make the calculation of Reynolds number difficult. The convective coefficient will also vary significantly with distance from the seat of the fire. Unfortunately none of the full-scale test programs performed to date appear to have included measurement of concrete temperature gradients above the fire. Calculation of the value used here was made assuming high near fire net velocities. This was calibrated with both the results of FDS sample modeling of fire below concrete structure and with the temperature gradients produced in SP Test Program 2008:53 (14). The value derived gave reasonable correlation with both.

### Table 3, Properties used in the heat transfer equations

<table>
<thead>
<tr>
<th>$T_i$ (°C)</th>
<th>$K_c$ (W/mK)</th>
<th>$C_{pC}$ (kJ/kgK)</th>
<th>$\rho_c$ (kg/m$^3$)</th>
<th>$h_c$ (W/m$^2$K)</th>
<th>$T_{hC}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.73</td>
<td>880</td>
<td>2100</td>
<td>22</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 4 Comparison of Temperatures with and without FFFS

Without a FFFS, temperatures at both the concrete surface and rebar depth far exceed NFPA 502 prescriptive temperature requirements of 380°C and 250°C respectively. With a FFFS, temperature is well below prescriptive criteria for the average air temperature case. Concrete surface temperature exceeds criteria by just 3°C for the localized high temperature case and falls well below at rebar depth. Additional mitigation would not appear to be required.

It should be noted that studies of the behavior of concrete at elevated temperature have shown concrete to spall at relatively low temperatures. In the SP program report, this was shown to occur at approximately 600°C for both the standard fire and hydrocarbon fire tests. In the hydrocarbon test, spalling began at 1:20 seconds from start of fire, just at 600°C. While spalling in and of itself may not constitute a great risk for tunnel structure, the loss of concrete surface exposes rebar to elevated temperature much quicker than would be from direct heat transfer through concrete. For fast growing tunnel fires this could occur before a FFFS could be activated. The addition of polypropylene fiber to concrete add-mixes is shown in the same study to dramatically reduce concrete spalling. Concrete with fiber in quantities equal to 1.5kg/m$^3$ was shown to resist spalling to temperatures in excess of 900°C. In the heat transfer analyses presented, it was assumed that concrete did not spall and that conduction to rebar depth was through an intact surface layer.

**CONCLUSION**

A properly designed fixed fire fighting system can significantly reduce temperature impinging on structural elements in a large tunnel fire. The degree of temperature reduction can make further mitigation strategies unnecessary. In the example presented in this paper, and at the discretion of the tunnels structural engineer, additional measures to mitigate temperature would not be required. If
Protection of structure from fire is being considered for a project, cost will often be a major determinate. A comparison should be made of the effectiveness and cost of the competing alternatives such as a FFFS and thermal insulation board. The designer should also consider that a FFFS offers other advantages beyond temperature mitigation such as reduction in the FHRR to be used in ventilation design and rapid return of roadway to service after a fire. A recent study by Melvin et al (17) showed that installation of a FFFS can offer economic advantages beyond the control of fire and temperature control. All these elements should be taken into consideration when determining the best measures to be taken for a particular project.

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Water Mist Concept – Effective Choice for Improving Safety in Road Tunnels

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ABSTRACT

Tunnel fires pose not only a life safety threat for passengers, but can also cause severe damage to the tunnel lining and mechanical and electrical systems.

Fixed fire suppression systems for road tunnels increase safety by suppressing and controlling the special solid and liquid fires that occur in tunnels. Typically, these systems are designed according to customer specifications and some of the technical requirements are verified in full-scale fire tests, which then form the basis of the system design. Performance-based parameters can be defined properly only as the result of a complete understanding of the tunnel conditions and specified fire types.

Experience drawn from fire testing and field installations shows that water mist technology can provide an excellent level of fire protection with modest water consumption. This paper describes the effectiveness of high-pressure water mist technology as used for tunnel fire protection. Water mist fire protection systems as installed in the Paris A86 West tunnel, Madrid M30 tunnel and Helsinki City Service Tunnel are described in detail.

KEYWORDS: water mist system, road tunnel fires, full scale fire tests, flow rate

INTRODUCTION

Tunnel fires pose not only a life safety threat for people, but can also cause severe damage to the tunnel lining including the concrete construction but also to mechanical and electrical systems. These fires can grow extremely quickly, generating very high temperatures and amplifying the dangers posed by fuel spills and toxic smoke. This makes fire fighting operations very dangerous and slow if not impossible.

Following the fatal tunnel fires in the Mont Blanc, Tauern and St. Gotthard tunnels, all of which caused long closures and massive expenses, the European commission published in 2004 a new directive on tunnel fire safety, 2004/54/EC [1], in order to improve the safety in tunnels. However, this directive requires a very basic level of fire protection for tunnels over 500 meters long belonging to the trans-European road network. In Europe as a whole, the fire protection of tunnels is therefore in practice still rather inadequate and further investigations, resources and money are needed for the basic upgrading of old tunnels still in service and to optimize the safety systems for the new tunnels.

Safety and asset protection are prime concerns for the tunnel operators. They have the responsibility for tunnel fire protection and need to ensure that the fire protection of their tunnels is at a level commensurate with the particular fire risks associated with these tunnels. Ideally, the evaluation of these risks would be carried out by acknowledged tunnel fire protection experts. They would recommend the appropriate level of fire protection and, where possible, also how to go about achieving the required level. On this basis, the analysis and intercomparison of different fire protection systems could begin.
Since its introduction water mist technology has rapidly developed a reputation for superior fire suppression capability, becoming often the requested fire protection solution for many applications. With regards to challenges in tunnel fire protection the modern water mist systems offer efficient, durable technology to improve safety not only for passengers but also tunnel infrastructure. In Europe several tunnels have already been fitted with water mist system bringing their safety to a new level.

WATER MIST FIRE PROTECTION IN ROAD TUNNELS

Historically active suppression systems have been used in road tunnels only in Japan and Australia with good experiences for several decades. Experiences drawn from fire testing and field installations in Europe during the last years have proved that high-pressure water mist technology can provide an excellent solution for preventing direct and consequential damage to people, tunnel infrastructure and traffic. These experiences have also convinced fire safety authorities and increasing number of high-pressure water mist systems are being installed and working to protect underground transportation infrastructure such as road tunnels, especially in Europe. In this environment water mist systems beat down fire instantly upon activation, suppressing and controlling it before it can spread, using minimal amounts of water.

This paper describes the effectiveness of water mist technology for tunnel fire protection. It also describes the development and implementation of a water mist system for tunnel fire protection based on the experience gathered from a number of full-scale fire tests undertaken by the water mist system supplier. Real-world experiences gathered in three different tunnel fire protection projects equipped with the water mist fire protection system are presented: the A86 West tunnel in Paris, the M30 tunnel in Madrid and the Helsinki Service Tunnel in central Helsinki.

The discussion in this paper is based on one water mist fire protection system and its variants developed specifically for tunnel fire protection. The observations made in this paper are unlikely to be applicable to all water mist systems, because the water mist systems of different suppliers have their own unique technical characteristics which are difficult to compare accurately outside the test laboratory.

There are no standards or general recommendations governing the use of water mist technology for tunnel fire protection. Therefore, the customer must rely greatly on the water mist system supplier’s professional skill, installation experience and understanding of the system’s effectiveness and reliability. It is very advisable to use analyses contributed by an objective, third-party expert during the evaluation phase in order to avoid problems later.

Designing the water mist system

Three main categories of requirements need to be fully dealt with during the planning phases of water mist system design for tunnel fire protection in order to ensure a proper operation of the water mist system

System performance

Due to the large variety of water mist system types, it is impossible to have generic design methods to cover them all. The only acknowledged way for evaluating the performance of different water mist systems is through full-scale fire testing in real tunnel environment.

All the important system installation parameters are defined in the relevant fire tests. “System performance” comprises categories such as e.g. water flow rate in l/min/m² (or in l/min/m³), nozzle type and spacing, micro-droplet size, system pressure, max ceiling height and/or max volume and the distance between the spray heads.
Figure 1 HI-FOG water mist uses high pressure to generate a fine water fog with excellent penetration

Thoroughly tested systems can be adapted for use in other tunnel types as is or with small adjustments, as long as the central performance parameters are not substantially altered.

System technical design

System technical design defines the placement of pump units, and associated systems, back-up pumps, water sources, the water and electrical power intake system, the types and placement of zone valves and pipes, the system's reliability, life-span, maintenance and so on.

These technical parameters must all be thoroughly analyzed and carefully designed. The fundamental technical and structural characteristics are different from tunnel to tunnel, and need to be reflected in the requirements of the customer and local authorities.

System Interaction

System interaction defines the possible interactions and connections between the tunnel fire protection system and other tunnel systems such as the fire detection system, the central control system, the ventilation system, the smoke evacuation system, and the traffic monitoring, control and alarm systems. Seamless interaction between these systems, delivered by different system providers and having different operational priorities, is one of the greatest tunnel fire protection challenges. It would be important to rely as much as possible on research data and experience drawn from successful projects.

For example modern fire detection systems that have been thoroughly tested reported on and accepted by authoritative third parties as being fast, accurate and reliable can be used with a water mist system. The response time of such a fire detection system is dependent upon the fire location, fire size and air current velocity. The fire detection system’s ability to pinpoint a fire within a particular water mist zone is critical to the performance of the water mist system.

TUNNEL FIRE PROTECTION CASE STUDIES

This chapter presents the three main categories of requirements from the point of view of a water mist system provider and its experience of three large tunnel projects.

A86 West tunnel, Paris: The world largest water mist system installation

The A86 West tunnel in Paris, protected by a high-pressure water mist system, is probably the world’s largest tunnel protected by an active fire protection system. This tunnel is a feat of engineering and design at 10 km long with two superimposed levels, one in each direction.
Each 2.55 m high level has two traffic lanes and a hard shoulder. Reserved for light vehicles, the tunnel is equipped with all the latest safety devices, exceeding the requirements of new French regulations governing tunnel safety.

Front-line fire protection is provided by a high-pressure water mist system with the following mission in case of fire: reduce the ambient temperature, facilitating the evacuation of motorists to the emergency exits located at 200-metre intervals; meanwhile, moderate conditions for the emergency services arriving on the scene, allowing them to contain, control and extinguish the fire.

The tunnel is equipped with a modern ventilation system distributing fresh air through both levels via dedicated air ducts. The smoke evacuation and fresh air ducts run along the ceiling and under the road surface. The tunnel is scheduled to open to traffic in early 2011.

Fire tests

The importance of fire protection is magnified in this type of tunnel, which will carry very dense traffic. The ceilings are very low: even small quantities of smoke may be difficult to evacuate. The heat given off by a fire will also very quickly affect the low-lying ceiling structure and equipment. Despite the delayed activation by purpose, the water mist system must be able to effectively suppress large combined-automobile fires. The spray head-type system tested, featuring open spray heads, fulfilled all the fundamental requirements of the customer including temperature reduction, heat flux and heat release rate [2].

System dimensioning

The designed water flow rate is realized with spray heads placed longitudinally in staggered formation at ca. 4-metre intervals and laterally at 2.8 meters on the tunnel ceiling. Each zone of coverage is 33 meters long and the system must always be able to activate three zones simultaneously. Tunnel areas of higher ceiling height, up to 7-8 meters, were protected with open spray heads of higher k-factor based on the fire tests conducted. Thanks to the system’s modest water flow requirement, high pressure, and double pumping station design, the size of the main feed pipe in only 76 mm.

Zone valves

The A86 tunnel does not have wall recesses in which to place zone valves and pipes safely away from traffic, therefore they are installed on the tunnel ceiling. The valve cabinets are therefore tested at
800 °C for a half-hour and at 400 °C for a full hour to fulfil customer specifications. Tests were carried out at the VTT (Technical Research Centre of Finland) [3] with the customer present. The zone valves are monitored from the local control cabinets, and from there to the central control system. Each zone valve is assigned a unique address in the tunnel which corresponds to a fire detection cable zone.

Notes

The water mist system is activated remotely as part of the operator’s 24/7 operational monitoring system, as a result of information gathered at the fire location. The system is activated by an electrical signal from the central control system which starts the pump units in the correct pumping stations and opens the correct zone valves: water is then discharged from the spray heads in the zone corresponding to the fire. In order to prevent a backlayer phenomenon the air velocity of 3 m/s is used in case of fire. Water mist performed effectively at the air velocity in the A86 fire tests.

The customer selected a water mist system and water mist system supplier on the basis of a detailed evaluation carried out by an expert consultant. The selection was partly the result of a reasonable price and the advanced technology it brought, but it also took into account the supplier’s long experience as a water mist system developer — including over 6,000 fire tests and successful water mist system design for many different applications.

The “water hammer” phenomenon was simulated [4]. In addition, a dynamic analysis of the piping was carried out [5], pipe fixture corrosion was studied, and so on. Pump station and individual pump unit performance were simulated during the factory acceptance test, before deliveries began. Every aspect of the system design was documented with care, accepted by the customer, and saved in the project design database. Techniques were developed to speed installation — pipe installation was made more efficient by maximizing pre-assembly, for example.

When completed, the A86 tunnel water mist system will be the world’s largest water mist fire protection system with 16,000 spray heads distributed over 850 zones, altogether, 24 km of tunnel will be protected HI-FOG® micro-droplets rapidly absorb heat, particularly by evaporation, giving very effective cooling. They greatly reduce the amount of smoke a fire gives off, by limiting the development of its heat intensity. This contributes to safe evacuation and saves lives during the first critical seconds and minutes of a tunnel fire.

M30 Madrid; Urban traffic management at its most modern

The Madrid M30 project is the world’s largest urban tunnel project, involving 99 km of new road construction with 56 km comprising tunnels. Over a number of phases the M30 project has been re-routing major sections of the road through new tunnels, freeing up surface areas for redevelopment into green areas, footpaths, bicycle paths and new housing while significantly reducing inter-city travel times.
The M30 tunnel is completely different from the A86 tunnel. The tunnel’s average height is 6 meters and it contains many junctions in widths between 7 and 25 meters. Furthermore, all type of vehicles is allowed.

In the project planning phase, seven tunnel segments were identified as requiring an active fire protection system. A quick inspection of the tunnel’s width measurements, height measurements and possible large fire loads (HGVs) makes it clear that some compromises have to be made when dimensioning a water mist system to protect it from fire.

**System dimensioning**

Full-scale tunnel fire tests of the water mist fire protection system were carried out in Spain in 2006. Main objective was to investigate the dimensioning issues associated with the very wide tunnel areas described above. The tests showed that the three types of water mist systems (spray head, hybrid and sprinkler) performed almost equally well. Since the performance and dimensioning parameters of the three water mist systems were established in the fire tests, it was possible to design and offer a system that would protect the extra-wide tunnel areas, deal with the large possible fire loads (HGV) and still use modest amounts of water. A hybrid-type water mist system was proposed with three 24m long zones activated simultaneously — with a measured flux density of at least 0.4 l/min/m³ in two of the zones, and 0.8 l/min/m³ in the third. The powerful cooling effect of the water mist system made it possible to set the three-zone length at 72 meters [6]. Where the tunnel height is 6 m and the tunnel width 17 m, the total water flow rate is 3,917 l/min over the three zones. This is almost 2,000 l/min (33%) less than that of an equivalent water mist spray head type system. This means that smaller pumps, pumping rooms, wastewater sewers, pipes, valves, water intake system are required and less electricity.
This means significant savings with no penalty in protection: the fire tests proved that the system can handle large fire loads. We can confidently say that the hybrid-type water mist system is the right system for tunnels which require a high level of fire protection — a level that becomes too expensive when provided by a spray head type system requiring more water to cover e.g. extra-wide tunnel areas.

Project experience

The M30 water mist system protects a special 1,000-metre section of the tunnel that comprises two separate tunnels and a number of slip road connections. Two electrically driven pump units were installed in this section, one at each end. Both pumping stations are equipped with back-up pumps of the single failure type.

The main feed pipes were installed on the tunnel ceiling and connected to piping leading down to the valves. The valves were installed in fire-proof cabinets. The spray heads are installed on the ceiling at the intervals established in the fire tests. In this hybrid system, every second nozzle is a water mist spray head and every other one is a water mist sprinkler. The water mist sprinklers are protected by a cap which prevents them from activating too early. The activation of this system is based on activation of the fire detection system. If necessary, zones can be closed and then opened again depending on the fire location.

Notes

The M30 water mist system was fully tested with various air ventilation systems. Semi-transversal ventilation is installed in some sections of the tunnel, and the fire tests showed that it works very well with the water mist system. The water mist kept the fire and resulting smoke down, and the smoke was extracted through the ceiling hatches in the upper channel away from the tunnel. Semi-transversal ventilation is the best for tunnels according to the tests.

The M30 water mist system was also tested with longitudinal ventilation (in the region of 2 … 3.5 m/s). As was expected, a smoke backlayer quickly developed with the longitudinal air velocity at ca. 1 m/s. When the system was activated, a positive phenomenon occurred: the water mist helped the ventilation to clear the backlayer quickly, and the smoke moved downstream even at this low velocity.

Helsinki Service tunnel; Safe underground logistic

The Helsinki service tunnel was built in 2007-2009 and is protected by Finland’s first automatic tunnel fire protection system. The total length of the tunnel is 2 km. This new tunnel will be as the main thoroughfare for lorries carrying supplies to stores and shops downtown. Getting delivery vehicles off the streets will have direct positive impact in city traffic and air quality. Furthermore, tunnel gave for
the large department stores new, modern and effective service and parking areas and old parking and service areas were utilised for new sales areas. All these improvements are expected to increase the desired attractiveness of stores and the city centre as a whole.

Figure 5 HI-FOG® system is a part of the fully automatic fire protection system in the new Helsinki service tunnel (green tunnel area). Old Kluuvi tunnel area shown under the red circle.

The tunnel is the most complex underground construction in Finland; the average height of the tunnel is 5.5 meters and the width varies from 7 m to 20 m. It has two-way traffic, connections to several other infrastructure projects, underground crossings including four roundabouts on average 30-40 metres below ground level. It was a considerable technical challenge to implement the water mist system zone sizing taking into account the complexity of the tunnel while maintaining the required performance together with the ventilation and fire detection systems.

Figure 6 HI-FOG spray head system installed in roundabouts in Helsinki service tunnel

System designing

The water mist system is designed to discharge over two 25m long zones simultaneously. The system flow rate is secured by three large pump units driven by diesel engines. The flow rate of each pump is 1200 l/min; two of them are required to operate simultaneously with the third designated as the back-up unit. The back-up pump unit can be deployed to add flow rate, covering larger areas if needed. Water for the water mist system pumps is supplied from two separate sources: a main city sprinkler
feed and a water reservoir located close to the high-pressure pumps. The water is fed from the water reservoir by a diesel pump unit for one hour of operating time.

A general fire protection principle governing this type of project requires all water used to fight fire to be collected in a separate collection reservoir. This is a clear cost-cutting benefit of HI-FOG water mist system compared to the more water consuming conventional deluge systems.

Water mist’s excellent cooling capability is considered to be an essential advantage. It is notable in tunnels that, if there is no fire suppression system to provide cooling, fire fighters cannot approach the fire close enough to fight the fire effectively using their fire hoses. Furthermore, experience gathered from full-scale tunnel fire tests showed that the velocity of the longitudinal ventilation during a water mist discharge can be less than when water mist is not being discharged. This helps the fire brigade approach the fire scene safely from the upstream side — they will not be impeded by a loss of visibility.

The hydraulic calculations were made using the Darcy-Weisbach method for high-pressure flows according to the latest edition of the NFPA 750 handbook. [8].

Antifreeze

The climate in Finland can be extreme during the winter and the temperature inside the tunnel can drop to -15 C. Thermal protection is needed for the water mist system piping: a trace heating system is needed for the main tubes affected by temperature. Also, roads in Helsinki are treated with salt to prevent icing in temperatures just below zero. The salty conditions at the tunnel entrances require the water mist system components and pipes to be made of high-grade stainless steel to give the best protection against corrosion in aggressive tunnel environments. This will naturally prolong the life-time of the water mist system.

Cost savings

Two options were considered for protecting the tunnel: conventional sprinkler systems and water mist system. The lower water consumption of water mist combined with its excellent heat and smoke suppression meant that there would be considerable savings in other systems. The drainage system could be more compact, the water supply and input/output channels smaller, the ventilation system could be smaller, and instead of multiple pump stations, a single, large pump station could serve the entire tunnel. The total amount of water needed for a conventional sprinkler system would have meant much larger tanks and water collection ponds. It also would have been very difficult for the city's water supply to feed a conventional sprinkler system.

Water mist system into the old Kluuvi tunnel

The old Kluuvi tunnel had an aging sprinkler system that was not dimensioned according to the area discharge, but rather relied on traditional glass bulbs breaking. Fire in this old Kluuvi section was a major risk for the stores connected to the tunnel, some of which do not yet have modern fire doors. It was decided to extend the Water mist system into this Kluuvi section of the service tunnel to ensure the entire tunnel has the same level of protection. This project was executed early 2010. The already existing water mist system of the new tunnel was easy to extend to this old tunnel area using the same pump room. Area of the old Kluuvi tunnel is shown in picture 5.

Notes

As of the time of writing, the Helsinki Service Tunnel water mist system installations have been done. System testing during the commissioning was carried out in order to ensure seamless interaction with other safety systems. Training of operating personnel and the local fire brigade were included to Marjoff’s turn-key delivery in the Helsinki Service tunnel project.
DISCUSSIONS AND CONCLUSIONS

The dimensioning of water mist systems for tunnel fire protection according to the tunnel measurements and expected fire loads is of fundamental importance. There is no recipe book of possible solutions for the job. The three main categories of requirements — system performance, system technical design and system interaction — have to be gone through exhaustively. If an extra assurance of operational reliability is desired, safety margins can be added to a number of operational parameters: water supply can be increased, for example, and the activation zones can be lengthened.

Water mist technology offers many advantages over conventional sprinkler technology in the tunnel environment: superior cooling and heat blocking, and much reduced water consumption. Water mist systems are also made of high-grade stainless steel, offering superior reliability and spreading of the investment over a longer system lifespan.

Water mist systems for tunnel fire protection have been extensively fire-tested with various fire loads from 1999-2006. The results of these tests enable water mist system suppliers to offer water mist technology for tunnel fire protection with known levels of performance and established dimensioning expertise.

The successful installation of a water mist system for tunnel fire protection is the result of excellent design, project management and installation, and good cooperation between the various stakeholders. If cost-cutting is the only motivation, safety margins will get whittled down to nothing and the investment will receive only cosmetic protection. We cannot over-emphasize the importance of regularly testing and maintaining the water mist system — and also training emergency personnel to deal with fires and system malfunctions in the most realistic scenarios possible. This is the final assurance of receiving the greatest possible benefit from an investment in a water mist system for tunnel fire protection.

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Automatic sprinkler system in tunnel fires

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ABSTRACT

The performance of an automatic sprinkler system in a 1:15 model scale tunnel with longitudinal ventilation were tested and investigated. Glass bulbs were installed beneath the ceiling to activate the nearby nozzles. The activation of the nozzles, maximum heat release rate and collapse of the automatic sprinkler system were analyzed. The results show that high ventilation and low water flow rates result in collapse of the automatic sprinkler system. The main reason was the effect of the longitudinal flow on the fire development and the hot gas flow close to the sprinklers. The fire development and the activation heat release rate of the first activated bulb are intimately related to the ventilation velocity.

INTRODUCTION

Interest in tunnel fire safety has increased dramatically in recent years owing to numerous catastrophic tunnel fires and extensive media coverage. New technologies, such as water sprinkler systems, have been developed to improve the fire safety in tunnels. Yet it is generally accepted that automatic water sprinkler systems (AWSs) can be adversely affected by ventilation during tunnel fires, but this viewpoint has not been fully investigated. This was why, before adopting a position on the matter, we decided to investigate how AWS systems function in various longitudinal ventilation flows. The system widely accepted today is the deluge system, where one or two zones of sprinklers are activated in the event of a fire.

To improve the fire safety in some applications, an automatic sprinkler system can be used. If a fire grows to the threshold at which the bulb is activated, the water is released to suppress the fire development immediately. Heskestad [1] proposed the controlling equation for the heat-response element, i.e. bulb, of an automatic water sprinkler. A response time index, i.e. RTI, was defined, which proves to be a constant for a given automatic sprinkler. Different classifications of bulbs were conducted according to the link temperature, from ordinary (135 - 170 °C) to ultra high (500 - 575 °C). For low-RTI sprinklers the heat loss by conduction to the sprinkler mount was included. The cooling of the bulb by water droplets in the gas stream from previously activated sprinklers was considered by Ruffino et al. [2-4]. De Ris et al. [5-6] developed a skip-resistant sprinkler with a cylindrical shield around the bulb. A series of test was conducted in a plunge tunnel apparatus in a steady state. The results show that the proper shielding of a sprinkler can significantly reduce skipping, i.e. cooling of sprinklers adjacent to an activated nozzle prevents their activation and causes the sprinkler activation to “skip” such nozzles.

Limited studies on water spray systems in tunnel fires have been presented. Ingason [7] carried out a series of model scale tunnel fire tests with a deluge system and a water curtain system using hollow cone nozzles, in order to improve our basic understanding of water spray systems in a longitudinal tunnel flow. The water spray system used consisted of a commercially available axial-flow hollow cone nozzles. The model scale tests show that the non-dimensional ratio of HRR, excess gas temperature, fuel consumption, oxygen depletion and heat flux downstream of the fire, all correlate well to a non-dimensional water flow variable. There are also some full scale water spray tests reported in the literatures, such as the Ofenegg tunnel tests in 1965, P.W.R.I tests in 1980, Shimizu...
tests in 2001 and 2nd Benelux tunnel tests in 2002 [8]. Recently application of water mist system in tunnels has obtained much attention and a series of tests were carried out in Europe, such as VSH Hagerbach tests [9] and San Pedro de Anes tunnel tests in 2008 [10].

No systematic study of automatic sprinkler systems in a tunnel fire has been available. Despite this there appears to be consensus concerning the ineffectiveness of such a system due to the effects of the ventilated flow in the references cited above. This consensus is mainly related to the assessment of whether the ventilation will jeopardize the effectiveness of the system. However, how much the ventilated flow affects the performance of an automatic sprinkler system in a tunnel fire has not been quantified. Therefore there is a need to systematically investigate how the system works in various longitudinal ventilation flows.

The heat from a fire plume rises vertically, if there is no wind in the tunnel but, in longitudinal air flows, the heat and flames will be deflected and accumulate downstream of the fire. For example, it is possible that sprinklers being activated are too remote from the fire to deliver water effectively. We also wanted to address whether too many sprinklers might activate, thereby exceeding the water delivery capacity of the system. A fully AWS system in a tunnel is assumed here to cover the entire length, without being split into different zones. A deluge system will activate one or two zones, which means the risk of it not being able to fight the fire decreases considerably. Deluge systems are not very sensitive to the effects of longitudinal air flows. However, when individual sprinkler bulbs activate over a large area, the AWS system will fail as it cannot deliver the amount of water needed to control the fire. This study aims to find out why such systems fail. A scale model was used, as it is cost-effective and can, if correctly designed, provide vital, reliable information.

SCALING

The widely used and well known Froude scaling technique has been applied in this study. Although it is impossible and in most cases not necessary to preserve all the terms obtained by scaling theory simultaneously, the terms that are most important and most related to the study are preserved. The thermal inertia of the involved material, turbulence intensity and radiation are not explicitly scaled, and the uncertainty due to the scaling is difficult to estimate. However, the Froude scaling has been used widely in enclosure fires and results from model scale tests seem to fit full scale results well, see references [11-15]. Since the ratio of tunnel length to tunnel height should be great enough to scale a realistic tunnel fire, it is very expensive to build a model tunnel in full scale. The scaling ratio should not be smaller than about 1:20 in order to preserve the Froude Number and to avoid producing a laminar flow in the model tunnel. Our experience of model tunnel fire tests in the scale used here (1:15) shows there is a good agreement between model scale and full scale test results on many focused issues [16-20]. The model tunnel was built in a scale of 1:15, which means that the size of the tunnel is scaled geometrically according to this ratio. The scaling of other variables such as heat release rate, flow rates and water flow rate, and response time of the automatic sprinkler can be found in our SP Report [21].

TEST PROCEDURE

In all, 28 tests were carried out in a 1:15 scale tunnel model. Longitudinal ventilation was established using an electrical axial fan attached to the entrance of the model tunnel, see Figure 1. Average longitudinal velocities of 0.5 m/s, 1 m/s, 1.5 m/s and 2 m/s, obtained by adjusting a frequency regulator, were used in the test series. The corresponding full-scale velocities were 2 m/s, 4 m/s, 6 m/s and 8 m/s. In some tests, the ventilation velocity inside the tunnel was decreased from a higher value, i.e. 2 m/s or 1.5 m/s, to 0.5 m/s to optimize the performance of the automatic sprinkler system. This measure was called Variant Ventilation Strategy. However, in most tests a constant ventilation velocity was used, called Constant Ventilation Strategy.

The tunnel itself was 10 m long, 0.6 m wide and 0.4 m high, corresponding to 150 m long, 9 m wide and 6 m high respectively in full scale, see Figure 2. The model, including the floor, ceiling and one
of the side walls, was constructed using non-combustible, 15 mm thick Promatect H boards, while the front side of the tunnel was covered with a fire resistant window glaze, mounted in steel frames. The thickness of the glaze was 5 mm.

Figure 1  A photo of the 1:15 model scale tunnel using automatic sprinkler system.

The fire load consisted of wood cribs (pine). The total weight of a wood crib was about 4.4 kg. The free distance between each horizontal stick was 0.033 m and the total fuel surface area of a wood crib was estimated to be 1.37 m². The estimated heat release rate was about 200 MW in full scale. During each test, a cube of fibreboard measuring 0.03 m, 0.03 m and 0.024 m and soaked in heptane was placed at the same level as the bottom of the wood cribs and on the upstream edge of the wood crib. Two wood cribs were arranged in the tunnel fire tests to investigate the risk for fire spread. In most tests, the free distance between two wood cribs was 1.05 m (15.75 m in full scale), except 0.6 m in one test.

Figure 2  The layout and identification of instruments in the series of tests (dimensions in mm).

Various measurements were conducted during each test, see Figure 2. The temperature was measured with welded 0.25 mm type K thermocouples (T). The location of the thermocouples is shown in Figure 2. Most of the thermocouples were placed along the ceiling at a distance of 0.04 m from the ceiling. A set of thermocouple was placed 4.65 m (pile A in Figure 2) and 8.75 m from the inlet opening (pile B in Figure 2), respectively. The thermocouples in each set were placed in the centre of the tunnel and 0.04 m, 0.12 m, 0.20 m, 0.28 m and 0.36 m, respectively, above the floor. Four plate thermometers were placed at the floor level during the tests. The locations of the plate thermometers were 2.3 m, 4.65 m, 6.25 m and 8.75 m from the tunnel inlet at x=0. Two bi-directional probes were placed at the centreline of the tunnel 1.3 m and 8.7 m, respectively, from the inlet. Another bi-directional probe was installed in the centre of the exhaust duct at the floor level and 3.75 m horizontally away from the tunnel inlet. The gas concentrations 8.8 m from the entrance, including O₂, CO₂ and CO, were sampled by two probes consisting of open copper tubes. They were located at two different heights, 0.2 m and 0.35 m above the floor.
A drawing of the water spray system using 9 couples of nozzles can be seen in Figure 3. Eighteen nozzles were installed in the second section of the model tunnel, 35 mm below the ceiling. The interval between two neighbouring nozzles is in all cases 0.3 m. A pressurized water tank was used to supply the water. The total water flow rate in the main water supply pipe was measured with a Krone flowmeter. Bulbs were placed 35 mm below the ceiling and special activation equipment was used to activate the nozzles immediately after the corresponding bulbs were activated. In the deluge tests, all automatic valves were open at 75 s after ignition. Each nozzle covered one tunnel section with 0.3 m × 0.3 m area. The water density is defined as the average water flux in this specific section.

The narrowest nozzle passage diameter was 0.7 mm (10.5 mm in full scale). The spray angle was 120°. The tested water flow rate of a single nozzle was 0.38 L/min, 0.46 L/min and 0.58 L/min, corresponding to 16.5 mm/min, 20 mm/min and 25 mm/min at full scale, respectively. The bulbs used in the tests were F1.5×16 with RTI of 14 and a diameter of 16 mm and a length of 16 mm, produced by Job Thermo Bulbs. The corresponding RTI is 107 in full scale. Two types of bulbs with the same geometry and different link temperature of 68 °C and 141 °C, respectively, were used. 

**RESULTS AND DISCUSSION**

**Activating auto sprinklers**

The activation of the first bulb plays an important role in the performance of an automatic sprinkler system in a tunnel fire. The first bulb to activate is normally capable of suppressing the fire spread in the growth period since it is location close to the fire source. In the following we analysis the activation conditions for the first activated bulb.

Figure 4 show the activation heat release rates (AHRR) of the first activated bulb, $Q_{a1}$, as a function of the ventilation velocity, $V$, with a link temperature of 141 °C. It can be seen that there is a strong correlation between these parameters. The activation heat release rate increases linearly with the ventilation velocity. This is as expected since the higher ventilation cools the gas, which in turn increases the AHRR necessary to fulfil the activation conditions for the bulb. In addition, the linear correlation between the AHRR and the longitudinal ventilation velocity shows that the activation ceiling temperature is almost a constant according to the equations proposed by Li et al. [19]. The reason may be that the ceiling gas temperature plays a much more important role than the gas velocity in the activation of the bulbs in a tunnel situation. If we assume that 1/4 of the wood crib was burning at the upstream edge of the wood crib at this time, since the heat release rate is very low compared to the maximum heat release rate in the corresponding free-burn test, the calculated activation temperature according to the equations proposed by Li et al. [19] is about 206 °C for a link temperature of 141 °C. This corresponds to an excess activation temperature is 65 °C higher than a link temperature.
Maximum heat release rate

Figure 4 shows the dimensionless maximum heat release rate in an automatic sprinkler test with a link temperature of 141°C using Constant Ventilation Strategy. A dimensionless maximum heat release rate, $Q_{\text{max}}/Q_{\text{max,freeburn}}$, is used to normalize the results. Since no free burn tests with a ventilation velocity of 2.0 m/s were carried out and the fire is fuel-controlled, the maximum heat release rate under these ventilation conditions is assumed to be equivalent to that with a ventilation velocity of 1.5 m/s which is a conservative assumption. In practice the fires in free burn tests are fuel controlled. This implies that the maximum heat release rates are almost the same under different ventilation.

Figure 5 shows the dimensionless maximum heat release rate in an automatic sprinkler test with a link temperature of 141°C as a function of the dimensionless longitudinal velocity. In Figure 5 the maximum heat release rate increases linearly with the ventilation velocity when the dimensionless longitudinal velocity is in the range of 0.2 to 1.0. This means that the maximum heat release rate in an automatic sprinkler test is almost independent of the water flow rate. It should be kept in mind that the water flow rates, i.e. 0.38 L/min, 0.46 L/min and 0.58 L/min, are at a high level so that the fire can be extinguished immediately if applied in a deluge system. Under such conditions, only part of the nozzles will have an influence on the fire development through cooling of the flame and burning surfaces, depending on the ventilation velocity. Most of other nozzles simply cool the hot
gases downstream to prevent the collapse of the system. The correlation in Figure 5 can be expressed as:

$$\frac{Q_{\text{max}}}{Q_{\text{max,freeburn}}} = -0.10 + 0.82V^*$$

(1)

where the dimensionless longitudinal velocity is defined as $V^* = V / \sqrt{gH}$, $Q_{\text{max}}$ is the maximum heat releaser rate in a test with an automatic sprinkler system, $Q_{\text{max,freeburn}}$ is the maximum heat release rate in a free-burn tests in the tunnel without water spray system. A correlation coefficient of 0.9554 was found for Equation (1).

**Collapse of the system**

For an automatic sprinkler system installed in a tunnel, the key issue is whether this type of system will collapse or not for certain conditions. If too many nozzles are activated, the automatic sprinkler system cannot work properly, which is designated as a system collapse.

Failure of an AWS system during a fire is defined as it having an activation range equal to or greater than 100m at full scale, i.e. a dimensionless activation range of about 15 (15 times the tunnel height). In our tests, the furthest bulb was placed 6.5 m downstream of the fire source, which corresponds to 98 m in full scale. Normally the bulbs upstream were not activated. Therefore the furthest bulb at the end of the tunnel is used as a mark of the collapse of an automatic sprinkler system in the tests. This is a conservative definition as there were no nozzles with water close to the bulbs further than 1.6 m downstream of the fire source centre. If that would have been the case, probably less bulbs would have been activated.

**Effect of ventilation**

Figure 6 shows the effect of longitudinal ventilation velocity on the range of activated nozzles with different water flow rates. A collapse line, corresponding to a distance of about 100 m at full scale, is also included. A data point lying on this line indicates that the automatic sprinkler system has collapsed. In Figure 6, it can be observed that the activation range increases significantly with the ventilation velocity. This means that an automatic sprinkler system collapse more readily at a higher ventilation velocity.

![Figure 6. The effect of ventilation velocity on the activation range (TL=141 °C).](image)

Increasing longitudinal ventilation velocity results in a greater deflection of the fire plume. Therefore the position of the maximum temperature moves further downstream. On the other hand, the forced ventilated flow deflects the water spray in the downstream direction. Therefore at a high ventilation
velocity, the nozzles above the fire cannot be activated immediately. In other words, the first activated nozzle and the activation range move further downstream as the velocity increases.

According to the analysis of the maximum heat release rate in Section 6.3 (Figure 5), it is known that the maximum heat release rate increases linearly with the ventilation velocity. This indicates that a higher heat release rate in a high ventilation results in a higher gas temperature. Both the high gas temperature and the high ventilation enhance the heat transfer to the bulbs. As a consequence, the activation range moves further downstream, which results in the collapse of an automatic sprinkler system.

*Effect of water flow rate*

Figure 7 shows the effect of the water flow rate on the activation range in an automatic sprinkler system with a link temperature of 141 °C. It clearly shows that the activation range decreases significantly with the water flow rate, especially at higher ventilation.

![Figure 7. The effect of water flow rate on the activation range (T_L=141 °C).](image)

There may be two reasons for this decrease in the activation range with increasing water flow rate. Firstly, more efficient suppression of fire development due to activated nozzles close to the fire. The water droplets absorb a large amount of heat from the fire and hot gases, which decreases the heat gain on the burning surface and results in a lower burning rate. Secondly, more efficient cooling of hot gases due to activated sprinklers on the downstream side.

However, according to the above analysis of the maximum heat release rate, the tested water flow rates are at such a high level that the fire could be extinguished immediately in a deluge system. Therefore the maximum heat release rate is only dependent on the ventilation velocity under the tested water flow rates. This means that there is no significant difference in the effect of water flow rates at the tested level on the fire development in the tests. In other words, the difference in the effect of water flow rate on the collapse of a system in these tests mainly results from the different effect of cooling the hot gases downstream of the fire.

*Determination of collapse of an automatic spray system*

For application of these results to real cases, several dimensionless parameters are defined here:

Dimensionless water flow rate: \( q^*_w = \frac{q_w}{\sqrt{W}} \)

Dimensionless activation range: \( L'_\text{range} = \frac{L_{\text{range}}}{H} \)

where \( W \) is tunnel width, \( H \) is tunnel height, \( q^*_w \) is the water density, \( L_{\text{range}} \) is the activation range.
A 3D plot of the dimensionless activation range as a function of the dimensionless longitudinal ventilation velocity and the dimensionless water flow rate is shown in Figure 8. The dimensionless longitudinal velocity is defined in Equation (1). It is shown in Figure 8 that the ventilation velocity and the water flow rate have an insignificant influence on the activation range for low ventilation velocities and high water flow rates. However, the water flow rate plays a much more important role in the activation range under higher ventilation velocities and lower water flow rates.

![3D plot](image)

**Figure 8** A 3D plot of the dimensionless activation range as a function of the dimensionless longitudinal ventilation velocity and the dimensionless water flow rate (TL=141 °C).

To better illustrate the results, a figure consisting of contour lines is shown in Figure 9. It is clearly shown that the water flow rate has little influence on the activation range when the dimensionless longitudinal velocity is lower than 0.5. However, both the ventilation velocity and the water flow rate play important roles in the activation range under higher ventilation conditions.

![Contour plot](image)

**Figure 9** Determination of collapse of an automatic sprinkler system (TL=141 °C).

As discussed previously, the collapse of an automatic sprinkler system can be recognized when the dimensionless activation range is over about 15. The collapse line of $L_{\text{range}} = 15$, as shown in Figure 9, can be approximately expressed as:
Equation (2) is valid when the dimensionless water flow rate is in the range of 5.5 to 8.3. From Equation (2), it is shown that under high ventilation conditions, the water flow rate must be increased linearly with the ventilation velocity to prevent collapse of an automatic sprinkler system in a tunnel fire.

It should be pointed out that no nozzle was installed further than 1.6 m (4 times tunnel height) downstream of the fire source. Therefore the data presented and the conclusion made here are conservative and only valid within the tested range.

Use AWS system under low ventilation
High ventilation velocities promote fire development, resulting in failure of the AWS system. It should be used in tunnels with low ventilation velocities or natural ventilation. Therefore, it is recommended that AWS systems be used in tunnels having transverse ventilation or in bi-directional tunnels, since in these tunnels longitudinal ventilation velocities will be relatively low. To prevent the collapse of the system, a robust strategy is to divide the system into several zones, similar to the deluge system. This system can be called zoned individually automatic sprinkler system, which reduces the total water requirement compared to a deluge system but prevents release of zones beyond the fire zone and prevents collapse of the automatic sprinkler system.

AWS systems are not recommended for use in longitudinally-ventilated tunnels with high ventilation velocities, except when variant ventilation strategies or special control strategies are applied. These two strategies are not discussed here but can be found in the report [21]. Note that after the velocity reduces to a level of about critical velocity after first activation, the system works well. In any way, large-scale tests will be required to further verify these results.

CONCLUSION

The performance of an automatic sprinkler system in a tunnel fire under different ventilation conditions was tested in a 1:15 model scale tunnel. The activation of the nozzles, the maximum heat release rate and the collapse of an automatic sprinkler system were investigated. Both the activation heat release rate (AHRR) of the first activated nozzle and the maximum heat release rate in a test were found to increase linearly with the ventilation velocity.

High ventilation and low water flow rates result in the collapse of an automatic sprinkler system in a tunnel fire. Note that the tested water flow rate for a single nozzle was 0.38 L/min, 0.46 L/min and 0.58 L/min, corresponding to 16.5 mm/min, 20 mm/min and 25 mm/min at full scale, respectively. The results show that the longitudinal ventilation plays the most important role in the collapse of a system by stimulating the fire development, i.e. the maximum heat release rate and the fire growth rate under the tested water flow rates. The different tested water flow rates do not show any obvious effect on the fire development, although, the downstream nozzles with higher water flow rate cool the hot gases more efficiently to prevent the collapse of the system. It can be concluded that the most important parameter for an automatic sprinkler system under the tested water flow rates in a tunnel fire was the ventilation velocity rather than the water flow rate. The fire development was intimately related to the ventilation velocity, and almost independent of the water flow rate under such conditions. The maximum heat release rate in an automatic sprinkler system was found to increase linearly with the ventilation velocity.

Note that no nozzle was placed further than 1.6 m (4 times tunnel height) downstream of the fire source in the tests. The cooling effects were therefore underestimated in some of the tests. The presented data concerning the activation range and the conclusions drawn here are therefore conservative.
REFERENCES

A study of the interactions between a water suppression system and a longitudinal ventilation system in a tunnel

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ABSTRACT

The present study investigates the interaction between a suppression system and a longitudinal ventilation system in a tunnel. The full-scale experimental program was conducted using a sprinkler system in a laboratory tunnel equipped with a longitudinal exhaust system. The cooling effect and radiation attenuation were examined by activating the sprinkler system over a propane fire which generated a constant HRR. Based on the results of the tests, the study proposes a method to quantify the effect of both systems on smoke cooling and suggests a method to calculate the velocity required to resist backlayering when the suppression system is active.

KEYWORDS: tunnel fires, water suppression systems, ventilation systems

INTRODUCTION

Mitigating the effects of fires in tunnels relies mostly on mechanical ventilation systems that extract the hot smoke from the tunnel. Commonly used in unidirectional traffic tunnels, longitudinal mechanical ventilation minimizes smoke backlayering (i.e. smoke flow against the direction of the ventilation air flow) and clears the tunnel from smoke upstream of the fire, where motorists are likely to be queued due to the fire. A concern associated with longitudinal ventilation systems is the fact that the systems blow fresh air into the tunnel, which may cause rapid fire growth and fire spread to other vehicles queued in the tunnel.

Early fire fighting is effective in minimizing losses due to fires, yet the use of Water-based Fixed Fire Fighting Systems (WFFFS) has not been considered for many years despite their proven abilities to suppress fires, control fire growth and prevent fire spread. This is mainly because of a lack of knowledge about the effectiveness of the system as well as some concerns over the use of the system in tunnels. One of the main concerns regarding the use of WFFFS in tunnels is that water spray may destroy the smoke layer and lower visibility in the tunnel.

The expectation is that if both WFFFS and longitudinal ventilation systems are employed in tunnels they can compensate for each other weaknesses, and both systems can effectively control smoke, prevent fire spread and mitigate hazards in the case of tunnel fires. There are, however, no experimental data to show whether the systems can actually work this way, and to provide guidelines for designing these systems.

The objectives of the present study are: to examine the interaction of WFFFS and longitudinal ventilation systems; to investigate the effects of using both systems, and ultimately to develop methods that can be used to design both systems.

EXPERIMENTAL PROGRAM

Full-scale suppression tests were carried out in the laboratory tunnel of Carleton University. The tunnel is 10 m wide, 5.5 m high and 37.5 m long. Figure 1 shows a schematic of the tunnel.
Tunnel ventilation system

The tunnel is equipped with an exhaust system (see Figure 1) with a maximum capacity of 132 m³/s, which extracts smoke from the tunnel through ceiling openings located at one end of the tunnel. At the main opening to the tunnel flow straightening vanes were installed to promote uniform air flows over the cross-section of the tunnel. Tests were performed with the exhaust fans at 25%, 50%, and 100% of their capacity, which created longitudinal air flows in the tunnel of 0.5-0.7 m/s, 1.3-1.5 m/s and 2.8-3.0 m/s (calculated based on the exhaust fan capacity), respectively.

Sprinkler system

Figure 2 shows the test arrangement in the laboratory tunnel. Figure 3 shows the sprinkler system and instrumentation used in the tunnel. A sprinkler system was installed under the ceiling of the tunnel above the fire area (See Figure 3 (a)). An open deluge sprinkler system used in the test program. The system was manually operated during the tests. Four different water spray rates ranging from 3 to 14 l/min/m² were examined. The water spray system had 5 parallel, 9 m-long branches spaced at a distance of 3.7 m. Each branch had four sprinkler heads spaced at 2.5 m. The sprinkler nozzles had a thread size of 15 mm and a K-factor of 161.3 l/min/bar⁰.⁵ (11.2 gpm/psi⁰.⁵) which generate large droplets.

For most tests, three branches (#1, #2, #3) over the fire area were open for a spray area of 111 m². Water spray rates of 3, 6 and 9 l/min/m² were used. In two tests, two branches (#2, #3) were open for a spray area of 74 m² to test a water application density of 14 l/min/m². Water flow rates and pressures of the sprinkler system were measured for each test. Table 1 shows the operating pressures for each water application rate tested.

Fire

Shielded propane fires with a constant HRR were tested under the sprinkler system to simulate the condition when the suppression system successfully holds the growth of the fire and controls the HRR to its value at the time of activation. Fire sizes of 5, 10 and 15 MW were tested. In each test, the fire started without the sprinkler system active. After steady-state data were acquired for about 5 min without suppression, the sprinkler system was open for about 5 min in most tests or 10 min in some cases where two different water application rates were tested in succession. This test set-up was
suitable for a comparison of the condition in the tunnel without and with the suppression system active. Table 2 shows a list of the tests carried out.

**Table 2 List of tests performed**

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<td>H15M50%9</td>
<td>9</td>
<td>15</td>
<td>2.66</td>
<td>1.3</td>
<td>50</td>
</tr>
<tr>
<td>19</td>
<td>H15M100%6</td>
<td>6</td>
<td>15</td>
<td>2.66</td>
<td>2.8</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>H15M100%9</td>
<td>9</td>
<td>15</td>
<td>2.66</td>
<td>2.8</td>
<td>100</td>
</tr>
</tbody>
</table>

As shown in Figure 3, the fire was placed 12 m from the tunnel opening. The propane burners were capable of generating a HRR up to 10 MW, so for the 15 MW fire tests, a heptane pan fire was used.
together with the propane burners. The size of the rectangular pan was 1.5 m by 0.76 m. The pan was about 0.3-0.4 m deep, which was deep enough to ensure a constant pyrolysis rate over the surface of the pan. The pan was placed next to the propane burners, under the metal shield (2.9 m × 4.9 m) that was built over the fire area at the height of 2.8 m (see Figure 2).

Instrumentation

The ceiling temperatures at a distance of 0.16 m from the ceiling were measured along the centre line of the tunnel. The locations of the thermocouples are shown in Figure 3 (b). Four thermocouple trees were placed along the centre line of the tunnel, two downstream of the fire, one near the fire, and two upstream of the fire. The thermocouple trees measured temperatures at the height of 1.35, 2.35, 3.35 and 4.35 m.

Heat fluxes were measured at a height of 1.5 m at two locations 8 m downstream of the fire and 8 m upstream of the fire. Water-cooled sensor, Garden gauges as well as plate thermometers were used to ensure accurate measurements of heat flux. A plate thermometer measures adiabatic surface temperature, based on which the incident heat flux can be calculated. More details of the heat flux measurements and the heat flux calculations based on the temperature measurements by the plate thermometer are available in [2].

RESULTS

Longitudinal ceiling temperature profiles

Time-averaged temperatures during the steady-state condition were obtained in each test without and with the sprinkler system active. Figure 4 presents the longitudinal ceiling temperature (ΔT) profiles from the 10 MW fire at an air velocity of 1.5 m/s and different water spray rates.

![Figure 4 Longitudinal ceiling temperature profiles (ΔT) from the 10 MW fire at air velocity of 1.5 m/s (50% fan speed) with the sprinkler system active](image)

Ceiling temperatures along the length of the tunnel dropped with the sprinkler system active, in particular, in the area upstream of the fire and the spray section. Test results show that the combination of a large longitudinal air velocity and water spray effectively cools the hot gases. When a water flow density of 9 l/min/m² was used, the ceiling temperature from the 10 MW fire was reduced by about 50% in the vicinity of the fire.

Vertical temperature profiles upstream of the fire

Figure 5 shows the vertical temperature (ΔT) profiles 10 m upstream for the 10 MW fire. The figure demonstrates clearly that the backlayering was reduced with the use of the sprinkler system. The effect was more significant with the larger water flow densities. With a water spray density of 9 l/min/m² the backlayering completely disappeared even though the air flow of 1.7 m/s generated by
the fan speed of 50%, was less than the critical velocity of 2.3 m/s required for the 10 MW fire.

![Graph](image)

**Figure 5** A comparison of vertical temperature ($\Delta T$) profiles 10 m upstream of the 10 MW fire with and without the sprinkler system operating at air velocity of 1.5 m/s (50% fan speed)

**Heat flux measurements**

Figure 6 compares heat fluxes measured 8 m downstream ($q_{+8}$) and 8 m upstream ($q_{-8}$) for the 10 MW fire with an air flow of 0.5 m/s (25% fan speed) and a water spray density of 6 l/min/m². Before the sprinkler system was activated, heat fluxes measured at both locations were about 6-8 kW/m², which are high enough to cause death to people [3]. After the sprinkler was activated, heat fluxes at both locations were reduced to between 3-4 kW/m². This decrease in heat flux is mainly from radiation absorption and scattering caused by the water droplets.

![Graph](image)

**Figure 6** A comparison of heat flux ($q_{+8}$) measured 8 m downstream and heat flux ($q_{-8}$) measured 8 m upstream of the 10 MW fire (air velocity of 0.7 m/s, water spray density 6 l/min/m²)

**DISCUSSION**

**Analysis of the cooling effect of WFFFS along with longitudinal air flows**

Gas temperatures near the ceiling in the vicinity of the fire are of interest as they represent the severity of the fire and govern the amount of heat that the tunnel structure would receive in the event of a fire. The maximum ceiling temperature data obtained from the suppression test program were analysed, and a method is proposed to estimate the cooling effect of the sprinkler system together with the longitudinal ventilation system on the temperatures in the vicinity of the fire.

With the data obtained from the suppression test program of the present study, $\frac{\Delta T_{\text{max}}}{T_o}$ without the sprinkler system active are analysed. $\Delta T_{\text{max}}$ is the maximum ceiling temperature rise in the vicinity of the fire, and $T_o$ is the ambient temperature. A correlation with $Q^{2/3}$, $\left(\frac{V}{Q^2}\right)^{1/3}$ is found as shown.
below, based only on the test data. $Q^*$ is dimensionless HRR, and $V^*$ is dimensionless longitudinal air velocity. $\rho_o$ is ambient air density. $C_p$ is heat capacity of the hot gases, and $T_o$ is the ambient temperature. $H$ is the hydraulic tunnel height that is defined as the ratio of 4 times the tunnel cross-sectional area to the tunnel perimeter. More detailed discussions about the correlation are available in [2].

$$\frac{\Delta T_{\text{max}}}{T_o} = 9.94 \left( \frac{Q^{\frac{2}{3}}}{V^*} \right)^{0.44} \approx 10 \left( \frac{Q^*}{V^*^{1/3}} \right)$$

(1)

where $V^* = \frac{V}{\sqrt{gH}}$, $Q^* = \frac{Q}{\rho_o C_p T_o \frac{g^{1/2}H^{5/2}}{5/2}}$, if $\frac{Q}{\rho_o C_p T_o \frac{g^{1/2}H^{5/2}}{5/2}} > 0.2$, $Q^* = 0.2$

Figure 7 compares the results of the correlation with the test data. In addition, full-scale test data from the Runnehamar tunnel [4], Reparfojord tunnel [5, 6], Memorial tunnel [7] and the second Benelux tunnel [8] are also plotted, and $T_{\text{max}}$ data available from small-scale tests by SP [9] are also plotted to see whether data from other studies fit the correlation. These data have been taken from a wide range of fire sizes (5 MW-390 MW) and longitudinal air velocities (up to 6 m/s). Note that for large fires, if the calculated $\frac{Q}{\rho_o C_p T_o \frac{g^{1/2}H^{5/2}}{5/2}}$ is greater than 0.2, the asymptotic value of $Q^*$, 0.2, is used.

Despite the various geometries of the tunnels and test conditions used in the previous studies, the data from other studies fit to the correlation. Full-scale test data from the 2nd Benelux tunnel sit on the correlation line. However, some data deviate considerably, especially at higher values of $\frac{\Delta T_{\text{max}}}{T_o}$. This is because, for larger fires, $T_{\text{max}}$ does not represent the gas temperature as $T_{\text{max}}$ reaches the flame temperature and $\frac{Q}{\rho_o C_p T_o \frac{g^{1/2}H^{5/2}}{5/2}}$ becomes greater than 0.2.
Maximum ceiling temperature with a suppression system active

In general, the spray characteristics of WFFFS that mainly govern the cooling effect of the system include the water spray rate, the discharge pressure and droplet size as well as the water spray distribution. The most critical of all these is the water spray rate \( \omega \), which is considered in the analysis. In addition the ratio, \( \frac{Q^*}{V^{1/3}} \), which was used in the analysis of the maximum temperature without the suppression system operating, is also considered. The cooling effect of the sprinkler system is proportional to the water spray density \( \omega \) and the gas temperature. The temperature of the horizontal smoke flow can be correlated with \( Q^{2/3} \) [10], thus the factor \( \omega Q^{2/3} \) is used in the analysis. More detailed discussion can be found in [2].

The maximum ceiling temperature data obtained under suppression \( \Delta T_{\text{max,s}} \) from the suppression test program are plotted in Figure 8 and a correlation is found based on the data from the present study.

\[
\frac{\Delta T_{\text{max,s}}}{T_0} = 23.5 \left[ \frac{Q^*}{V^{1/3}(\omega Q^{2/3})^{1/3}} \right]^{1.642} = 23.5 \left[ \frac{Q^{7/9}}{(\omega V^*)^{1/3}} \right]^{8/5}
\]  

(2)

The model was tested using the test data from the SP small-scale experiments. The maximum temperature data measured under suppression sit in the vicinity of the correlation line. However, further validation is necessary. This correlation is only valid within the range of tested fire sizes (5-40 MW), water spray densities (3-9 l/min/m²) and air velocities (0.5-3 m/s). It can only be applied for a similar type of sprinkler system.

Based on Eq (1) and Eq (2), a factor of \( \frac{\omega^{1/3}Q^{1/3}}{Q^{1/4}} \) is found which controls the combined cooling effect of the sprinkler system and the longitudinal ventilation system on the maximum ceiling temperature. In Figure 9 the results of \( \frac{\Delta T_{\text{max,s}}}{\Delta T_{\text{max}}} \) from the suppression test program are plotted.

\[ y = 23.498x^{1.6423} \]

\[ R^2 = 0.9366 \]
Analysis of backlayering during suppression along with longitudinal air flows

The temperature data 10 m upstream of fires obtained from the suppression test program was examined to find the impact of the sprinkler system on smoke backlayering phenomena. Based on the data analysis, a method to estimate the degree of backlayering with suppression operating is proposed.

The degree of backlayering under suppression, \( \frac{\Delta T_{-10}}{T_0} \), is correlated with the dimensionless HRR (Q*), water spray rate (\( \omega \)) and the ratio of the ventilation velocity to the critical air velocity (\( V/V_c \)). The critical air velocity (\( V_c \)) is calculated by the method suggested by Wu and Bakar [11]. In Figure 10, using test data obtained from the experimental program of the present study, the degree of backlayering, \( \frac{\Delta T_{-10}}{T_0} \), is correlated with the dimensionless source factor.

\[
\frac{\Delta T_{-10}}{T_0} = 1.7 \left( \frac{\omega (V/V_c)^2}{Q^*} \right)^{-1.2}
\]  

(3)

\( \frac{\Delta T_{-10}}{T_0} > 0.1 \) is considered as a criterion to determine the presence of backlayering, the critical source factor comprised of Q*, \( \omega \) and \( \frac{V}{V_c} \), is 9, from equation (3), which ensures no backlayering. For a source factor greater than the critical value, the cooling effect of the spray system combined with the longitudinal air flow result in minimizing smoke backlayering. The correlation can be used to determine whether there would be backlayering for a given fire size, water spray rate and air velocity.
Applying this criterion to a tunnel with a hydraulic diameter of 7.1 m, the V/Vc required to prevent smoke backlayering is plotted in Figure 11 for various HRR from 5 to 30 MW with respect to water spray densities. The figure shows that the smoke backlayering can be controlled with a lower velocity that the critical velocity calculated by the current well-established model when the sprinkler system is accompanied with the longitudinal ventilation system. For a 15-MW fire, the required velocity is reduced by 50% when the sprinkler system is applied with a water spray density of 10 l/min/m².

Radiation attenuation by the water spray

Heat fluxes were measured during the suppression tests, and the collected data were analysed to investigate the effect of radiation attenuation by the water spray. Fractions of transmitted radiation, \( \frac{q_s}{q_o} \), are plotted with respect to water spray densities (\( \omega \)) in Figure 12 (a) and (b) for upstream and downstream locations, respectively. The fraction of transmitted radiation is the ratio of incident radiation measured with water spray (\( q_s \)) to that measured without water spray (\( q_o \)). In Figure 12 (a), for the same size of fire and ventilation, transmitted radiation heat flux measured upstream of the fire decreases exponentially as the water spray rate increases, and the rate of attenuation is about 0.4-0.5 with a water spray rate of 10 l/min/m² in most cases. A greater degree of radiation attenuation was observed particularly in the tests where significant smoke backlayering was observed (as in T10M25% and H15M50%).

![Figure 11](image1.png)

**Figure 11 The required velocity to prevent the backlayering with the suppression system active [2]**

![Figure 12](image2.png)

**Figure 12 Fraction of transmitted radiation with respect to water spray rates**
Since the air flow shifts the water spray downstream, the water spray zone extends toward the air flow direction. As a consequence, the radiation attenuation is more significant in the area downstream than upstream because downstream the radiation is transmitted from the flames as well as from the hot gases. As shown in Figure 12 (b), the rate of transmitted radiation decreases exponentially with the increase of water spray densities. When the water spray density is larger than 10 l/min/m², about 60-80% of the radiation is reduced due to the finer droplets that were distributed more evenly over the spray zone.

CONCLUSIONS

The cooling effect of the sprinkler system and the longitudinal ventilation system was examined by observing the temperature distribution in the tunnel. A method to estimate the maximum gas temperature near the tunnel ceiling is proposed, which can be used to predict the thermal intensity that the tunnel structure would experience during the fire. The proposed correlation gives a relatively good prediction over a wide range of fire sizes and velocities, as well as water spray densities.

By cooling smoke temperatures, the suppression system enabled the longitudinal ventilation system to prevent backlayering of smoke at a lower velocity than the critical velocity. An analysis of temperature data upstream of the fire was performed to correlate the degree of backlayering with the given conditions of air velocity, water spray density and fire size. From the data analysis, a method to calculate the velocity required to resist backlayering in the case when the suppression system is active is proposed.

The heat flux measurements with the sprinkler system operating show that radiation attenuation by the sprinkler system increases as the water spray rate increases. The radiation attenuation was significant particularly in the area downstream because the radiation transmitted from the fire as well as the hot gas is effectively attenuated by the water spray that acts as a shield.

REFERENCES

Automated fire detection and mitigation in railway tunnels designed for freight trains

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KEYWORDS: tunnel safety, train tunnel, fire detection, mitigation algorithm, deluge sprinkler.

INTRODUCTION
The rail infrastructure in the Netherlands has recently been extended with new railway systems dedicated to freight transport and high speed passenger trains. For both railway systems it is of the utmost importance that the trains safely pass through, over and under the densely populated regions of the Netherlands. As a consequence, each new railway system includes several tunnels. A number of high safety standards need to be met, and therefore these tunnels require sophisticated safety systems to ensure effective and safe operation. These safety systems are highly automated and are designed to detect potentially dangerous situations, such as stopping trains, fire, gas and high water levels. The safety system responds by taking automated action to mitigate the effects of these situations, and it activates evacuation and rescue scenarios.

This paper addresses the automated mitigation of a freight train fire and discusses the solution developed for five railway tunnels in the Betuweroute in the Netherlands.

THE BETUWEROUTE FREIGHT TRAIN LINE
In the early 1990s, the volume of goods to be transported through the Netherlands into the European hinterland was predicted to grow significantly, as a result of the expansion of the Port of Rotterdam. One of the modes of transportation would be by train; however, the existing railway lines from Rotterdam into Germany were reaching their maximum capacity. It was not an option to expand the capacity of these lines, as they ran through major cities and other heavily populated areas; moreover, using the existing lines was considered a safety hazard since there would be no restriction on the transport of hazardous goods. Eventually the Dutch government decided to build a new railway connection between the Port of Rotterdam and the German border that was especially designed for and exclusively used by freight trains. This 165 kilometre long railway was built between 1997 and 2007 and is known as the Betuweroute. It traverses some densely populated areas and several waterways; in order to negotiate these, the line contains a series of tunnels.

Figure 1 presents a map of the Betuweroute with the five major tunnels indicated and Table 1 gives an overview of dimensions of the tunnels.
ACTIVE FIRE-FIGHTING SYSTEM

The Betuweroute tunnels have been equipped with an active fire-fighting system which comprises a deluge sprinkler system, a longitudinal ventilation system, a fibre-optic based linear fire-detection system and a control system that automatically activates the sprinkler and ventilation systems in case of fire.

The fire-fighting system protects both the tunnel construction and the infrastructure inside the tunnel by fighting the fire at the location of the incident and reducing the effects of the fire on the tunnel lining at the location of the fire and in the downstream direction of the fire. Downstream direction is considered relative to the airflow in the tunnel.

The design parameters for the sprinkler water spray density, the ventilation systems capacity, the sprinkler pumps and the sprinkler water distribution system capacity are based on two reference incident scenarios: (1) a pool fire with a potential heat release rate of 240 MW and (2) the prevention of a possible BLEVE in case of fire on a train carrying LPG. In both cases the incident is assumed to occur on a 750 meter train and the fire would be positioned halfway into the tunnel, which is the most unfavourable position for the ventilation system. An additional requirement was that all systems had to be uniform for all five tunnels, which vary in length from 0.5 to 6.3 kilometres.

Based on these requirements, the fire-fighting system was designed as a deluge sprinkler system with 30-meter sprinkler sections. Each section can be individually activated by the control system. The sprinkler sections are constructed as three-pipe strands each fitted with sprinkler heads at every 3.5 meters. The ventilation is designed as a longitudinal ventilation system with jet fans positioned along the length of the tunnel.

Protection of the tunnel construction at the location of the fire is accomplished by spraying 10% of the water released by the activated sprinkler sections back onto the tunnel lining, thus cooling the concrete. In addition, the tunnel lining downstream of the fire is protected by the ventilation system that forces the fumes and gases through the activated sprinkler sections, thus cooling down these fumes and gases to a temperature below 360 °C.
Since both the water storage capacity at the tunnels and the capacity of the water distribution system in the tunnels are limited, the sprinkler system has been designed and optimized for operation with a maximum of four adjacent sprinkler sections activated at any one time. This has resulted in 120 meters of activated sprinkler sections, releasing a total of 14,500 litres of water-foam premix per minute. The 120 meter section is considered the minimum length to be activated and the nominal water spray density needs to cope with the two reference scenarios mentioned earlier.

For fire detection, a redundant fibre-optic based linear temperature measurement system was installed. This system measures the air temperature at the tunnel ceiling. Temperatures above a 58°C threshold value are considered a fire and trigger the control system. An additional requirement for the temperature measurement system was the ability to determine the location of a fire within 15 meter intervals, which is 50% of the length of the sprinkler sections. Establishing the correct location of a fire is critical to ensure the activation of the correct sprinkler sections.

Figure 2 shows a typical cross section of one tunnel tube, with the location of (1) the sprinklers, (2) the jet fans, (3) the fibre-optic cables, (4) the valve cabinet and (5) the water distribution.

Figure 3 indicates the positioning of temperature measurement intervals or detection zones (1) and the sprinkler sections (2). It also shows the valve configuration or Valve Cabinet (3) used to connect the sprinkler sections to the sprinkler water distribution line (4) and activate a specific sprinkler section when needed.
ACTIVATION OF THE SPRINKLER SYSTEM
If a fire is detected, i.e. the threshold value is reached for one of the measurement points, a total of four adjacent sprinkler sections are activated. The first section activated is the section which includes the measurement point with the highest temperature. This is presumed to be located directly above the fire and to be the one nearest to the detected fire position. In Figure 4, this would be section N. Simultaneously, the two adjacent sections are activated (N+1 and N-1), in order to cool down the tunnel construction and the parts of the train adjacent to the fire position. The fourth section to be activated is in the downstream direction of ventilation (N+2).

FIRE POSITION DETECTION FAULT
Detection of the correct location of the fire by the temperature measurement system is important to establish the activation of the correct sprinkler sections around the actual fire position.

It was anticipated that the location of a fire detected by the temperature measurement system would be influenced by the airflow through the tunnel as well as the speed of the fire development. Especially in the early stages of fire development, the measurement system will react to the convection heat and this heat will be moved by the airflow.

Moreover, the water spray released by the sprinkler system will be driven in the same direction as the airflow generated by the ventilation system. Both phenomena result in poor coverage of the fire with sprinkler water on the upstream side of a fire as indicated in Figure 5.
The results of different tests with controlled pool fires in the Botlek, Zevenaar and Sophia tunnels showed that with airflows between 1.5 and 2 m/s, the indicated position (measured maximum temperature) can differ up to 10 meters from the actual fire position. With increasing airflow (> 2.0 m/s) variations of up to 15 meters were detected. The water spray was also observed to change direction. With airflows of > 2 m/s, the water spray could be pushed further down the tunnel, for up to 15 meters.

Airflow speeds in excess of 2 m/s are to be expected, either due to the longitudinal ventilation system activated at train standstill and at detection of a fire, or due to the airflow generated by the train when coming to a standstill in the tunnel.

FIRE DETECTION AND CONTAINMENT ALGORITHM
The fire detection and containment algorithm was specifically developed to compensate for the shift in the temperature profile measured at the tunnel ceiling, relative to the actual fire position. In addition, based on the temperature profile, the algorithm determines the direction of the airflow in the tunnel, in order to activate the optimal ventilation direction.

The temperature profiles shown in Figure have been recorded with the temperature measurement system of the Sophia tunnel while system tests were being performed. The measurement locations were at 15 meter intervals, and the curves show the temperatures at measurement point t001 to measurement point t017 at the moment the threshold value of 58 °C was reached at one of the measurement points. Air was flowing from t001 in the direction of t017.

The test pool fires were created using square metal pans of 1 m² with ethanol, placed on a flatbed railway trolley. In both Tests 1 and 6, the fire was located at measurement point t005.

1. Test 1: pool fire of 4 m² ethanol with an airflow of 0.2 m/s.
2. Test 6: pool fire of 16 m² ethanol with an airflow of 2.4 m/s.

As the airflow increases, the temperature profiles show a shift in the maximum temperature location in the same direction as the airflow. It also shows a change in the shape of the profile. For Test 1, the maximum temperature was detected directly above the fire location (t005). For Test 6, the maximum temperature was detected one measurement point downstream (t006) of the actual fire location (t005).

At low airflow speeds, the profile is shaped symmetrically around the maximum temperature point as may be expected. However, as the airflow increases, there is a sharper rise of the temperature in front of (or upstream of) the maximum temperature point and a long ‘tail’ downstream in which the temperature hardly drops.
CORRECTION FOR MEASUREMENT SHIFT

The control system algorithm uses the temperature profile to determine whether a shift has occurred in the maximum temperature position and in what direction a correction should be made. If \( T_{\text{max}} \) is the measurement point with the maximum temperature, the algorithm calculates the difference between the temperature value two points in front of \( T_{\text{max}} \) (\( T_{\text{max}-2} \)) and two points after \( T_{\text{max}} \) (\( T_{\text{max}+2} \)). If the delta between these values is greater than 20\(^\circ\)C, a correction will be made. The algorithm will then calculate the temperature drop relative to \( T_{\text{max}} \) for \( T_{\text{max}-2} \) and \( T_{\text{max}+2} \). The highest temperature drop indicates the front of the temperature profile, in other words the upstream side. The lowest drop in temperature indicates the tail, or the downstream side. The position of \( T_{\text{max}} \) will then be corrected by 1 measurement position upstream.

For the temperature profiles shown in Figure 6, this would result in the following data:

<table>
<thead>
<tr>
<th></th>
<th>( T_{\text{max}-2} )</th>
<th>( T_{\text{max}} )</th>
<th>( T_{\text{max}+2} )</th>
<th>( T_{\text{delta}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td>( t003 = 33 , ^\circ)C</td>
<td>( t005 = 59 , ^\circ)C</td>
<td>( t007 = 33 , ^\circ)C</td>
<td>0 , ^\circ)C</td>
</tr>
<tr>
<td></td>
<td>drop = 26 , ^\circ)C</td>
<td>drop = 26 , ^\circ)C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Profile 2</td>
<td>( t004 = 11 , ^\circ)C</td>
<td>( t006 = 63 , ^\circ)C</td>
<td>( t008 = 35 , ^\circ)C</td>
<td>24 , ^\circ)C</td>
</tr>
<tr>
<td></td>
<td>drop = 52 , ^\circ)C (up)</td>
<td>drop = 24 , ^\circ)C (down)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For Profile 1, no correction would be applied; for Profile 2, the location of the maximum temperature would be corrected from measurement point \( t006 \) to \( t005 \).

The control algorithm will use the corrected detection location to determine the first sprinkler section (N) to be activated. Subsequently the other 3 sections will be activated relative to this section. This would result in correction of the activated sprinkler sections as illustrated in Figure 7 below.

Compared to the activated sprinkler sections as shown in Figure 5, the total spray pattern has been shifted upstream, resulting in better coverage of the actual seat of the fire.
CONCLUSIONS
Based on the results of the fire tests in the Sophia tunnel, it has been determined that the detection and control algorithm will respond correctly if the following settings are maintained:
1. the minimum difference in temperature which leads to a correction (delta $T_{\text{min}}$) = 20 °C
2. the number of detection zones left and right of the location with maximum temperature (for determining delta $T_{\text{min}}$) = 2

At longitudinal airflow speeds in excess of 2 m/s, these settings will ensure a correction of the measured position of the fire as well as the fire extinguishing pattern. At such airflow speeds it is to be expected that the measured position of the fire will indeed differ from the actual position of the fire.

With the settings presented above, the detection algorithm will always make a correction, especially in the case of such a high heat release and an airflow speed which is expected to lead to transfer of the heat and thus shifting of the measured position.

Thus it is warranted that:
1. there is sufficient coverage of the spray pattern upwind (before the seat of the fire), and
2. there is a water spray of adequate length downstream (from the seat of the fire) for sufficient cooling of the exhaust gases.

Finally, it should be noted that even with the detection algorithm settings mentioned above, there is still the possibility of the algorithm erroneously correcting the fire position and thus the extinguishing pattern. Such an erroneous correction may take place at airflow speeds of 1.2-1.3 m/s. A shift in the fire extinguishing pattern may then result in a shorter section of water spray downstream of the seat of fire.

It is assumed to be more important to ensure that a correction is made at higher heat release rates and at higher longitudinal airflow speeds than to prevent erroneous corrections at lower heat release rates and lower airflow speeds. Moreover, good coverage of the fire extinguishing pattern at higher heat release rates is considered to be of greater importance than the coverage at lower heat release rates.
BIBLIOGRAPHY


Gas analytics for the early detection of fires in road tunnels

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ABSTRACT

Today, fire detection in road tunnels by gas analysis has not yet reached notable spread. Thus, the goal of the gas analytics project is to identify such a gas sensor and optimize its placement inside the tunnel to serve as a reliable early detection system for evolving fires, even prior to visible smoke or heat formation. Fundamental insight into mechanisms leading to vehicle fires shall be developed, supported by computer simulations and validations by experiments in the test gallery. After successful calibration of the simulation models, other situations shall be extrapolated in order to be able to supply various tunnels with warning sensors in an efficient and effective way.

Although the main focus in the project is on safety, the environmental aspect and further knowledge of the very different materials that could catch fire, e. g. vehicle components or cargo, and the distribution of their combustion products, are expected as a by-product of the project.

The Project work is done according to the following steps:

- Identification of (gaseous) components which form at the very early phase of a fire
- Evaluation of a sensor for reliable detection these components
- Evaluation of an optimal positioning of sensors in the tunnel
- Validation of the findings through pilot experiments at the Hagerbach test gallery

INTRODUCTION

Many studies and research projects have been carried out on the topics of tunnel safety, fire including heat and smoke, fire detection and the protection against fire of humans, goods and buildings. However, one of the common denominators is the fact, that early detection of fire is estimated as a very efficient measure to mitigate and reduce consequences of an incident. Consequently, the consortium composed of VSH Hagerbach Test Gallery Ltd, Xirrus GmbH, and Combustion and flow solutions GmbH (all Switzerland) intended to transfer knowledge and technologies from the optimization of combustion processes and translate it into questions regarding the early detection of fire, aiming at a mode of detection sensitive to substances forming prior to smoke and open flames.

Main objective of the project, of course, is to improve the safety level in road tunnels by earlier detecting the origin of fire on vehicles. Early and reliable fire detection is important, since preventive measures are – from an economic point of view – better than mitigation measures, repairs and refurbishment. The idea is to identify substances specific to the very early stage of fire development and by detecting these substance to win time in order to reduce impact of an incident to a tunnel. For that purpose, a very basic domain analysis is needed resulting in knowledge about mechanisms and procedures leading to fire on vehicles. In a next step, chemical simulations should help identifying one or more specific key elements indicating increasing heat and the start of fire.
The project plan is split into two phases, the first of which is dealing with analyses of fires in vehicles based on literature studies allowing for specific chemical simulation of the start of fire. Most important in this phase is the distinction between substances indicating fire from those being part of tunnel air during normal operation. So the first milestone is a catalogue of both gaseous and solid substances in tunnels during normal operation and in case of an incident. The next step is about identifying a substitute for detection in the large-scale tests. The substitute must form substances clearly indicating fire in relevant concentration. The selection of this substitute is supported by chemical investigations of combustion and by simulation on molecular scale. Resulting from these first two investigations, a sensor needs to be identified sensitive to the corresponding substitute but not to regularly polluted tunnel air.

In case of a successful sensor evaluation, a large-scale fire test shall prove the results of investigations. To guarantee for best possible relevance, scenarios are taken from previous research projects in the field of large-scale tunnel fire tests carried out in the facilities of VSH. Cross section, geometry, type of vehicles, and air velocity (interaction of ventilation and turbulences caused by moving vehicles) play an important role as well as the development of fire in terms of heat release and spread of gases. Based on specific scenarios, the distribution of gas concentration in the cross section of the tunnel will be calculated. Earliest possible detection and reliability regarding different heat sources and the level of concentration required for activating the sensor are key issues to be taken into consideration.

STATE OF THE ART

The understanding of the state of the art is important to formulate the right equations to be solved in the simulations. Consequently, following issues have been tackled to create a sound base of the scientific project work.

- Fire in vehicles: Where does the fire ignite? What materials start to burn – for what reason? Circumstances of ignition? What substances are generated?
  These questions may help narrowing the range of substances to be observed
- Availability of tunnel air analyses? Which gases (in what concentration) and which particles can be found in tunnel air? Substances resulting from combustion engines (burning fuel, bio-fuel)?
  This analysis may help identifying substances disturbing detection
- Sensors available for fire detection? Gas sensors? How do they work? Specifications, characteristics, advantages and disadvantages, that range and accuracy are they covering?
  This overview shall help understanding problems of gas analysis based fire detection
- Availability of early detection systems and functional description? Specifications? Advantages, disadvantages, experiences? Requirements from operational point of view?
  These questions may help get a sound feeling for the domain as a whole

Following sensors/technologies are currently available for fire detection:

- Smoke detection through visibility measurement / particle detection
- Temperature measurement, rapid increase leading to an alert
- Gas sensors
- Optical measurements, based on image analysis detecting smoke and flames

Early detection via gas analysis is well considered, whereas mostly CO₂, CO, sometimes H₂ are detected. Main technology used is semiconductor-oxide sensors with very high accuracy. Reliability of sensors in case of disturbance is primarily investigated in private or industrial buildings. One way to tackle this problem is the combination of different sensor technologies. But the specific requirements to such a combined sensor technology is always linked to a very specific application and following hardly
transferable. Tunnel environment has not yet been investigated in that sense.

Further, the question of ignition of fire in vehicles is not sufficiently answered – leading to the assumption for a wide range of reasons and origins of fires in vehicles. It is hardly possible to reduce the number of substances indicating ignition. So the picture is not very complete, since the situation is complex, and investigations are detailed and punctual instead of covering the problem as a whole. This is the reason for increasing the number of simulations in the project in order to best possible cover all sources of fire in a vehicle.

**CHEMICAL COMBUSTION SIMULATION**

We are looking for intermediate products that occur during combustion of substances, with the consideration that such product will also escape from the fire before complete combustion occurs. Such intermediate products will be candidates for the sought fire marker.

However, the literature showed that such studies are incomplete (and also experimentally demanding due to high temperatures, high pressure, and extremely short-lived species). Moreover, no clear indication of where a fire usually starts, was found. Fortunately, chemical reaction simulation made such a progress in recent years that we are able to systematically scan for intermediate products in combustion simulations of a rather large set of diverse polymers that could catch fire. Simulation has the immense advantage that the system is fully known at any moment. So we can store frequent snapshots during combustion and analyze them afterwards for intermediate products occurring during all types of combustion and fire substrate. Such a molecule would represent an ideal fire marker. This is a visualisation of the concept of digital chemistry:

![Starting point; a lump of polyethylene, representing a bulk polymer. Carbon and hydrogen atoms are shown as black and white balls respectively.](image1)

![Snapshot during pyrolysis with oxygen (red). The polymer chain disentangles, breaks up, reacts with oxygen, and reformulates to intermediate products.](image2)

![A statistical analysis then reveals all the molecules that were observed during pyrolysis.](image3)

The following polymers were studied, representing a wide chemical diversity and with good chances of occurring in vehicles:

- Polyethylene (PE): casings, pipes, fairings
Polypropylene (PP): car interiors, dashboards, crash absorbers
Polystyrene (PS): casings, dampings
Polyamide 6.6 (Nylon) (PA): suction systems, fuel pipings, motor covers, insulations
Poly (Acrylnitrile-Butadiene-Styrene) (ABS): casings, car parts, covers, fairings
Poly(methyl methacrylate) (Plexiglass) (PMMA): rear lights, flasher lights, reflectors, fiber optics, door linings
Polyurethane Lack (PURL): paint, lacquer, varnish, sealings
Polyurethane Foam (PURS): rubber foam, upholstery, stuffings, paddings
Cellulose (CLL): paper, cotton, wood

To cover a broad range of combustion conditions, both thermolysis – decomposition under the effect of heat only – and pyrosysis – decomposition under heat in oxygen atmosphere – were simulated for each polymer. For both decomposition types, 4 temperature points were simulated at 800 K, 1000 K, 1200 K and 1500 K, or in centigrade 527°, 727°, 927° and 1227°.

Results
From the catalogs of intermediate products observed during the combustion simulations, molecules were extracted that occur in all cases. These are candidates for the sought universal fire marker. The frequency of observations gives a rough estimate on the ranking of candidates, however, it should not be taken as a measure of release of the marker.

At the time of this writing, not all of the simulations and analyses were complete. So these results cover 45 simulations out of 72 in total (9 Polymers, 2 combustion types, 4 temperature points each).

<table>
<thead>
<tr>
<th>Molecule name</th>
<th>frequency of observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propinyl radical</td>
<td>13551</td>
</tr>
<tr>
<td>Ethenyl radical</td>
<td>210701</td>
</tr>
<tr>
<td>Ethenylbiradical</td>
<td>220710</td>
</tr>
<tr>
<td>Ethine (Acetylene)</td>
<td>245584</td>
</tr>
<tr>
<td>Ethene</td>
<td>1972287</td>
</tr>
<tr>
<td>Ethinyl radical</td>
<td>3486823</td>
</tr>
<tr>
<td>Methylene triradical</td>
<td>8041492</td>
</tr>
<tr>
<td>Methylene biradical</td>
<td>8666056</td>
</tr>
<tr>
<td>Methane</td>
<td>33063390</td>
</tr>
<tr>
<td>Ethane</td>
<td>45388436</td>
</tr>
<tr>
<td>Hydrogen atom</td>
<td>201466881</td>
</tr>
</tbody>
</table>

Common combustion products like water, carbon dioxide and carbon monoxide are missing here as some systems like PE and PP thermolysis did not contain oxygen and fall short of the condition of occurring in all cases. Looking at the pyrosysis results only, the named substances are prominently represented.

The simulation results show confidence that the universal fire marker can indeed be found. As there are multiple candidates so far, there might even be room for taking more criteria into account, such as good detectability. However, first the rest of the simulations shall be analyzed to confirm the found results.
CONCLUSIONS PHASE 1

Literature studies and screening of results of previous research projects in the scope of tunnel fire and tunnel safety provide a good overview of the state of the art in terms of fire development, active and passive fire protection, fire fighting and scientific approaches for fire simulation. However, the majority of investigations is starting at the point where fire develops without searching for the really specific origin of fire. Scenario descriptions provide information, e.g. about where the fire is breaking out, standards are referring to the ignition of fire and specify the energy source. But the real technical reason for fire, including information on material or specific parts of a vehicle, are lacking.

The distinction of the fire origin location, being it the passenger area, luggage compartment or cargo is certainly important. But the gas analytics project is scrutinizing the phase before – when temperature is already raising, whereas neither flames nor smoke is yet visible. Based on the results of the literature study it is hardly possible to filter the selection of materials involved in the ignition phase, so that more simulations where needed than initially planned. However, it was possible to identify a specific indicator of fire.

Figure 1 – Phases of full burn fire development [SCHN 02]

Finally, two options to proceed where identified:

- Option 1: The sensor to detect the substitute does exist and is available by financial means of project recourses. In this case, the result of the dynamic flow simulation will be validated by large scale tests according to the plan of the project.
- Option 2: The sensor is not available. Consequently, the search for a specific chemical element in the tunnel air could be inverted and translated into a search for something unknown by analysing a well-known gas which is polluted tunnel air.

Either way, deeper understanding chemical processes in the ignition phase of a fire could help to win these five to six relevant minutes prior to detecting fire with today’s technology reacting on smoke or visible flames – in order to get a fair chance to minimize or avoid large fires in tunnels.
LARGE SCALE TESTS

In the second phase of the project large scale fire tests will be carried out aiming to prove the simulation of gas distribution in the tunnel cross section connected with positioning of sensors in the tunnel. The facility chosen for the tests is the fire test gallery of VSH. The gallery has a length of approximately 220 m and a cross section of 9.5 m width by 5.5 m height which is in the range of a two lane motorway tunnel. In the area where fire tests and fire fighter trainings are carried out, the surface is protected with fibre reinforced shotcrete. The tunnel has a gradient of approximately 4%. Depending on the cross section of the test area, wind velocity can be controlled up to about 5-6 ms⁻¹, which was realized in the frame of the large scale fire tests for the A86 water mist system.

As the project is focusing on the very early phase of ignition, no big fire will be needed for the large scale tests. But what is very important is the proper installation of sensors well distributed in the test tunnel’s cross section. The planning of sensor placements will base on the results of simulations.

Further, the selection of materials for combustion, including the location in the car and in addition ventilation control in order to have a realistic scenario, will be defined.

Figure 2 – Measuring equipment for air velocity and extraction tubes for gas analyses

Figure 3 – Fire test gallery of VSH during calibration tests for the A68 water mist system investigations

The tests will be possibly linked with another ASTRA funded research project dealing with compartmentalisation of tunnels in case of fire.

REFERENCES


KEYWORDS: Tunnel safety, fire detection, early warning, detection, sensors, combustion, simulation
CFD-based Assessment of Fixed Fire-Fighting Systems in Tunnels

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ABSTRACT
Tunnel safety has become a major concern since the late 90s. New means are constantly being named to raise the safety level in tunnels. FFFS are often cited by rescue services and tunnel owners alike. Because of the specific aeraulic characteristics of tunnels, derivation of FFFS efficiency from their traditional applications is not straightforward. Proper assessment of those devices, keeping in mind a general approach of safety, is still needed. This paper presents a midscale tunnel fire test program and the two-phase flow CFD calculations performed. Despite good agreement between CFD and experimental data away from the fire, discrepancies in the fire zone need to be addressed. Comments are drawn on how two-phase CFD can be used to assess FFFS efficiency in tunnels.

KEYWORDS: Fixed fire-fighting systems, midscale fire test, smoke stratification, CFD modelling

INTRODUCTION
Since the late 90s and the catastrophic fires of the Mont-Blanc, Tauern and Gotthard tunnels, which where particularly striking for the public, road tunnel safety has become a major concern for authorities. The latest fire events (Frejus tunnel, 2005 and Channel tunnel, 2008) highlight an increasing need for tools to improve the safety of tunnels in case of a fire, from both life safety and asset protection viewpoints. Beyond regulatory requirements, which are progressively enforced, new means are constantly being named to raise the safety level in tunnels.

Among these new means, fixed fire-fighting systems (FFFS), and particularly those using water as an extinguishing agent, are often cited by rescue services and tunnel owners alike, each having different objectives regarding their use. However, such a device can have an interest only if it is correctly integrated into a general approach of safety. Some characteristics, especially aeraulic, of tunnels are indeed very different from those of closed spaces which are more traditional applications of FFFS: compartments, ship machinery rooms, warehouses, etc. France, following other European countries, has always been reluctant regarding the installation of such systems in its tunnels. The assessment of a FFFS should be carried out considering not only its intrinsic performance but its integration as an element of a safety system at tunnel scale, and analysing the efficiency of the whole system [1].

Therefore, a fire tests program in a midscale tunnel, involving various fire loads and ventilation regimes, was carried out with CSTB as a partner. This experimental campaign aimed at improving the understanding of the physical phenomena at stake on the one hand, and assessing the efficiency of a FFFS on the other hand. Meanwhile, a CFD-oriented study based on the experimental results was run [2] aiming at validating a CFD modelling methodology and set-up for the complex two-phase flow resulting of FFFS activation on a tunnel fire.

FIRE TESTS EXPERIMENTS
To install a FFFS in a given tunnel, the present state of the art implies to perform full-scale fire tests to assess the optimum parameters of the FFFS and the efficiency in case of a fire. However, due to the
high costs of full-scale fire tests, it may be interesting to perform midscale experiments that are very cost-efficient. Actually, with such experiments, three main objectives can be achieved:

- supply information for a better understanding of the phenomena
- feed the numerical models with input data
- test new measurement techniques.

**Test tunnel**

The experimental program was conducted in the midscale tunnel (approx. 1/3 scaling factor) at CSTB facilities [3]. The tunnel is 43 m long, with an hydraulic diameter of 2.17 m and a cross-section of 4 m² (see fig. 1). Longitudinal ventilation is provided in the test tunnel through an extracting ventilator located at the downstream end. The fan can provide a longitudinal velocity up to 5 m/s – corresponding to 9 m/s in a tunnel at scale 1 with a 1/3 scaling factor.

![View of the test tunnel](image1.png)  
(a) View of the test tunnel  
(b) Cross-section view

*Figure 1 Experimental installation.*

**Test program**

More than 30 fire tests were conducted during this program. They involved open or semi-hidden fires consisting in heptane pools, wood cribs or pallets. Partly covered heptane pools were used also to assess the efficiency of the FFFS in a more realistic case. The fire source sizing was calculated assuming a full-scale HRR of 30 MW and applying Froude scaling laws [4]. For each fire source, two ventilation regimes were considered: an over-critical velocity one corresponding to the usual smoke control scenario in one-way tunnels with longitudinal ventilation and a low velocity one to address stratification issues.

**Measurement points**

Figure 2 gives an overview of the measurement points inside the tunnel. More than 200 measurement points were installed, including:

- Air velocity: 24 velocity measurement points are installed in two sections: one section at 5 meters upstream from the fire and one section at 18 meters downstream from the fire.
- Temperatures: 52 thermocouples are implanted in six measurement sections. In addition, 8 special thermocouples, protected from water droplets impact, are installed. The values provided by these specific thermocouples are compared with the values obtained from non-protected thermocouples.
- Radiative heat flux: 6 fluxmeters are located in a section 7 m upstream from the fire and 6 others fluxmeters are located in a section 7 m downstream from the fire.
- Opacity was measured using different techniques (laser, white light transmission, scattering) since reliable data regarding visibility in the presence of water was still missing. The measurements were located 13 m downstream from the fire for the punctual laser, 22 m and 23
m downstream respectively for the usual tunnel sensors based on scattered light principles and the sensors based on white light extinction principles.

- **CO/CO\textsubscript{2}** concentration point measurements: to assess the tenability conditions, regarding toxic gases, of tunnel users, two point measurements are located at 0.5 and 1.5 m high, 23 m downstream of the fire. The aim is to represent in full-scale, the effects of toxic gases on tunnel users trapped downstream of the fire.

Figure 2  
*Sketch of the measurement sections inside the test gallery*

Concerning the HRR which is a very crucial measurement for assessing the efficiency of the water mist system on the fire, two different methods are used. The first one is based on the measurement of the loss of mass of the fire source, whether it is an heptane pool, a wood crib or a wood pallet. A correction accounting for non-complete combustion is applied. The second method is based on the oxygen consumption calorimetry [5]. Downstream of the fire, measurements of the volume flow rate and the concentrations of O\textsubscript{2}, CO and CO\textsubscript{2} are performed in this purpose.

**Water mist system**

After some preliminary tests, the water mist system retained for the experiments was composed of a single line in the centre of the tunnel. The 14 nozzles are located every 1.5 m beginning at 3.5 m upstream of the fire. Fire tests with less nozzles in operation were also conducted to assess the FFFS performances. This configuration is more or less equivalent to a full-scale installation where the spraying lines are usually located above each traffic lane. The system operates at a high pressure around 90 bar and discharge a Class 1 water mist.

**INPUT DATA FOR CFD MODELLING**

The experimental campaign provided highly valuable data for CFD modelling. However, data analysis was still necessary to get access to a mean HRR (or mass-loss rate of fuel) for each fire test and to the spray distribution. These two parameters are key input data for a relevant CFD modelling of the fire tests.

**HRR data processing**

As stated before, two different methods were used to estimate the HRR of the fire. Comparison of both techniques for a reference test is given in Fig. 4. The gap between the oxygen consumption calorimetry and the raw mass loss signal is quite important.

The data obtained by mass loss measurement globally accounts for the fire load mass loss whether the fire is well-ventilated or ventilation-controlled. Therefore, the mass loss signal needs a correction to
integrate the local ventilation conditions. According to [6], we can expect a maximum correction of around 4% for heptane pool fires and 10% for wood pallets/cribs. Even using these values, there is still an important gap between the two methods.

To get a satisfactory agreement between the two curves, a correction of 30% is applied to the mass loss data (see dot line on Fig. 4). Because the oxygen sensors are located 18m downstream of the fire, the data recorded there is only related to the convective HRR. The losses by radiation or non complete combustion (ventilation-controlled) are thus not taken into account. The energy balance in [7] provides a more complete explanation.

![Figure 4](image)

*Figure 4*   
Comparison of HRR estimation techniques for a reference fire test.

For an heptane pool fire, the time evolution can be considered to reach a steady-state after around 80s (see figure 4). Therefore, a constant mass flow rate input was derived for the CFD calculations using Babrauskas formula [8].

**Characterizing the water mist system**

The water mist input data were obtained through individual nozzle characterization using a Phase Doppler Anemometer (PDA) at laboratory scale [9]. The nozzle was a research nozzle provided by Fogtec. It consists of 5 injectors, four peripheral and one central (see Fig. 5). Each one is a pressure-swirl atomizer producing a solid-cone spray.

![Figure 5](image)

*Figure 5*   
Technical sketch of the nozzle used.

The droplet size distribution and the velocity profile were only measured for the central injector.
Actually the solid-cone sprays produced by the injectors outline a quite independent behaviour until a distance of around 50 cm from the nozzle where they collide to produce a single solid-cone spray. However, the experimental set-up did not allow us to measure the droplet-size distribution farther than this 50 cm limit. Very fine droplets entrainment was observed and this phenomenon disturbed the measurements.

Figure 6 presents the experimental results and the equivalent Rosin-Rammler distribution. The fitting parameters obtained are $\delta = 50.15 \, \mu m$ and $n = 2.85$ (see [10] for the exact equation defining a Rosin-Rammler distribution).

![Figure 6] Droplet size distribution as a function of cumulative mass fraction

The cone angle was also quantified for the central injector. It appears to lie around 20°. However, this value does not represent accurately the global cone angle from the nozzle.

VALIDATING CFD COMPUTATIONS

The CFD modelling was done with the ANSYS-CFX code. A RANS turbulence model was used to simulate the fire tests. To obtain proper initial conditions for the computations involving water mist, preliminary calculations were done using the experimental data for the gas phase only.

Gas phase modelling

The first step was to assess correct values of the ventilation velocity and the HRR inside the computational domain to reproduce the temperature levels measured in the tunnel. Only, heptane pool fire tests at both ventilation regimes were considered. This was done to simplify the CFD modelling keeping in mind the calculations of the two-phase flow in a second step. Moreover, the combustion data concerning heptane are better known than the one for wood.

Experimental data in the case of low-velocity (around 1.3 m/s) fire tests show important scattering for the velocity and thus the temperature levels (see Fig. 7). An averaged computation based on averaged values of the fuel mass flow rate and the outlet velocity was performed. The comparison to the experimental data shows important discrepancies [2], especially in the far field, downstream of the fire. This behaviour contradicts usual comments on CFD modelling of tunnel fires: the code usually agrees quite well the experimental data in the far field but often under-predict the temperature level close to the fire. However, because the fuel mass flow rate is constant in the CFD calculation, the HRR time
evolution and the heat losses at the walls are not correctly captured by the code.

Figure 7  Vertical temperature profiles at 12 m downstream of the fire – Experimental data, low-velocity case.

Considering the over-critical velocity case (around 2.2 m/s), the agreement between the CFD computation and the averaged experimental data is satisfactory for velocity and temperature levels (see Fig. 8). A typical under-prediction of the code is observed in the near field, both upstream and downstream of the fire. Thus, the two-phase flow modelling will be performed for an over-critical velocity using this CFD data as an initial condition.
Two-phase flow modelling

When modelling a multiphase flow – or at least a two-phase flow – with a CFD code, the degree of coupling between the gas phase and the dispersed one is a key issue. The higher the degree of coupling is (from one-way to four-way coupling, see [11]), the more complex the models involved in the CFD computation will be. From a tunnel fire safety perspective where the dispersed phase contains fine water droplets in a relatively low volume fraction – compared to the overall fluid volume inside the tunnel at a given time – two-way coupling is adequate [11]. In this kind of coupling, the effect of particle-fluid interactions (drag force, thermal source terms) dominates the overall transport of particles. Because of the low volume fraction of the dispersed phase in the resulting two-phase flow, lagrangian tracking for the droplets coupled to a eulerian approach (RANS or LES depending on the CFD code used) for the gas phase is often retained.

Such an approach was used in modelling the activation of a water mist system on an heptane pool fire. As stated before, the results from the computations without water mist are set as initial conditions for the simulations with water mist. Transient simulations of the two-way coupled flow were performed, modelling the nozzle spray according to the droplet size distribution measured. Preliminary calculations were done on the Sommerfeld and Qiu experiments [12] to assess the key input parameters in ANSYS-CFX multiphase models [2].
Figure 9 depicts the decrease in temperature provided by the code for an over-critical velocity case and for three different nozzle configurations: the complete 14 nozzles ramp, a fire centred configuration with 6 nozzles in operation and a upstream only configuration with 3 nozzles upstream of the fire in operation.

![Figure 9](image_url)  
Temperature decrease versus time for the three nozzles configurations, 8m downstream of the fire, at 0.5m above floor (solid lines) and 1.5m (dashed lines).

The steady-state behaviour is captured accurately by the CFD code whereas the transient evolution is found 2 to 3 times faster than in the experiments. The temperature values computed along the tunnel are similar to the one measured in over-critical velocity experiments with water mist. Despite the assumption of a fixed fuel mass flow rate in the calculations, the steady state conditions are well predicted. However, the path to these steady state conditions seems different in the computations. A close look to the fire zone in the simulations tends to prove that the code predicts a stagnation zone at the ceiling and slightly upstream of the fire. The temperature time evolutions plotted on figure 9 confirm this statement: in every nozzle configuration, the same transient behaviour is observed with a rapid temperature drop. This stagnation zone is probably an outcome of the under-prediction of the spray penetration by the code. The drag force and the vertical momentum of the droplets are counter-balanced by the quite important recirculation upstream of the fire plume.

**INSIGHT ON FFFS/SMOKE MOVEMENT INTERACTIONS**

One of the major concerns about FFFS activation in tunnel is about smoke stratification and backlayering. From a user safety point of view, maintaining stratification as long as possible is a key issue [3] especially in two-way tunnels (or one-way tunnels with stalled traffic downstream of the fire).

The stratification criteria based on temperature derived in [13] was applied by Meyrand [14] to the experimental data. When the water mist system is activated, the downstream flow can be considered as destratified (criteria S below 1.7) even in the case of a low longitudinal velocity. The downstream visibility measurements support this conclusion (see for instance [3]). However, from the stratification criteria it is not possible to correctly assess the dominant physical phenomena that take place at the interface between the smoke layer and the droplet spray. For this deeper analysis, key parameters driving smoke layers movement, such as buoyancy flux [15] need to be addressed.

Therefore, the CFD modelling was used to gain a better insight into FFFS/smoke movement
interactions. The smoke buoyancy flux was computed downstream of the fire to evaluate smoke movement with and without direct impact of a FFFS nozzle in the three configurations depicted earlier and is plotted on figure 10.

Figure 10 Time evolution of the buoyancy flux B downstream of the fire for three different nozzles configurations: 3 nozzles upstream (black line), centred configuration (blue) and complete nozzles ramp (red).

The decrease of the buoyancy flux is mainly due to droplets evaporation inside the smoke layer, resulting in the advection of lower temperatures in the downstream sections. For the 3 nozzles configuration, the same comment as for the temperature decrease can be made. The CFD code under-predicts the spray penetration upstream and thus lead to the same behaviour as for the other two configurations, with massive evaporation in the fire zone. For the 3 nozzles configuration, the temperature measurements downstream of the fire do not agree the numerical outcomes. Moreover, the mechanical entrainment due to droplets high velocity is depicted as a second order phenomenon by the CFD calculations.

DISCUSSION

This paper outlined a two-phase flow CFD modelling based on experimental data from midscale tunnel fires with water mist. Despite the scattering in these data, the steady state behaviour is correctly captured by the code. General cooling downstream of the fire is observed and smoke layer propagation is reduced. CPU-intensive transient calculations were performed to understand the physical mechanisms leading to this general cooling and smoke destratification.

Whereas monophasic CFD calculations can deal with relative uncertainties concerning the input data in order to provide a good agreement with experimental data, two-phase CFD computations require very detailed input data mainly concerning the water spray produce by the nozzles. In a real case scenario, these input data are out of reach. Nozzle characterization experiments are still needed to assess the correct parameters. Even with a detailed characterization of the water spray as the one performed in this research program, the impact of the water mist on the fire source is not correctly predicted by the CFD code. The under-estimated penetration of the spray leads to an over-predicted water mist efficiency in the case of an upstream only nozzles configuration.

Therefore, even if two-phase flow CFD is a promising tool, a careful analysis of the transient results is required. A validation by experiments at midscale, at least, is still necessary to assess reliability of the computations.

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University of Lyon (France), 2008.


FIRE IN ROAD TUNNEL IN SLOVENIA

JANUARY 2010

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Administration for civil protection and disaster relief of Slovenia

ABSTRACT

Slovenia is a small country bordered with Italy, Austria, Hungary and Croatia. Geographical position makes this EU member country very important transit way from the northeast to southeast and from northeast to southwest. Modern motorways were built in past years to follow increasing of traffic in this region. Diverse landscape on very small area was a big challenge for constructors of motorways. The result is that many road tunnels were built on both main directions. On Slovenian roads at the moment there is app. 50 kilometers of road tunnels, including the bi-national single tube 8 kilometers Karavanke tunnel on the border with Austria.

Entering EU in 2004 rapidly increased heavy traffic and consequently, risk on motorways, especially in road tunnels.

Technical equipment for safety in all tunnels is modern and adequate. All longer tunnels are covered with video cameras from nearest communication center 24/7 running by national road Company. All tunnels are equipped with SOS phones, fire extinguishers, proper hydrant system and communication system. Slovenian road Company DARS provided safety instructions for all drivers and published them in different ways. All longer tunnels are also equipped with mobile phone signal and frequency of national radio.

Operational respond in Slovenian tunnels by first responders is developed and organized depending on risk and organization of firefighter's services in single areas. Slovenian road Company DARS together with National Administration for Civil Protection and Disaster Relief bought special vehicles for emergency respond in road tunnels specially developed for fighting fires in tunnels. National fire school prepared special training for fire teams responding in tunnels depending on a type of the tunnel. In some areas, we also organized special fire teams close to the tunnel to reach respond in case of fire or other emergency in less than 15 minutes. For each area with longer tunnel, regional offices of Administration for Civil Protection and Disaster Relief prepared to respond to plans including all first responders and other services in case of large-scale emergency in a tunnel. In the special decree is also regulated the training of those plans, with adequate exercises.

20th of January 2010 fire occurred in 3 kilometres two-tube Trojane tunnel. Fully loaded truck stopped due to failure app. 500 meters inside of the tunnel and caused the crash with 4 more trucks.

Fire team with three firemen drove to the scene in special fire truck. The team is placed close to the tunnel especially for this purpose.

When firefighters came to the portal, they were informed immediately about the position of the fire, and about numbers of vehicles that stayed in the tunnel after the fire started. Information was that many trucks were caught in the tunnel and that location of the fire is 500 meters away from the entrance.

Approaching the fire, they rescued two drivers to the parallel tube and after that started to fight fire with water and lately also with foam.

In the meantime, other fire teams according to operational plan came to the portal and helped to the initial team in order to finish the fire.
The fire was extinguished in approximately 30 minutes. Two trucks were partially burned and damage on construction of the tunnel was minimal. Tunnel was closed for 4 days, and damage was app. 100 000 €. Slovenian concept of operational preparedness was half way already developed at the time and the conclusion was that first steps of the concept with small team of full time firefighters near the tunnel was for this fire sufficient. Decision was to follow the concept and develop it further more also for other areas in Slovenia with similar risk.

Keywords: Tunnel, fire, Slovenia

FACTS ABOUT SLOVENIA

Picture 1: Slovenia - in the north borders to Austria; Hungary is to the east; Croatia to the south and Italy to the west.

**Full name**: Republic of Slovenia (Republika Slovenija)
**Inhabitants**: 2,048,488 (April 2010)
**Capital**: Ljubljana (260,000)
**State**: Democratic parliamentary Republic since 25 June 1991, Member of the European Union since 1 May 2004
**Currency**: Euro
**Official languages**: Slovene; also in bilingual areas also Hungarian and Italian
**Largest cities**: Maribor, Kranj, Celje, Koper, Novo mesto, Velenje
**Religion**: Roman Catholic (58 %, 2002 censuses); together, there are 43 religious communities registered in Slovenia; the Evangelicals are most widely present in the northeastern part of Slovenia.
**Area**: 20,273 km²
**Length of borders - 1,370 kms**: to Austria 318 kms, to Italy 280 kms, to Hungary 102 kms, to Croatia 670 kms)
**Length of coastline**: 46.6 kms
**Relief**: The territory of Slovenia is geographically divided into four basic types of landscape - Alpine in the north, (42.1%), Mediterranean in the south-west (8.6%), Dinaric in the south (28.1%), and Pannonia in the east (21.2%)
**Climate**: Alpine, Continental, and Mediterranean
**Forests**: almost 58% of the Slovenia territory
**NATIONAL MOTORWAY CONSTRUCTION PROGRAM**

In order to provide an adequate and efficient road system, to improve road safety and to ensure integration with the broader European area but also to boost economic growth (strategic goals), maximize effects and minimize the pollution of the environment, in order to ensure greater economic, social and tourist benefits, and at the same time maintain the existing motorway infrastructure (structural goals), the National Assembly, enacted the National Motorway Construction Programme in the Republic of Slovenia (published in the Official Gazette of the Republic of Slovenia No. 13/96), on 15 November 1996. On 23 April 1998, the National Assembly enacted all the amendments to the National Motorway Construction Programme (the Official Gazette of the Republic of Slovenia 11/98).

National Motorway Construction Programme envisages the completion and improvement of motorways and other roads in mainly two directions:

- **Northeast - Southwest** from Šentilj (Slovenian - Austrian border) to Koper with exits till the Slovenian -Italian border at Fernetiči and Vrtojba and Slovenian - Hungarian border at Pince and Dolga vas, from Maribor in direction Gruškovje on Slovenian - Croatian border and Postojna/Divača till Jelšane on Slovenian - Croatian border;
- **Northwest - Southeast** from the Karavanke Tunnel on the Slovenian - Austrian border to Obrežje on the Slovenian - Croatian border.

The Slovene motorway route heading from East to West is in line with the V. European Transportation Corridor (Trieste, Koper, Postojna, Ljubljana, Budapest), the motorway heading in the direction North - South is also in line with the X. European Transportation Corridor.

On the abovementioned lines, the National Motorway Construction Programme envisages the building of the following:

- 538.6 kms of motorways and expressways;
- 34 kms of other public roads serving as feeders to the motorway network;
- the renovation of 101 kms of public roads due to the motorway construction; and
- implementation of 28 re-routing and similar such as construction projects where motorway construction impinges on the national railway network.

Reconstruction and other improvements and upgrades of part of the main and regional roads, which will temporarily facilitate the tasks of the not- yet-built motorway network, are a part of the National Motorway Construction Programme. These improvements to the road system will make a connection of the bigger inhabited areas to the motorway system easier and provide better flow of traffic on the V. European Transportation Corridor.

The anticipated estimate of the investment value of the motorway construction and construction of other public roads and work on the railway system after the changes and modifications of the National Motorway Construction Programme in the Republic of Slovenia is the USD 4.1 billion.
SAFETY IN SLOVENIAN TUNNELS
Driving through tunnels is essentially different from driving on an open road. Overtaking in single-tube tunnels is prohibited (the only single-tube tunnel on Slovenian motorways is the Karavanke tunnel). In tunnels, it is also prohibited to turn, drive in reverse or stop, except in emergencies, when we can stop the vehicle in an emergency turn-off – in such a case, we must stop the engine immediately! When entering and exiting a tunnel, especially in bad weather, driving conditions change very quickly, so we must be more careful than normally.

Safety in tunnels on Slovenian motorways is technically supported by:

- traffic surveillance from control centers via a video system,
- built-in systems of automatic fire detection and reporting, and in newer tunnels also automatic detection of traffic and congestions,
- built-in traffic signaling and communication equipment (traffic lights, systems for emergency calls, safety lighting, etc.),
- emergency turn-offs in longer tunnels,
- in newer double-tube tunnels (Jasovnik, Ločica, Trojane, Podmilj, Kastelec, Dekani, Šentvid) with cross connections between the tunnel tubes.
What is proper driving in a tunnel?

- Turn on the radio and listen to traffic announcements on Radio Slovenia – Val 202 (frequencies: 88.5, 90.0, 91.8, 92.9, 94.1, 96.4)
- Take off sunglasses.
- Observe traffic signaling – prior to entering a tunnel pay attention to the traffic lights which are placed on the portal before the entry into the tunnel and in no case drive into the tunnel if the light on the traffic light is red!
- Keep the prescribed safety distance.
- Cargo vehicle drivers are not allowed to overtake in tunnels.
- Observe traffic regulations and traffic signaling both before the tunnel as well as in it.
- Mandatory: check the level of fuel in the vehicle and turn on the radio even before entering the tunnel!

What is to do in case of bottlenecks in a tunnel or a traffic accident?

- Turn on all four indicator lights.
- Pay attention to traffic signaling.
- Keep safety distance, regardless of whether the tailback is moving slowly or standing.
- If the tailback stopped, drive to the uttermost right side of the carriageway and turn off the engine.
- Observe the instructions of the tunnel operator on the Val 202 frequencies (88.5, 90.0, 91.8, 92.9, 94.1, and 96.4) or via loudspeakers in the tunnel.
- Observe the traffic signaling.
- Do not leave the vehicle unless necessary.
What is to do in case of vehicle break-down or being involved in a traffic accident?

Picture 11: Vehicle stopped

- Turn on all four indicator lights!
- Remove the vehicle to an emergency turn-off; if that is impossible, to the utmost right side of the carriageway!

Picture 12, 13, 14: Emergency turn-off

- Turn off the engine and leave the key in the ignition to start your vehicle!

Picture 15: Turn off the engine

- Carefully leave the vehicle!
- Call help using SOS phone – emergency call, and not using a mobile phone!

Picture 16, 17, 18: SOS phone in tunnel

- Provide first aid to the injured, if any!

Remember: Longer tunnels are equipped with video surveillance! Call help exclusively via SOS phone – emergency call! Do everything you can to prevent further accidents!

What to do in case of tailbacks–started fire in your vehicle?

If possible, leave the tunnel with the vehicle! In case that is impossible:
• drive the vehicle to the uttermost right side of the carriageway,
• turn off the engine and leave the key in the ignition to start your vehicle,
• leave the vehicle immediately,
• call help using SOS phone – emergency call, and not using a mobile phone,
• provide first aid to the injured,
• if possible, put out the fire on the vehicle using the fire extinguisher in your vehicle or an extinguisher which is placed in the tunnel,

Picture 19, 20: Fire extinguishers

• Leave the tunnel!

(Slovenian public Road Company)

**FIRE IN TROJANE TUNNEL**

20th of January 2010 at 15:12: The fire occurs in 3 kilometers long second tube of Trojane tunnel. Fully loaded truck stopped due to failure app. 500 meters inside of the tunnel and caused a crash with 4 more trucks. First two trucks started to burn immediately.

Picture 21: Crash
Immediately 3 men fire team drove to the scene in a special fire truck which was designed years before in Slovenian national fire school within Administration for civil protection and disaster relief together with cooperation with Rosenbauer Company from Austria. This team was strategically placed close to the tunnel specially for this purpose because regular professional fire stations were more than 15-minutes-drive away from the tunnel. This decision was made after thorough analysis of many fires in tunnels all over the world and through discussion within expert bodies in Slovenia.

Fire team entered into the tunnel where the fire occurred. Normally, they would enter from the parallel tunnel but in this case because of location of the fire and current traffic conditions to enter to the tunnel with fire.

Because according to our alarm plan, each fire with a truck involved is considered as big fire. That means that at the same time 2 professional and 6 volunteer fire stations were alarmed. 2 professional stations are 25 and 30 kilometers from the tunnel; volunteer fire stations are 5 to 20 kilometers from the tunnel. Altogether 63 firefighters with 13 vehicles were on the scene.
When firefighters entered at 15:27 hours, they were informed immediately that fire is on approximately 500 meters into the tunnel and that many trucks were involved. They proceeded close to the fire and stopped at proper distance. Tunnel was already filled with smoke in this moment. Some workers from Road Company were nearby when fire occurred, and they helped a lot with traffic regulation. Consequence was that first and other fire trucks reached the tunnel portal much easier and quicker.

*Picture 23: Entering the tunnel*

*Picture 24: Approaching the fire*
After they stopped team leader command to proceed in the way that he was walking in front of the fire truck with thermal camera to carefully check area close to the fire in case some injured people would be there. Soon, they found first person in smoke, and they rescued him to parallel tunnel. After few meters they found another victim lying on the ground. One of the firefighters placed on him rescue mask, and they rescued him as well to the parallel tunnel. They started to fight the fire, and they have noticed the third person which was the truck driver in the third truck. He was sitting in his truck and was not willing to get out. They forced him to get out and rescued him as well.
They fight the fire with water and after some time with foam. Fire was estiguished in approximately 30 minutes. Two trucks were partially burned and damage on construction of the tunnel was minimal. The tunnel was closed for 4 days and damage was app. 100 000 €. In the worst case, the damage could be tens of millions of Euros.

Slovenian concept of operational preparedness for tunnel incidents is to have full time firefighters close to the tunnel with special equipment meaning special tunnel fire truck and special breathing apparatus together with special training for fighting fires in tunnels. At the time, the concept is not yet developed completely but results so far are good and show us that we are on the right path. We pursue this concept in all Slovenian tunnels depending on local specific conditions.

**REFERENCE LIST**

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An integrated functional design approach for safety related tunnel processes

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INTRODUCTION
With the poster presentation ‘Determination and analysis of tunnel safety requirements from a functional point of view’ [1] at the ISTSS2010 an approach was presented to determine the main safety functions and requirements for a tunnel in the Netherlands in order to analyze and verify, from a functional point of view, whether the tunnel can be regarded as safe, both in design phase and during operation. Based on such a functional approach a design approach has been developed for the integrated functional design of systems that are involved in the safety related tunnel processes.

SHORTCOMINGS IN TUNNEL DESIGN PROCESSES
In The Netherlands the last new tunnels were opened after long delays and with budget overruns. Problems with verification and validation of the requirements for tunnel installations were the main causes. These problems were not caused by stricter regulations, after the introduction of the European directive, but by the absence of a solid functional basis for the tunnel system, a system that had become more and more complex over the years.
As described in the report of the quick scan [2] that was executed in 2010 by the Dutch Ministry of Infrastructure and the Environment on the Dutch tunnel projects, the first tunnels in the forties and fifties were considered as local controlled stand alone objects. Today tunnels have become a complex subsystem in an even more complex remote controlled road system. The technical systems in the tunnel and alongside the road have increased in number and complexity and the same is true for the information that is handled by the systems and the people who work with them. Technical developments made all this possible and the control systems developed as far as the technology enabled it (bottom up) but there was too little attention for the development of the functionality of the complex system that evolved (top down). Control systems were little more than a means to tie all systems together. The fact that there was little attention for the development of the functionality also meant that there was little attention for structured methods to develop it. This situation was accepted as long as no problems arose from it.
In most tunnel design processes a set of technical systems is designed on the basis of a set of pre-described systems (bottom up), design rules and a model organization. The systems and organization are then adapted to the actual situation. Often this is a situation of which the dynamics are known in general, but not in detail. By doing further risk analyses a check is made whether the tunnel is safe in relation to a limit or curve, e.g. an fN-curve, however this is on a high level and no check on the proper integration of technical systems and organization is done. Furthermore, no hard safety requirements, e.g. availability and reliability, are deducted from it for the individual installations. This means that values of parameters that have an important effect on the design are the result of experience, rule of thumb and best guesses and therefore often so called ‘magic numbers’. Values of parameters could be too weak or too strong or even unrealizable.
When the values for these parameters are then used for the design there is no guarantee that the combination of technical systems and organization is fit for its purposes in all cases and assuring a reliable, available and safe tunnel. We can ask ourselves: We built the designed system well, but did we design the right system? Is the system doing the right thing in the various tunnel processes,
especially during incidents? And what if parts of the system fail? Do we have a fall-back? This process is known as validation.

When these validation items are not properly addressed problems occur mainly in the control system of the tunnel as this is the platform in which the behaviour of all individual tunnel systems is combined and interaction with the users takes place. The effects can be such that in some situations installations behave in an unexpected way, in extreme cases even leading to dangerous situations, and operators and other parties involved do not have the right controls, the correct and necessary information or just too much information. As mentioned before, in the Netherlands this has lead to validation problems during commissioning of tunnel systems, resulting in delays and budget overruns.

NEED FOR A DIFFERENT BUT PRACTICAL APPROACH

Due to the past problems the need for a good validation basis for approval has grown. With an integrated approach with full transparency of design decisions, faults in the system can be detected earlier than at the final test phase. An explicit scope description, not only of the technology but also of the interfaces with the organization leads to a stable functional baseline at the beginning of in a structured design approach in which the tunnel installations are designed as an integrated system where safety is the prime importance.

In the Netherlands, Systems Engineering is considered as the right approach to do this, but application of the method is considered difficult. One of the reasons for this is that no practical method is available for application of Systems Engineering to tunnels. Problems usually occur in the first stages of the design when formulating the requirements. An underestimated difficulty is that operators, technical designers and safety experts often have no full understanding of the operational context and the required functionality. This makes validation difficult. Often there is no consensus about which operational decisions should be made by the operator and which should be left to the control system. For liability reasons, there is a tendency to move as much as possible to the technical systems, making them more and more complex. This means that the numbers of requirements are very large and the overview is easily lost. Therefore we need a structured design method with a more formal way to describe the system more explicitly and to give us the possibility to analyze it from different points of view. As stated before, today tunnels are a complex subsystem in an even more complex remote controlled road system. The Second Coentunnel, now under construction in Amsterdam, shows how complex such a system can be.
The two Coentunnels are an important link in a complex and very busy road system in a dense area with little space. One of the two tubes of the Second Coentunnel is a so-called tidal flow tube; the direction of the traffic flow in the tube depends on the traffic situation at a certain time of the day. In this case special attention for the proper functionality of the safety related systems is of great importance for the prevention and handling of incidents.

**AN INTEGRATED FUNCTIONAL DESIGN APPROACH**

A proper integrated functional design approach is therefore necessary to be sure that the system that is realized fits with the organization and all the defined processes. For this reason Royal Haskoning, together with strategic ICT partner Soltegro, undertook research into the (in)efficiency and transparency of the usual design approach and came up with a new way of working. A new method containing eleven development steps was created by combining methods of varying origin from the infrastructure design practice, such as Systems Engineering and RAMS, and the ICT environment, such as UML (Unified Modeling Language). The method ensures a functional basis for the tunnel installations and for the validation of it (did we build the right thing?). The approach ensures that the final installations contain the required functionality and it provides the methodology for verification and validation of these installations from within the design phase. As a benefit this method ensures the correct formulation of performance requirements that are related to the functionality instead of the technology.

We called our method the Diamond Model because of the different aspects that are integrated in one model. Figure 2 gives an overview of the method and its individual steps. These steps are further explained in the following paragraphs.

![Diagram of the Diamond Model](image)

**Figure 2  Diamond model**

In the Diamond Model we use SysML (Systems Modeling Language, based on UML) to ensure the consistency and traceability between requirements, design elements and design decisions. This approach gives us an accurate and thorough verification of the design process.
Preconditions and preparations for applying SysML

Because of the complexity of the project and the large amount of data, it is advisable to use a suitable design tool that fits within the systems engineering process and supports SysML. The decision regarding which tool to apply primary depends on the way the project team is going to work. In our project we used the tool Enterprise Architect. The most significant selection criteria for our project were: multi-user environment, document generation, import and export facilities of requirements and integration with other Systems Engineering tools. Based on our Systems Engineering process and incorporated deliverables we mapped all the SysML diagrams to each phase of the process and defined which diagrams we had to add to our product list. After that we created and customized the SysML repository by creating the package structure and setting all kinds of authorizations. Also the views and report templates were created and the basic report templates were extended to support the required output.

Step 1  Create a list of appropriate scenarios

As the required functionalities of the tunnel system are determined by the scenarios they are used in, the first step in the Diamond model is the creation of a list of scenarios. The list should be a complete, but practical list that not only contains the likely and less likely incident scenarios, but also the remaining scenarios such as those during normal operation, system or power failure and maintenance. In this step it is of utmost importance to extensively consult the tunnel owner and all other relevant stakeholders. Those stakeholders are the parties who are involved in the different scenarios or have an interest in some way, such as traffic centre operators or tunnel operators, road staff, emergency services and maintenance crew.

It is important to achieve mutual agreement and commitment because the list of scenarios is the fundamental element of the development process. This will prevent many discussions in the future. A great advantage of this step, and the next one, is also that it will help the tunnel owner and the stakeholders to properly think about the detailed use of the tunnel and their role.

For the Second Coentunnel a list of around 30 scenarios was created. In some scenarios up to 8 different stakeholders were involved.

Step 2  Describe the chronological interaction in the scenarios

The next step is to establish and describe the interaction between required technical functions and stakeholders for each scenario. This is done in a so called ‘swim lane diagram’, as shown in Figure 3. In the swim lane diagram the circumstances in the scenarios, the physical events, are described chronologically, stage by stage. To each stage the involvement of stakeholders and technical functions is added as well as the state the tunnel tube system is in. The possible states are defined in this step and can be itemized as ‘normal’, ‘maintenance’, ‘standby after detection’ and ‘emergency’ or ‘open’ and ‘closed’. We used the SysML state chart diagram to model the states and modes. The state charts define the control of the states and transitions on the level of the planned road section, service building, civil construction, tunnel tube and components. This is important to know because an energy installation is related to the planned road section whilst a traffic detection installation is related to a tunnel tube and the installation for detecting vehicle heights is component related. The control of an installation on the level of a component is modeled in another way than an installation at the level of a tunnel tube.

Development of the swim lane diagrams is undertaken in close cooperation with the stakeholders because at this point important decisions are made concerning functionalities and allocation of them to a stakeholder or a technical system. For example the swim lane diagram in Figure 3. The swim lane describes the scenario when a car breaks down in the tunnel. As shown in the diagram design decisions have been made. The red circle expresses that there will be an automatic speed measure visible in the tunnel when the operator gives a command to close the tunnel. This is a design decision, because you can also choose to decide that there is no automatic action from this command or there is another chronology.

It is important that the technical functionalities, and therefore the scenarios, link up with the standard processes stakeholders have or might have. For instance in The Netherlands the national road authority Rijkswaterstaat has standardized its processes in ‘Uniform Primary Processes’ (UPP’s) and
the emergency services in their own standard action plans. Existing operational concepts, organizational plans, roles and functions of stakeholders can be valuable input to this first step. A big advantage of the swim lane diagram is the fact that it explains in a clear visible way how a scenario develops and therefore it is an excellent means for consultation and discussion with stakeholders. Particular attention is paid to the interaction between the stakeholders themselves and their interaction with the tunnel system.

Figure 3  Swim lane diagram of car break down scenario

Note that Step 1 and 2 are not necessarily sequential to each other; they can be executed in parallel. From other projects, our experiences are that this is the moment to identify the external interfaces and to incorporate them in the functionality of the system. When the scenarios are clearly described and agreed on, a baseline can be defined. The baseline is the starting point for the next steps of the Diamond Model.

From the model it appeared for the Second Coentunnel that part of the functionality, as originally required, was not adequate for the process it was meant for, i.e. handling the specific type of incident. At this stage of the project changes could be made easily. From the analysis it also appeared that the four tube tunnel system, including organization, is capable of handling two simultaneous incidents, a fire and a non-fire incident, without additional facilities.

Step 3  Define the functional entities

From the column Technology in the swim lane diagrams the entities that should be included in the technical system are derived. The entities are called ‘functional entities’. Functional entities are in fact objects on a high abstract level that fulfil a function. For the Second Coentunnel we defined 3 groups of functional entities: a ‘man-machine’ group, containing 4 different functional entities, a ‘control”
group, containing 3 different functional entities, and a ‘field’ group, containing around 50 different functional entities. Each group in fact is a layer in our default system architecture. Examples of functional entities are: control room (MMI), local control system, speed detection, ventilation and lighting. The entities are not elaborated further, so ‘ventilation’ could be any type of ventilation.

For the functional entities, we create a model by using the SysML block diagram. The three most important items that a block diagram describes are, in our project context, the structural behaviour of a functional entity, the relations between functional entities and the functions a functional entity will fulfil. All functions of a block describe the complete set of responsibilities of a specific functional entity. The complete set of the block diagrams represents the whole system. When creating the model, we took explicit design decisions because natural language does not always enforce this while SysML requires this to be exact. For the detail design, the blocks are decomposed for one lower level of detail. This means for example that the functional entity ‘drainage’ is decomposed into at least several kinds of pumps, valves, flame arrestors, frequency converters and sensors. Interactions between the functional entities are handled by the interfaces of the block diagrams. A functional entity has at least one interface. All functional entities make use of a common interface to exchange data for the status, states and error handling. This common part is included into the specific interface of each functional entity, so changes in the common interface are propagated directly to all the interfaces of the functional entities while changes are made at one place only. Report templates are created to generate interface requirements specifications from the model. These interface requirements include the commands, input and output data and the generated requirement number in the predefined format.

The next step is to identify the interaction between those functional entities.

**Step 4 Describe the interaction between functional entities (happy flow)**

So far all the diagrams contain ‘static’ views. When all functional entities are defined, we can check if these elements work together correctly for each scenario. This is done with SysML sequence diagrams as shown in Figure 4. A sequence diagram represents, in our project context, the working order of functional entities. It gives insight in the communication and interaction between the various functional entities in time and describes the functionality in more detail than the swim lane model. This means that in this step additional design decisions are made. When these decisions are implemented in the diagram, the diagram proves the correct working of a scenario and therefore the correct working of, a part of, the system design.

In Figure 4 is shown part of the sequence of functional interactions from the scenario when a car breaks down in the tunnel. The applicable functional entities are in the top row. The detection system detects that stationary vehicles cause deterioration of air quality and sends a message to the control system, which automatically sends a message to the local control panel. From this diagram it becomes clear how the functional entities need to function in more detail. The sequence shown here is called the ‘happy flow’. This happy flow results in additional functional requirements and functional interface requirements.

As expressed in Figure 1, Step 3 and Step 4 are executed in an iterative process. However, the
Fifth International Symposium on Tunnel Safety and Security, New York, USA, March 14-16, 2012

Functional entities are the cornerstones for deriving sequence diagrams. We modeled this for the happy flow. The unhappy flow is not modeled in the exact same way because most part is the same as the happy flow and therefore time consuming. A more efficient way is: performing a what-if analysis. This is done in Step 6.

**Step 5 Define functionality of functional entities**

Based on the sequence diagrams the functional entities are specified in terms of functionality. For example the functionalities of the detection system, is detecting, sending messages to other functional entities and so on. Subsequently, based on all scenario descriptions a ‘function tree’ is created containing all functions including a functional description, functional interfaces and the functional requirements. An example of a function tree is shown in Figure 5.

![Function Tree Example](image)

**Figure 5 Part of function tree of the Second Coentunnel containing top safety functions**

The function tree gives a good overview of all the tasks that are performed by the technical system, the system that supports the different stakeholders, for example the traffic controller (or tunnel operator), in successfully dealing with the defined scenarios.

For the Second Coentunnel around 275 functions were defined and described of which around 130 concerned safety.

**Step 6 Determine additional functionality based on what-if analysis of the happy flow (unhappy flow)**

In the next step the sequences are analyzed for their robustness in case of (complete) failure of a functional entity. This is done with a ‘what-if analysis’ as shown in Figure 6. For every sequential step the question is asked: ‘What if the functional entity fails?’ The sequence with the failure is called the ‘unhappy flow’ as the entity functions not as desired and not as specified.

As shown in Figure 6 of the example from the scenario when a car breaks down in the tunnel, there is an unhappy flow if the detection system fails to detect the deterioration of air quality stationary vehicles cause. Subsequently the seriousness of the consequences of this failure is examined. As a result additional functionality may be required in terms of prevention of failure, back-up or fall-back. This additional functionality can be translated into system, maintenance, or procedure requirements.
The output of this step leads to an update of the design decisions that were made in Step 3 and 4.

For example, for the Second Coentunnel this analysis showed that the control of the air quality ventilation was too vulnerable which led to the following additional measure:
- A watchdog on the ventilation control. If it fails, then the ventilation switches off automatically.
- An easily accessible manual control.

**Step 7 Determine performance requirements for functional entities**

In this step, the functional entities are specified in terms of performance requirements. The performance requirements include also non-functional requirements, so called ‘aspect requirements’. These requirements concern aspects such as environment, climate, availability, reliability, maintainability, safety, design, realization, maintenance & control and technical sustainability.

For example, in case of an emergency the ventilation system needs to generate a velocity of 2 m/s (reliability of the system). This step is an elaboration of Step 5 as shown in Figure 1.

**Step 8 Derive additional performance requirements from external factors**

Besides the requirements that were defined in the previous step, additional requirements need to be defined based on external factors, in our case weather, traffic and stage conditions. This includes sustainability in relation to estimated traffic development. For example, the preferred performance of the ventilation has a relation with the cars/trucks ratio and the traffic density, which could change in the future.

Stage conditions result in performance requirements for the dynamic behaviour of functional entities. The requirements are derived from the scenario decomposition of Step 2. For example, limits can be set to the maximum start-up or reversion time for the ventilation.

For the Second Coentunnel the general environmental requirements were specifically (SMART) described. For example, each system was classified in accordance with Dutch standard NEN 1010:2005 Annex CZ32.

**Step 9 Determine failure definitions and derive additional performance requirements**

The next step starts with defining when each functional entity may be regarded as ‘failed’. Remark: in Step 6 we just considered an entity as completely failed, without considering the cause or the objective of the entity. In this step a so called ‘failure definition’ is determined for each entity. In case of failure of a functional entity the main question that is answered is: ‘At what level of functionality must we close the tunnel for safety reasons?"

For example the tunnel lighting: When one lighting fixture is down, the tunnel will remain open. However, when all light fixtures are down the tunnel will be closed. The objective is to identify the limits in relation to the functional and the aspect requirements of the entity and the external factors. When these limits are identified, performance requirements can be set. In the example of the tunnel lighting this means that in some situations on basis of safety requirements a minimum of 80% of the normal lighting level is required, otherwise the tunnel needs to close. Closing is not a desired situation.
from the availability point of view. Therefore, availability requirements need to be set to reduce the risks of failure in conjunction with the top requirements regarding availability of the road system. As a result, in the example of the lighting, redundant lighting fixtures could be a design decision or prescription of certain types of fixtures or a higher level of maintenance.

For the Second Coentunnel the Client’s specification initially contained no definitions of failure. The design team developed them in order to be able to start the design process. Later in the process, a project Task Force confirmed the failure definitions.

**Step 10  Determine the objects**
Based on the previous steps the technical objects are determined and structured in the object tree. Together they form the technical system. Each object is linked to functions and states. For example, the ventilation installation performs the function ‘maintain air quality’ in the normal state and the function ‘prevent back layering’ in the emergency state.

The SysML state chart describes the observable behaviour and allowable order of functions for an installation. In normal mode, almost all functions are allowed. In case of incidents, the tunnel and/or installation can be switched to emergency mode. The state chart for the specific installation contains triggers which cause transitions from normal to emergency mode and the first (automatically, manually) and next actions. An important question we have to ask ourselves is: do the states and modes match with the requirements? We verified the completeness of the installation behaviour by focusing on the behaviour of only one installation. This reduces the complexity during the system design and makes the analyses more efficient. Missing requirements are added and additional detailed requirements are captured. Beside the allowed states, we defined not-allowed states. The system will prevent itself from reaching such a state. To ensure this, we deduced requirements in a traceable way to prevent the installation switching to the undesired state.

For the Second Coentunnel 44 systems were defined. These systems together ensure a safe, reliable and available tunnel.

**Step 11  Prepare plans for verification of requirements and validation of functionality**
The next step is to determine and record how the requirements should or could be demonstrated. This step consists of two objectives:

a. Validation and verification of the system. This means verifying the system that is developed so far. The objective is to check whether the defined system is in line with the project constrains and the scenarios defined in Step 1 and 2 of the approach.

b. Preparation of a validation and verification strategy for the further design development. The objective of this step is set up the first draft of the test master plan. From start of your design process you need to think how you are going to verify the requirements and validate the system functionality. Not only for the actual system, but also during intermediate design stages.

For the Second Coentunnel verification matrices were prepared for verifying the design of the integrated tunnel system as well as verification plans for the detailed design of each subsystem.

**Wrap up  Create a conceptual design report for further elaboration**
All results of the previous steps are recorded in a conceptual design document that is the functional basis for further development and design of the tunnel system. For traceability also a design verification report is created. In this verification report the design decisions are recorded including argumentation as well as the results of the validation and verification so far. These reports must be confirmed by all stakeholders. Then a new baseline can be set. This baseline is the starting point for the next design phase, ‘the detailed design’.
CONCLUSIONS

The approach resulted for the four tube Coentunnel in a design document that was accepted by all relevant parties as the correct description of the functionality and performance of the individual technical systems as well as the tunnel system as a whole. Besides being the basis for further technical design the information is also the basis for the safety plans and safety management of the tunnel organization and instruction and training of personnel, both for the tunnel organization and for the stakeholders, such as the emergency services. It will minimize validation discussions during commissioning, lead to a quicker opening of the tunnel and safer tunnel operation.

Application of SysML in a system integration project changes the conventional requirements driven approach to a more model based approach. For the system design of a tunnel it proved to have some important advantages:

- The method enforced a very early handling of ambiguities in the project, otherwise those issues could not be modeled. This meant early involvement of stakeholders and resulted in early capture of omissions in the incident handling procedures and a solid design basis.

- SysML is a (semi) formal visual modeling language that can be used for documenting the traceability between the requirements, the design and the decisions. The combination of the diagrams and models gives a holistic set of models representing the tunnel systems. This holistic set guarantees consistency between requirements, interfaces and the functional and technical demarcations, and creates a consistent level of detail for the design of the installations.

- From the perspective of IEEE-1471, Recommended Practice for Architectural Description of Software-intensive Systems, additional views, next to the textual view, prove the correctness and completeness of the installations and their mutual cooperation, and therefore of the system design. Based on other types of views such as structural, performance, physical and scenario views we were able to perform more additional analyses. Diagrams are a good way of presenting the design from different points of view and facilitate the communication with all parties involved on several levels of abstraction while the design as a whole remains inherent consistent.

The software tool proved to be a very useful aid to analyze mismatches and traceability gaps in the system design.

Future work

For new tunnel projects we will use part of the SysML system design of the Second Coentunnel again by creating a basic set that can be utilized as starting point. This will speed-up future projects and increase quality.

We did not make use of all possibilities of SysML within the design phase. For a next project, we will take into account the possibility for simulations of tunnel scenarios based on executable SysML.

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The Stockholm bypass – Enhanced design and interaction between safety systems

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ABSTRACT
The Stockholm bypass – E4 Förbifart Stockholm – is a new motorway linking southern and northern Stockholm resulting in a new route for the European highway (E4) past Stockholm. More than 18 km of the total of 21 km of the motorway link are in tunnels. By 2035 estimates show that the link will be used by approximately 140,000 vehicles per day.

A tunnel of this magnitude faces various challenges such as risk for congested traffic, driver fatigue due to monotony, complex fire fighting operations and a need of quick detection of incidents and fires. The basis of the tunnel safety concept is self-evacuation. Based on experiences drawn from the project Norra länken, the design of the Stockholm bypass also comprises a developed traffic management concept, enhanced detection systems for early fire detection and a new cost-effective water-based fixed fire fighting system which aims to keep a possible fire small; providing better conditions for escape as well as providing an opportunity for the Fire Brigade to attack the fire.

An in-depth Human Factor study aims to describe how human behaviour is affected by a complex traffic system, both regarding the normal driving experience and during an emergency.

This paper will focus on and describe the enhancement of certain safety systems, and the necessity of close interaction and coordination between the different safety systems in order to achieve a safe tunnel.

KEYWORDS: Human Factors, congested traffic, fire detection, fixed fire fighting system, evacuation

INTRODUCTION
The Stockholm bypass – E4 Förbifart Stockholm – is a new motorway linking southern and northern Stockholm resulting in a new route for the European highway (E4) past Stockholm [1]. A new link west of Stockholm has been under investigation for several decades and a large number of different alternatives have been studied. To reduce the impact on sensitive natural and cultural environments, just over 18 km of the total of 21 km of the motorway link are in tunnels. The construction work is planned to start earliest in 2012 and it will take 8–10 years to finish.

When the link opens for traffic it will be one of the longest road tunnels in the world. By 2035, the Swedish Transport Administration (Trafikverket) estimates that Förbifart Stockholm will be used by
approximately 140,000 vehicles per day. The tunnel system is designed for a variable maximum speed of 80-100 km/h.

**Why is E4 Förbifart Stockholm needed?**

The County of Stockholm is growing. By 2030, the population of the Stockholm region is expected to have increased from 2 million today to roughly 2.4 million. The Baltic region is estimated to have great international potential and the Stockholm region is extremely important, as a growth engine, to employment and growth throughout Sweden. If Stockholm is to be able to continue to develop, the region’s infrastructure must work well.

In the years to come, big investments will be made in the infrastructure in Stockholm. A new railway (Citybanan) through the central parts of Stockholm is currently being constructed. This will double track capacity through the city. Citybanan opens for traffic in 2017. The Norra länken project is also in progress. When it opens in 2015, it will form an inner ring road in Stockholm with the existing Essingeleden and Södra länken. With the existing Norrortsleden and the planned Södertörnsleden, Förbifart Stockholm will create an outer ring road.

**Figure 1** The Stockholm bypass - E4 Förbifart Stockholm
In summary, the Stockholm bypass aims:

- **To minimise vulnerability** – there is currently only one major road link, Essingeleden and one major rail link between northern and southern Stockholm

- **To relieve Essingeleden** - Essingeleden was opened in 1967 and was designed for 80,000 vehicles a day. Traffic is now 160,000 vehicles on a normal working day. And the traffic volume is increasing. This makes Stockholm’s transport system vulnerable and Essingeleden sensitive to traffic incidents.

- **To improve communications** - Förbifart Stockholm will provide better communications between the southern and northern parts of the county, which is intended to improve the potential for integrated labour, housing markets as well as service.

- **To provide a bypass for long-distance traffic** - The link will provide long-distance traffic with a bypass so that it no longer has to pass through the centre of Stockholm.

**Schedule for the Stockholm bypass**

The project phases feasibility study, preliminary design plan and consideration of permissibility are completed. Work with the final design plan, and the preparation of construction documents, is ongoing. The construction work is planned to start earliest in 2012 and it will take 8–10 years to finish.

**A SAFE JOURNEY**

A tunnel of this magnitude faces various challenges such as risk for congested traffic, driver fatigue due to monotony, complex fire fighting operations and a need of quick detection of incidents and fires. The tunnels are designed with the aim of creating a safe journey, with parallel tunnel tubes without oncoming traffic. Ramp tunnels are connecting the main tunnel to the surface road network, and these are also designed as parallel tubes without oncoming traffic.

**Safety concept**

The basis of the tunnel safety concept is self-evacuation. Congestion should normally be avoided, with the exception of accidents and incidents, which requires an active traffic management to regulate the traffic flow. Traffic downstream of an accident should be given possibilities to drive out from the tunnel system and away from a potential danger, whereas road users upstream of the accident can utilise escape routes to walk to the parallel tunnel tube. The escape routes, also referred to as exits, are located every 100 m in the main tunnels, and every 150 m in the ramp tunnels. The escape routes are designed as fire locks to prevent fire and smoke spreading from one tunnel tube to the other.

The tunnel system is to be monitored and controlled by a traffic control centre called Trafik Stockholm. To cater for this, the tunnels are fitted with 24 h CCTV, and various detection systems such as an automatic fire detection system, systems to monitor air quality and a system to detect incidents and stopped vehicles. Doors into the escape routes, emergency telephones and hand-held fire extinguishers are also monitored, which means that for example an opened door will render a signal in the traffic control centre.

The traffic control centre has action plans for all accident scenarios, e.g. vehicle fires, traffic accidents and accidental release of dangerous goods. Recovery plans are also an important part of this concept, with the purpose of restoring traffic in the tunnel as soon as possible after an accident has been dealt with by the tunnel operator and the emergency services. The tunnel system will also be served by a
road assistance crew, which among other things can handle minor accidents and prevent stopped vehicles from blocking the traffic flow. Based on experiences from Södra länken and Norrortsleden, the road assistance crew usually arrives to the accident scene at a very early stage, and is of a great help in assisting evacuation if needed.

Communication channels to give road users evacuation messages include variable message signs and emergency radio broadcasts. There will also be mobile phone coverage throughout the tunnel system.

The ventilation concept is based on longitudinal ventilation, both for the environmental and fire ventilation, achieved by jet fans mounted in the tunnel ceiling. Specific action plans, to be used by the traffic control centre, are developed for the operation of the ventilation system during fires and accidents, including consideration of the aspect congested traffic conditions. Three air exchange stations, and a specific smoke exhaust tower, divide the tunnel into ventilation sections with a maximum length of approximately 5 km. At the air exchange stations, air from the tunnel system is exhausted and fresh air is taken in from the surface. In addition to this, exhaust towers are located nearby the tunnel exits. Air exchange stations and exhaust towers, as well as the specific smoke exhaust tower, can be used for smoke management.

A water drainage system will be installed throughout the tunnel system, with the capacity of handling an accidental release of liquid dangerous goods, such as petrol. The aim is that there should be no restrictions on the type of transports allowed in the tunnel system.

Traffic management measures include, among others, controlled traffic lane signals, ramp metering and boom gates at strategic locations. In case of a fire, all tunnel tubes are closed for incoming traffic.

Fire fighter’s access is via the escape routes, which are equipped with fire hydrant outlets. A special fire fighters’ radio system, which can also be used by for example the police and ambulance staff, will be installed in the tunnel system.

A fixed fire fighting system will be installed throughout the tunnel system. The primary purpose of the system is to slow down the fire growth and assist evacuation.
CONNECTION BETWEEN HUMAN BEHAVIOUR AND TUNNEL DESIGN

The tunnels will be designed for a safe journey, where an aesthetic design programme aims to prevent accidents. The design principle of the aesthetic design programme is based on knowledge of human behavior in tunnels. Good ease of orientation is an important aspect that influences the design. Clear information about where one is in the tunnel system is also essential to the sense of safety.

Aesthetic design programme and driving experience

An in-depth Human Factor study, including a driving simulator, aims to describe how human behaviour is affected by a complex traffic system. The study is performed in cooperation with VTI, the Swedish National Road and Transport Research Institute. The study aims to examine the normal driving experience, and how it is affected by the aesthetic design programme.

The tunnel’s aesthetic design consists of for example artistic lighting, unique artwork associated with each traffic interchange and markers, or indicators, describing how far the road users have travelled in the tunnel. These features will be tested with regards to a number of driving aspects, such as visual distraction, lateral deviation (does the driver stay in the middle lane), average speed and differences in speed (are there any sudden speed changes), steering wheel movements and braking behaviour. Cameras measuring eye movements will determine what the test persons are looking at during the driving simulation, as well as how often and for how long.

After the driving simulation the test persons will answer a survey about the perceived safety of the tunnel, the ease of orientation, any feeling of monotony, and opinions about the aesthetic design of the traffic interchanges.

Emergency situations

Experiences from occurred vehicle fires in the tunnel Södra länken show that the behaviour of road users during an accident is hard to predict. The basic idea of the safety concept in Södra länken is similar to the Stockholm bypass, i.e. road users upstream of a fire should evacuate by foot, via escape routes, to a parallel tunnel tube. However, there have been a few cases where road users have been seated in their cars in a smoke free environment upstream of a fire, and despite this decided to leave the smoke free environment and drive into a smoke-filled tunnel section. This is a risky behaviour since conditions downstream are unknown and potentially dangerous should the fire grow large. There could be various reasons for this; the road users have not seen, heard or understood the evacuation message, they have understood but chosen to ignore the evacuation message since they are determined to fulfill the original purpose of their journey, e.g. to get home. It could also be that the stressful situation causes them to act irrational.

The project has an aim to further investigate this situation with the help of the driving simulator at VTI. In these studies, a test person would drive along the tunnel and suddenly reach an accident, e.g. a burning vehicle, partly blocking the road. The test person would still have the choice to drive past the accident into a smoke-filled environment. The aim of the study would be to investigate how people react to the situation of a burning vehicle partly blocking the road, and why they act one way or another. Step two would be to investigate how people actually react once they have driven into the smoke-filled environment where visibility is low and orientation difficult. Results from the study could be used to determine if any channels for communicating evacuation messages need to be improved or if any new channels are required.
ENHANCED FIRE DETECTION

Conditions in the tunnels in the Stockholm region are quite aggressive on equipment such as fire detection systems due to contamination and regular tunnel washes. Air velocities are usually high, approximately 5-8 m/s, due to either environmental ventilation or the piston effect created by the traffic flow.

Even though congestion should normally be avoided, with the exception of accidents and incidents, the safety concept must have an inherent robustness to handle congested conditions both upstream and downstream of a fire. Part of this work is to further enhance the possibilities to detect fires in the tunnel system, and this at the high air velocities created by the environmental ventilation that is the case if the traffic is congested. Early fire detection is important for the traffic control centre in order to quickly start the appropriate action plan. Thus, a research study lead by the Swedish Transport Administration has been undertaken.

Historically, linear heat detection has been used as a robust fire detection system, and the research study has investigated the possibilities to complement this with some kind of smoke detection. The tests were undertaken in the tunnel Södra länken, and the test equipment, consisting of systems from various suppliers, has been exposed to actual traffic conditions, including contamination and tunnel washes, for approximately a year.

One of the goals of the study was to investigate if there are systems able to detect a 1 MW fire within 90 seconds, at high air velocities. The results look promising, and several of the tested smoke detection systems were able to detect a fire as small as 0.5 MW at an air velocity of approximately 5.5 m/s.

One challenge is to find a balance between the risk of false alarms and the benefit of very early fire detection. One way to handle this is to use detection of a 0.5 MW fire as a “pre-alarm” level, which gives the traffic control centre an early notification of the accident.

FIXED FIRE FIGHTING SYSTEM

The decision to install a fixed firefighting system (FFFS) was made due to the desire to increase the robustness of the personal safety aspects of the safety concept. Under ordinary conditions, the tunnel can be evacuated without a FFFS should a fire occur. Experience from past fires however, highlights the difficulty of predicting road users’ behaviour during an incident. A FFFS can slow down and reduce the development of a fire, and as a result, prevent a large fire from developing into a catastrophe, even if the road users’ evacuate the tunnel at a slower pace than expected. The primary purpose of the system is therefore to slow down the fire growth and assist evacuation. The purpose is not to extinguish vehicle fires.

Naturally, fire fighting operations will be assisted by installation of the FFFS.

Cost-benefit analysis

A positive side-effect of installing the system is improved asset protection. The tunnel will play an important role in the region’s transport system, and reducing the recovery time after a fire is very valuable from a socioeconomic viewpoint. This aspect has in a large way led to the decision to install a FFFS in the Stockholm bypass, and was an important factor included in a cost-benefit analysis undertaken during the design work for the consideration of permissibility.
Included in the cost-benefit analysis were different safety systems and solutions, including installation of a FFFS (with and without foam), longitudinal ventilation with frequent smoke extraction points, and shorter distances between exits. The cost and benefit factors of the analysis included life safety and personal injuries, installation and maintenance costs for the different safety systems, asset protection (both tunnel infrastructure and vehicles), costs associated with recovery time, and transport economics from a socioeconomic viewpoint (closure of the tunnel due to e.g. a fire means that the traffic has to choose another route, potentially leading to congestion and delays on that route).

Based on the analysis, the decision was that installation of a FFFS (without foam) in all tunnel parts, and shorter distances between exits in the main tunnel (from 150 m to 100 m), was the most robust and cost efficient safety solution for this project.

**Cost of FFFS**

Earlier sprinkler systems in Swedish tunnels have been overlooked due to cost reasons, it has not been possible to show that the system has a sufficient benefit to make it economic in a cost-benefit analysis. Because of this the Swedish Transport Administration have, for the last few years, looked into the possibility of developing a simplified system that gives similar performance for a lower cost. One of these systems has now been tendered for the project Norra länken, and its cost is currently at approximately 30-50% of what was previously specified for a road tunnel sprinkler system.

**Technical description of the FFFS in the Stockholm bypass**

The fire fighting service’s water supply also supplies the water for the FFFS. This means that if the fire fighting service chooses to use the fire hydrant outlets at the same time as the FFFS, the water supply for the FFFS will partly decrease. The FFFS’s package of control valves are placed over the fire hydrants in the respective escape routes. In order to minimise the amount of piping, each section is 50 m long. This means that two pipe sections cover the distance between two escape routes. In the ramp tunnels the distance between escape routes is 150 m, and as a result the pipe length there is 75 m.

The pipes are prefabricated thermoplastic coated steel pipes. The pipes are joined in grooved tracks with precast connections. In every connection there is a downward-facing sprinkler cluster. All components must be capable of withstanding corrosion class C5 Marine Environment. At this stage, the inner pipe diameter is 150 mm, with an outer pipe diameter of approximately 162 mm.

One distribution pipe stretches from the escape route to the tunnel ceiling, where the 50 meter long sections are placed in the centre of the ceiling at the tunnel cross-section’s highest point. Every 5th meter there is a downward-facing T-pipe with two sideways-distributing sprinkler nozzles. The specially ordered nozzles have a distribution length of more than 8 m, which allows the system to supply a tunnel width of 16 m with an average water density of approximately 10 mm/minute.

The water supply is adjusted so that two sections can be activated simultaneously, if a fire were to occur at the joint between two sections. The sections are activated by the staff in the traffic control centre, Trafik Stockholm, which continuously monitors the systems in the tunnel. Fire detection should occur at an early stage, in theory the smoke detectors can raise a “pre-alarm” in the case of a fire as small as 0.5 MW. If the operators at the control center do not acknowledge the alarm within a certain period of time, the affected section is automatically activated. Should this happen, the tunnel automatically closes and ongoing traffic is directed out via the nearest exit.
For reference, the following figure shows the intended layout of the FFFS in the project Norra länken.

![Fixed Fire Fighting System (FFFS) in the project Norra länken](image)

**CONCLUSION**

The Stockholm bypass will be equipped with active safety systems such as FFFS and fire and incident detection. Smoke detection tests undertaken in the existing tunnel Södra länken indicate that fires as small as 0.5 MW can be detected at air velocities exceeding 5 m/s. Development of the FFFS will continue, where full scale testing is an interesting aspect. Passive safety measures include frequent escape routes and parallel tunnel tubes without oncoming traffic. Both the pre-crash and the post-crash perspective are interesting with regards to Human Factors, including how the tunnel design affects human behaviour and how people actually react when facing a potentially dangerous situation, e.g. a vehicle fire blocking part of the road.

The key to achieve a robust and safe tunnel is to approach active and passive safety measures, the ones mentioned in this paper as well as others, and Human Factors aspects, from a coordinated and integrated point of view. A quick fire and incident detection, provided by different systems that complement each other, is fundamental for the traffic control centre in order to get knowledge of the incident and in their turn to start the appropriate action plan, e.g. tunnel closure and activation of the FFFS. At the same time it is important that incorrect driving behaviour and accidents are avoided as far as possible and taken into consideration during early tunnel design phases. In order to achieve a safe tunnel different safety systems and technologies need to interact, and this needs to be considered from an early design stage of a tunnel project.

**REFERENSER**

Decision support to determine safe tunnel availability

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1. INTRODUCTION

During the last few decades, road and railway tunnel disasters have led to an increased interest in tunnel safety. One of the consequences of this has been the development of a model and from that a Decision Support System, the Tunnel Safety Indicator, for the five railway tunnels in the Betuweroute in the Netherlands. This system was tested, tuned and evaluated for a year and is now officially in use. The system has resulted in increased availability of the tunnels resulting in more hours of exploitation, prioritized maintenance based on the expected and actual deterioration of safety, and better judgment and less stress for operating staff if there are failing components in the tunnel.

Tunnel Safety
In general, tunnel safety is assessed by looking at the availability of Safety Functions (measures or provisions for safety) within the four Lines of Defense: prevention, mitigation, evacuation and rescue [1]. These Lines of Defense (LOD) must be at a certain minimum level for a tunnel to be considered safe to open for traffic. They are maintained by the Safety Functions within the tunnel complex. Safety Functions are the requirements for the systems and ultimately the technical installations in a tunnel.

We have created a model in which installation components have been combined into systems offering functional safety in order to maintain the Lines of Defense necessary for a safe tunnel. This model makes it possible to define business rules regarding the deterioration of installations and the ultimate effect of this technical deterioration on the more abstractly defined level of tunnel safety required by or agreed upon with the authorities. Using the output from the technical installation components through the SCADA system in combination with the results of regular inspections, this model provides an accurate and objective indicator of tunnel safety.

![Diagram of the model to determine safe tunnel availability](image-url)

*Figure 1: Model to determine safe tunnel availability*
Purpose
This model and related systems have been developed with three aims in mind:

1. To arrive at an accepted indicator of the agreed safety of a tunnel by which internal and external parties can be informed transparently and objectively.

2. To gain insight into the condition of a Line of Defense for internal use by the operator, by providing detailed information about the safety chain and thus the influence of the status of components on the final status of the LOD, in an objective and traceable manner.

3. To prioritize maintenance based on the expected and actual deterioration of tunnel safety.

2. MODEL

The first objective was to create a layered model which would make a link between an abstract definition of safety and concrete technical data. Using the TSI-SRT [1] Lines of Defense as a starting point for the abstract definition of safety, the Safety Functions have been defined such that they included these Lines of Defense. It appears that this collection of Safety Functions contains largely the same functions for different road and railway tunnel projects. These Safety Functions serve as functional requirements, so they were used to compile a definition of Logical Systems fulfilling these requirements. Finally these Systems were broken down into Components, which are the smallest technical units that produce status data. This approach led to a four-layer model: Lines of Defense – Safety Functions – Logical Systems – Components. The model resembles a graph fanning out from the Lines of Defense to the Components.

Between every layer there are business rules. These rules define how the status of a particular level influences the status of the level above it. This chain of reasoning propagates from the concrete Component layer up to the Lines of Defense and ultimately to the Tube.

Component layer behavior and business rules
The component layer contains the definition of all physical components in the Tunnel Technical Installation. The following business rules apply:

- A Component is always either Available (A) or Not Available (NA).
- The SCADA system indicates the status of Components.
- A Component always belongs to only one System, and each System contains one or more Components (one-to-many relationship).
- Each Component is given a weight, thus indicating its relative importance to the System to which it belongs.
- A Component may have a position (order) in the tube.
- The status of a Component is either reported by the SCADA system or manually determined as the result of an inspection.

Example:
A section valve and main valve for two adjacent sections are examples of components belonging to the same system. The main valve has twice the weight of the section valve, as its importance to the system is similar to two adjacent section valves. Section valves are numbered sequentially in the tube, which indicates their ordered position.
System layer behavior and business rules
The system layer models the physical systems as closely as possible. Systems are collections of components. The availability of these components determine the total system availability. The following business rules apply:

- A System consists of one or more Components
- A System has a maximum availability, which is determined by adding up the weights of all the Components contained:
  \[ S_{\text{max}} = \sum C \]  
  \[ (1) \]
- A System has an actual availability value determined by adding up the weights of all the components with the status Available:
  \[ S_{\text{actual}} = \sum C_{\text{avail}} \]
  \[ (2) \]
- Special rules for degradation may apply, in which case the system degrades further than the sum of the Non-Available components. An extra value R is subtracted from the system availability if such rules apply, acting as a penalty.
- Actual availability is never less than 0.
- A system can contribute to multiple Functions. The weight for each Function will be set in order to indicate the contribution of the specific system to that function.

Example (simplified):
A sprinkler system consists of 100 section valves with a weight of 1, so \( S_{\text{max}} = 100 \).
There is a special Rule that says that no two consecutive section valves may have state NA. If this rule is breached, then an additional deduction of \( R = 5 \) applies. In the following numerical example two adjacent section valves have status NA:
\[ 93 \ 5 \ 98 \]
\[ \Rightarrow \sum R = 98 - 5 = 93 \] . The system thus has a current availability of 93 out of 100 (or 93%, expressed as a percentage).

Function layer behavior and business rules
Safety Functions define abstract behavior of the Tunnel which can be realized by one or more (redundant) systems. It is particularly important to distinguish Safety Functions, which define functional behavior of an abstract system like “ventilation”, from system functions which describe technical behavior of an installation like a ventilator. The following business rules apply:

- A Function has either state Available (A) or Not Available (NA).
- A Function is realized by one or more Systems (many-to-one relationship).
- Within a Function, systems may overlap, for example handrail, lighting and exit signs overlap within the Function ‘offering an escape route’.
- For different combinations of Systems, the thresholds can be set per individual system. By using simple proposition logic (and/or combinations of Systems), the status of the Function can be determined.
- A function can be assigned to one or more Lines of Defense (one-to-many relation). For every Function-LOD assignment, a Safety Class Value will be set, indicating the contribution of the function to the LOD.

Example:
To realize the Function ‘cooling tunnel downwind’, the Sprinkler System availability must be at a 95% minimum (see also the previous example). The longitudinal ventilation system, which has a maximum availability of 30 based on the added weight of its components (ventilators), has a minimum limit of 80% when running on mains power. If running on emergency power, the minimum
limit on availability is 40%. Maximum availability for mains and emergency power is 1 (assumptions
for example):

<table>
<thead>
<tr>
<th>Overlap</th>
<th>System</th>
<th>Symbol for actual value</th>
<th>Smax</th>
<th>Slimit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sprinkler system</td>
<td>Ssp</td>
<td>100</td>
<td>95 (95%)</td>
</tr>
<tr>
<td>1</td>
<td>Longitudinal Ventilation</td>
<td>Slv</td>
<td>30</td>
<td>24 (80%)</td>
</tr>
<tr>
<td></td>
<td>Mains power</td>
<td>Smains</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Longitudinal Ventilation</td>
<td>Slv</td>
<td>30</td>
<td>12 (40%)</td>
</tr>
<tr>
<td></td>
<td>Emergency power</td>
<td>Semer</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

The availability for this safety Function can be presented as the following formula:

\[
F = S_{sp} \geq 95 \land \left[ S_{lv} \geq 24 \land S_{smains} \geq 1 \right] \lor \left[ S_{lv} \geq 12 \land S_{semer} \geq 1 \right]
\]  

(3)

**Line of Defense layer behavior and business rules**

Lines of Defense are maintained by Safety Functions. When one or more functions are lost, the LODs
deteriorate until they are breached. This mechanism is modeled by assigning Safety Class thresholds
to the different states an LOD can have. The following business rules apply:

- An LOD has the status Not Degraded, Degraded, Severely Degraded or Breached.
- An LOD is maintained by one or more Safety Functions (many-to-one relation)
- The LOD state is determined by summing the Safety Class of its underlying Safety Functions
  with state Not Available and evaluating that sum against a predefined threshold:

<table>
<thead>
<tr>
<th>Safety Class</th>
<th>Lost safety Functions (count) per LOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Degraded ( \sum = 1 )</td>
</tr>
<tr>
<td>2</td>
<td>Degraded ( \sum = 2 )</td>
</tr>
<tr>
<td>3</td>
<td>Severely Degraded ( \sum = 4 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Safety Class</th>
<th>Lost safety Functions (count) per LOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Severeley Degraded ( \sum = 4 )</td>
</tr>
<tr>
<td>3</td>
<td>Breached ( \sum = 6 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Safety Class</th>
<th>Lost safety Functions (count) per LOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Breached ( \sum = 6 )</td>
</tr>
</tbody>
</table>

**Figure 3 LOD thresholds set on Safety Class level 3 and 5**

**Example**

In the table above, the threshold for the status Degraded is 1. The next threshold, for the status
Severely Degraded, is 3 and the final threshold for the status Breached is 6.

**Tunnel Tube layer behavior and business rules**

On the highest level in the model, safety per tunnel tube is determined based on the state of its four
Lines of Defense. A Tube has an operating status. This state is OPERATION, MAINTENANCE or
EMERGENCY. Only during state OPERATION the Safety state is inferred. In all other cases the
safety status is Undetermined.
• A Tube has state GREEN (safe), YELLOW (degraded safety) or RED (unsafe)
• Safety of a tube is assessed through four Lines of Defense: prevention, mitigation, evacuation and rescue.
• State Severely Degraded in one LOD causes transition to YELLOW
• A tube can only have a Yellow status for a certain amount of time. If this maximum time elapses without transition back to Green, a status transition to Red occurs automatically.
• If the status of one or more LODs is Severely Degraded or Breached, this causes transition to Red. If transition occurs from Yellow to Red status, the maximum time for Yellow continues to count down in the background.
• If during the status Red, LOD conditions for the status Yellow are met, transition to Yellow takes place. The remaining time for the status Yellow is not reset but this time continues to count down.

3. TUNNEL SAFETY INDICATOR

Based on this model, a suite of applications has been developed under the name MUST™. This Tunnel Safety Indicator (TSI) application is operational in five railway tunnels and in the near future it will be implemented in several more road and railway tunnels. The system is certified by an accredited third party and is tamper-proof.

System architecture
The Tunnel Safety Indicator is part of the modular MUST™ Engineering, Simulation and RuleServer suite of applications.

*Figure 4: MUST suite of applications*

The model described above has been configured using the MUST Engineering application. With this web-based tool, the model can be configured for a specific tunnel. Simulations can be run using different configurations based on actual or simulated data from the SCADA system. Simulation can also be used for testing a new configuration and certifying it (FAT) before going into production.

Operational data is either retrieved by periodically reading out the SCADA data log, or real time through an OPC UA Alarm & Event server. The Tunnel Safety Indicator is implemented as a web application with regular browsers for clients. There is also an MMI component which acts as an OPC Client. This component can be embedded in existing SCADA MMI.
**System functions**

The main functions provided by the TSI system are the Safety Indicator, one traffic light per tube, and the underlying Safety Status overview, a tree-like overview of the model with detailed status information. These main functions are available through a standard web browser or SCADA MMI component.

![Tunnel Safety Indicator](image)

**Figure 5: Tunnel Safety Indicator**

Figure 5 shows the TSI for a tunnel with 2 tubes. Tube 1 is safe and has been in that state for more than 120 days, whereas Tube 2 has degraded safety. If this status is not resolved in less than 3 days, the tube will be declared unsafe, and this will result in closing off the tube.

From the TSI it is possible to drill down and obtain detailed information regarding the safety of the tunnel:

![Safety Status overview](image)

**Figure 6 Safety Status overview**
Figure 6 shows a drill down into the model underlying the TSI. The drill down has a tree-like format and shows exactly how failed components affect the safety of the tunnel. Figure 6 visualizes the examples in Chapter 2. Three ventilators are Not Available. As a result, the System “Ventilation East” loses 3/5 of its Availability and drops to 40%, which is below the threshold of 50% set by Function “SMOKE-FREE FLIGHTPATH”. This means the Function is lost. Apparently this function has a high Safety Class, because the loss of this single function is enough to breach the LOD Evacuation.

Secondary TSI functions such as prioritized maintenance advice, temporary suppression of false events, entering inspection results and reporting, are supported through the TSI web portal and accessed through a standard web browser.

4. REFERENCES


KEYWORDS: tunnel safety, safety indicator, decision support system, lines of defense, functional safety
PROBLEMS WITH TUNNEL SAFETY SYSTEMS

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Internationally, tunnel safety is receiving much greater emphasis as a result of serious fires, and terrorist incidents which have major economic impacts, structural / vehicle damage, and significant loss of life. Enhanced safety systems originally designed for buildings are now being adapted into tunnels to address the risks and prevent or mitigate impacts of these incidents.

This paper explores the challenges of bringing these systems into the tunnels, briefly outlines the advantages and reviews brief case studies as to why the problems occurred to ensure future installations will meet the design intent and continue to make tunnels safer.

We should understand that building safety systems have been designed, developed, tested and successfully operated for many years. They have a lengthy history of success and have years of research and operation to ensure they perform almost flawlessly.

However, the tunnel environment, different operating modalities, inexperience with these systems and their integration becomes problematic which can lead to unsatisfactory results. Unfortunately the lack of understanding and incorrect expectations about building systems, have occasionally led to problems that have discredited the use of these safety systems.

We should recognize the science of tunnel fires has greatly improved in recent years which have directly impacted safety systems. Our knowledge of the potential fire heat release rate, fire growth rate, and therefore the effects on the structure, and more importantly the timeline for life safety has radically changed our thinking in the last few years.

Understanding the fire potential, increased terrorism, major environmental events have changed what was singular concern about fires, to an ‘all hazard approach’. This ‘all hazard approach’ is being applied to the construction of tunnels, the safety systems installed and the management of incidents. Notably, terrorist activities have caused creation of new detection systems, and new methods to operate tunnels.

INTEGRATION

It is important to understand that the successful prevention of incidents and optimum mitigation now, more than ever, can no longer rely on any one individual system, but should utilize all available systems in an integrated manner. We now recognize how critical early detection of an incident can be to successfully and correctly identify the situation. Failure to understand how these systems work both alone, and as part of an integrated approach, can result in less than satisfactory results which may expose the operating agency to legal recourse.
The integration of systems and the greater understanding of tunnel fires and other risks have directly impacted the emergency responder community who must be included in the design of new tunnels and trained on the specific systems being used. This applies to both new tunnels and existing tunnels which, unfortunately, may still operate based upon inadequate knowledge of potentials for fire and other risks in their tunnel.

COMPARING TUNNELS WITH BUILDING SAFETY SYSTEMS

Building fire safety systems were initially developed to address the fires that resulted in large insurance claims from property losses and later, to address loss of life. Overtime, understanding the building fire science ensured development of fire and life safety systems that addressed specific problems within the fire and how this impacts the timeline of fire growth.

One of the earliest systems was a relatively crude sprinkler system developed in 1806.

“John Carey began experimentation with sprinkler systems in England. He created a sprinkler system that consisted of counter weights and a series of strings. The fire would burn the strings that attached the counter weights to the valves; when the weights fell, water emerged from the valves.” [1]

From this early type of fire detection and suppression, we have greatly expanded our extensive fire knowledge in buildings and developed a range of testing and fire science to address the various types of buildings, building contents, and occupant capabilities.

With the fire science development, it became critical to develop engineering to utilize the fire science in practical application. This has led to Fire Protection Engineering as a discipline integral to success. Given the huge diversity in building occupancies, structure types, building content, and the extensive array of equipment, devices and components used in fire systems, the Fire Protection Engineering profession has become an indispensable link in designing and operating successful fire systems. With the relatively new understanding of fire science in tunnels, it is essential to utilize well informed and experienced fire protection engineers in design, and installation of fire protection systems.

Specific equipment was needed to fully utilize the knowledge and meet the wide array of specific applications needed. Given the importance of the life safety system, components that fail could be catastrophic; therefore component testing is required under strict testing methods by an agency. Two notable international agencies are: Underwriters Laboratories [2] which is an ‘Independent, not-for-profit product safety testing and certification organization.’, and Factory Mutual Approvals [3] which provides third party certification of fire devices and components.

There are common misunderstandings of the intent of the fire and life safety systems. For example fire sprinklers were developed to prevent fire spread, i.e. suppression, not extinguishment. (There are in fact very few sprinkler systems that are designed and listed for complete extinguishment.)

The types of safety systems in a tunnel range significantly with the perceived and actual risk. However, we should not discount the uncommon and singular safety system that perhaps was designed for a relatively limited application. An example of this would be foam suppression in road tunnel runoff holding tanks.

We should also not disregard tunnel components that are perceived as normal use, structural, or intended for maintenance or other purposes. This includes tunnel lighting, traffic and train control.
signals, maintenance access panels, communications, etc. Remember that in an emergency the responders and tunnel staff will make decisions based upon ALL the resources that are available.

**TUNNEL SAFETY SYSTEMS** were initially often only carbon monoxide detection used to identify high levels of carbon monoxide from exhaust. Without detection, mechanical ventilation systems were manually activated based upon visible tunnel exhaust build up, or the ventilation was on automatic timers coinciding with peak traffic loads.

Exits were given special lighting to provide rapid identification to the users and maintenance personnel. However, exit spacing varied dramatically from jurisdiction to jurisdiction and from type of tunnels and perceived risks.

Fire was recognized as a significant threat and fire deluge sprinkler systems were installed as early as 1952. This early technology did not have a central control center, and relied on direct manual activation of the deluge system, and/or a pneumatic tube heat activated system.

Fire detection is recognized as one of the most important factors in tunnel safety, yet the fire detection systems used commonly in buildings are not well suited to use in the tunnels. Buildings most commonly use smoke detection technology which are either ionization or photo- electric methods to detect smoke. These detection systems are too prone to nuisance alarms to be used in tunnels and in fact are not generally approved for installation in outdoor type spaces such as tunnels.

**Definition of Nuisance Alarm** – “Any alarm caused by mechanical failure, malfunction, improper installation, or lack of proper maintenance, or any alarm activated by a cause than cannot be determined.” [4]

Recognizing the pivotal role detection plays in tunnel fires, a multiyear program was initiated on this topic. The Fire Protection Research Foundation (FPRF) and the National Research Council (NRC) of Canada conducted a two-year international research project, with support of government organizations, industries and private sector organizations, to investigate currently available fire-detection technologies suitable for tunnel applications. [5]

“In general, the performance of fire detection systems was dependent on fuel type, fire size, location and growth rate as well as detection method. Moreover, the performance was affected (delayed or shortened) under longitudinal airflow conditions. The linear optical heat detection systems, the optical flame detector, visual-based CCTV fire detectors, and smoke detection system were able to detect a small-unobstructed fire. The spot heat detectors did not detect fires sizes smaller than 1,500 kW. The performance of the linear heat detection system and visual-based CCTV fire detectors were, generally, not affected by fire location.” [6]

There are few fire detection systems in rail tunnels and even fewer detection systems on board trains where the risk to passengers is highest. Adding detectors on board will become more prominent.

Since no optimal detection system has been developed for road tunnels, various approaches have been utilized, sometimes with less than perfect results. This problem is exacerbated by the high incidence of nuisance alarms which result in unnecessary activation of systems, shutting down traffic, etc.

**CASE STUDIES**

**Case Study 1) Nuisance Alarms** An unusual example of the nuisance alarm impact occurred in Seattle with a retrofit of the Interstate 90 freeway Mt Baker and Mercer island tunnels. These tunnels were completed in 1992, and used ‘rate compensated spot heat detectors’ for fire detection. Besides
routine replacement of the control system, there was an attempt to reduce excessive nuisance alarms by rewiring the detection circuits which effectively doubled the detector spacing, but also resulted in a extremely slow response time to fires.

The original zoned spot heat detector system was revised to require multiple detectors in different zones to be activated before the fire ventilation or suppression system was initiated. With 45 m (150 foot) deluge zones, the heat from a fire would therefore need to travel over 45m (150 feet) to activate detectors in the second zone. Depending on fire size this could take considerably longer time that would be allowed under standards applicable at the time of renovation. Eventually, automatically starting of the sprinkler and ventilation systems was ultimately discontinued in favor of a manual start by the tunnel operator.

Unfortunately, the fire department, i.e. the Authority Having Jurisdiction (AHJ) on fire alarm systems, was not involved in review of the changes at the redesign stage nor approved the re commissioning, or they would have required a better solution to the problem.

The latest retrofit is planned with UL listed camera systems which detects both flame and smoke signatures and presumably will result in much quicker and more reliable detection through an alarm verification system. The spot heat detection system will be left in place as a backup system.

Not only does the detection type and method vary widely, the signals from the fire detection system must be managed in order to provide reliable information and avoid nuisance alarms.

Managing the alarm signal requires understanding the type of signal that can be received from the various detection systems. Although there are a variety of alarm signals, these signals can be grouped into three general areas: Trouble, Supervisory and Alarm.

Trouble “A signal initiated by a system or device indicative of a fault in a monitored circuit, system, or component.” [4]

Supervisory – “A signal indicating the need for action in connection with the supervision of guard tours, the fire suppression systems or equipment, or the maintenance features of related systems.” [4]

Alarm “A signal indicating an emergency condition or an alert that requires action.” [4]

In the building systems, an Alarm signal would automatically initiate a set of processes to:

- notify the occupants, owner, and emergency responders
- Start sprinklers (for deluge type sprinklers and other special suppression systems)
- Start smoke management systems, and miscellaneous actions such as closing fire doors, etc.
  as required by the code or standard for that specific building type

Generally there is only one type of exception to this automatic initiation of the various systems, and that occurs where a possible nuisance alarm could create significant business interruption, AND, where trained staff are always available to investigate the source of the alarm signal. This exception is the Positive Alarm Sequence (PAS) identified for protected premises in NFPA 72 in section 23.8.1.3.1.1. “The positive alarm sequence operation shall comply with the following:

(1) To initiate the positive alarm sequence operation, the signal from an automatic fire detection device selected for positive alarm sequence operation shall be acknowledged at the fire alarm control unit by trained personnel within 15 seconds of annunciation.
(2) If the signal is not acknowledged within 15 seconds, notification signals in accordance with the building evacuation or relocation plan and remote signals shall be automatically and immediately activated.

(3) If the positive alarm sequence operation is initiated in accordance with 23.8.1.3.1.1(1), trained personnel shall have an alarm investigation phase of up to 180 seconds to evaluate the fire condition and reset the system.

(4) If the system is not reset during the alarm investigation phase, notification signals in accordance with the building evacuation or relocation plan and remote signals shall be automatically and immediately activated.

(5) If a second automatic fire detector selected for positive alarm sequence is actuated during the alarm investigation phase, notification signals in accordance with the building evacuation or relocation plan and remote signals shall be automatically and immediately activated.

(6) If any other fire alarm initiating device is actuated, notification signals in accordance with the building evacuation or relocation plan and remote signals shall be automatically and immediately activated."

Using a PAS approach for tunnel systems control works very well as it provides the advantage of both manual control and automatic activation. However, this requires 24/7 staffing with at least two people. PAS also helps when we understand the demands now being placed upon tunnel operators. In an emergency they must be able to understand the various system signals and status messages, choose the correct use of the systems, while initiating emergency evacuation, modifying train/traffic signals, and make emergency notification calls to supervisors, and radio calls to tunnel staff.

The tunnel operators’ highly critical multi tasking function of the tunnel systems can actually be more complex than the typical fire alarm control panel (FACP) functions. The FACP is used to initiate the various fire life safety systems in a building as mentioned. Since an FACP could not be expected to automatically perform flawlessly in every possible situation that might occur in a tunnel given the movement of vehicles in the tunnel, there is clearly the need for a trained tunnel operator, however, the use of computerized systems such as SCADA, can provide a method to manage the complexity of systems found in tunnels.

In practice the multitude of tasks has been further streamlined into a set of ‘fire scenarios’ which group very similar fire situations into a type of automatic system response, with the primary variables being the fire location and occupant actions. As previously mentioned, the ‘all hazard approach’ has expanded the computer software controlled response to include weapons of mass destruction, loss of traction power, etc.

The use of SCADA type systems appear to provide an excellent method to manage the various systems, however, single decisions made by the design team, can lead to challenges such as the following

**Case Study 2) SCADA programmed incorrectly** A new light rail system utilized latest technological advances to ensure a high quality, safe, efficient operation though integration of the various systems. This required considerable effort by the owner, consultants, emergency responders, fire code officials in lengthy pre design and final design discussion. The control screens used a Windows based interface.

One of the design decisions for emergency response was for the tunnel operator to verify the correct fire scenario had been selected by the SCADA system. This was performed under the PAS approach which allowed the operator a short time to acknowledge the alarm, and then three minutes to
determine the validity of the alarm and to either launch the fire scenario, pick an alternate scenario, or abort the scenario that was pending.

The SCADA control system was designed to prevent changing the fire scenario once launched for two minutes. This was done in part as reversing the 14 large emergency fans operating at 118 cu m/sec (250,000 cfm) each, could further jeopardize the occupants who may have moved to a ‘safe’ position based upon early smoke movement.

However, during commissioning it was realized that although the protocols called for scenario verification, it was still possible for two, very simple human errors, to start the incorrect scenario with no possibility of correcting the error for two minutes. This could have dramatic consequences since the ventilation system flow direction, and the sprinkler zone selection could be wrong. If this error occurred, the fire could grow unabated, and the smoke might be pushed over the occupants moving towards the exit.

Special training was performed immediately while a software upgrade was developed. The ‘two minute lock out’ was therefore resolved without incident.

Use of software to integrate the fire scenario components into a cohesive response makes a great deal of sense; however, this poses an additional level of complexity when commissioning and re commissioning tunnel safety systems.

For building systems, the various individual fire detection, notification, etc. devices are individually tested and verified that they are correctly ‘addressed’ in the software. The most complicated building complexes generally evacuate everyone within the fire buildings which means most of the devices will be used for every fire.

In a complex, multi-tube set of tunnels not every device will be activated for every fire alarm since the risk may be limited to the tunnel where the fire started. The chance of a tunnel fire spreading long distances into adjacent tunnels is remote, but possible. Therefore there is no need to activate every device.

A more complicated commissioning process was used to verify that individual devices are correctly identified, as well as only the appropriate devices needed for that fire scenario. Therefore all devices are tested as part of commissioning rather than a representative sample.

The practice of testing every device worked well in the following situation.

**Case Study 3) Commissioning of all devices**  While commissioning a replacement sprinkler system in a set of bus tunnels, each sprinkler zone was being tested for each component. This included activation of the linear heat detector for each sprinkler zone, and verifying that the correct deluge valve opened and the sprinkler water application pattern was correct for that zone. Each sprinkler zone is 45 meter (150 feet) long.

At the conclusion of each of zone test, the applicable valves were reset as needed, testing staff were relocated to the new zone, other staff were notified of the next zone to be activated and necessary documentation was prepared.

The next zone test happened to be in the adjoining tunnel, however, when the linear detector in the correct zone was activated and the alarm signal sent, the sprinkler zone in the previous test area activated in addition to the correct zone. This was clearly an incorrect response of the system.
While testing in other zones was proceeding, sprinkler installation staff diagnosed that a piece of the new deluge valve in the failed zone had broken off, jamming the valve in the open position. The valve was replaced with a spare, and the commission process cycled back to this zone a short time later.

If the AHJ had not required the commissioning process to physically activate each valve as part of the test, the faulty valve might not have been testing before it was needed to suppress a fire. It is essential that the components are all tested in as close to a real situation as possible.

New risks and resultant technology also pose challenges as follows.

**Case Study 4) Terrorism detection** Not only is detailed commissioning needed, but review of the basis of design at the time of commissioning is also important. In the light rail start up, it was realized the terrorism threat using an airborne vector was more likely than previously expected, however there was no specific response by the fire and life safety systems designed for this threat.

The 2100 meter (1.3 mile) Downtown Seattle Transit Tunnel (DSTT) has three underground stations and two ‘depressed cut’ stations serving both bus and light rail. The fire scenarios were well developed for bus fires which used linear heat detectors in tubes and standard building fire detection systems in the underground stations.

A relatively new airborne WMD detection system was installed in the DSTT which detects a wide range of toxins which, if when detected above a minimum threshold, a signal is sent directly to the control center.

However, this added system was not in the final build out or subsequent upgrades as part of the SCADA system, therefore receiving the alarm in the control center is done on a laptop, while launching of an emergency system response in this tunnel had to be done manually. This response is comprised of three sections, 1) evacuate the tunnel of occupants which includes stopping trains and buses from entering, 2) stop ventilation systems to prevent unwanted spread of the airborne to other areas both in and outside the tunnel and 3) notify the emergency responders, the owner and operating agencies of the incident to mobilize their command and emergency response. This is remarkably similar to a fire scenario and it was decided to modify the software to run a ‘hazardous material release’ scenario via a new button on the controller screen. Pushing the button automatically stopped ventilation and evacuated the tunnel rather than remotely stopping 25 plus fans.

The challenge was to integrate a wide range of disciplines, including ‘fire alarm’ systems which would take considerable software upgrades. The lesson learned was to anticipate the future need for this type of response and install necessary wiring to accommodate adding new system(s), as well as preprogramming a hazardous material response based upon standard response information and emergency responder capabilities.

Subsequent to this the emergency responders clarified the ability for remote activation of a sprinkler zone adjacent to the platform if needed. This allowed use of the existing sprinkler system to perform gross decontamination of any occupants who might be contaminated.

Emergency Responders are often touted as being the ‘answer’ to any problem that may occur in the tunnels, however, designers and tunnel operators should recognize that allowing a fire to grow to a large size may make it impossible for fire fighters to successfully suppress the fire since the radiant heat will make the tunnel untenable for firefighters. Keeping smoke from spreading through a train is another problem which was dramatically pointed out in the Seattle Monorail Fire of 2004.
Case Study 5) Smoke Separation. The 1600 meter (1 mile) long Seattle Monorail runs an elevated Guideway roughly 12-18 meter (40-60) feet above the city streets and through a ‘tunnel’ in one building, the Experience Music Project. The monorail traction power (700vDC) system grounded to the vehicle as a result of a broken drive shaft. This ignited some combustible lubricating grease and miscellaneous ‘under car’ combustibles not prohibited in the 1962 design.

The monorail train has a three car consist and the smoke spread to the passenger cabin of the middle car from below the vehicle. Unfortunately the monorail operating agency had removed intervening car doors between the three vehicles. The lack of doors allowed the smoke to spread throughout the three cars and seriously compromised life safety. Even with the doors open the smoke filled the cars and people were seriously considering jumping from the car since no emergency walkway was provided in the 1962 design.

The emergency responders used aerial and ground ladders to begin evacuation and access the under car fire which was quickly extinguished. The rescue train was delayed as the emergency ramps needed to transfer people from one train to another had also been removed in a previous retrofit.

Operating walk through trains with cars fully open to each other will allow smoke to spread from the fire car to other cars significantly compounding the problem. However, if the monorail doors had been left in place per the design, the occupants could have moved to the non fire car and simply closed the door, thereby providing a physical smoke/fire barrier between the cars. Nine riders were treated at hospitals for smoke inhalation. No fatalities occurred in this instance.

As described, remodeling, retrofitting or expanding the approved use of a tunnels can present new challenges. When a bus tunnel, built to a previous standard, was retrofit to allow both bus and train use of the tunnel and underground stations, conflicts arose.

Case Study 6) Audibility vs Fan start up time. On occasion, codes/standards unintentionally conflict such as the case with NFPA 130 for fan start up time, and NFPA 72 audibility db level.

The large emergency fans are to be fully operational in 30 seconds but are unfortunately placed at the ends of each platform. The fan noise at the platform was high, roughly 110 db which, when added to the requirement for speaker volume to announce evacuation at 15 db was above the pain threshold.

Since the fan and audibility had conflicting requirements a compromise was reached of reconfiguring fans to lower the noise, increasing proximity of speakers to the platform and slightly delaying the fans start to allow two rounds of emergency announcements before the fans reached full speed and volume.

Potentially more of a problem was a simple error on the part of a subcontractor.

Case Study 7) Emergency Trip Switches (ETS) were required on the exterior of the traction power sub stations (TPSS) in lieu of the ‘blue light stations’ for the overhead catenary system. This was a jointly agreed to in pre and final design to allow emergency responders special key access to deenergize the catenary system if needed, while the control center maintained remote traction power disconnect ability. Although the plans called for the installation of the ETS, the contractor installed the switches inside the TPSS making them inaccessible to emergency responders. This apparent simple oversight resulted in delays for opening the new system. This also points out how important having direct inspection of the final product (field inspection) for compliance with plans, before...
allowing subcontractors to leave the project. In this case a follow on sub contractor was needed to complete the work by installing ETS as specified.

Possibly more important than this problem was the ongoing issues of software upgrades, as follows.

**Case Study 8) Delayed Status Display.** Many emergency control center rely on visual screens to display status of emergency systems and vehicles. The seven screens used in this light rail project provide real time information at the control center and backup center regarding the location and status of an alarm, location of vehicles, and affirm correct posturing of ventilation and fixed suppression systems.

During initial commission the screens simultaneously displayed the same information, however, after the software upgrade, a set of re commissioning tests were conducted to verify functionality was not lost. In these tests, it was noted that the display screens presented different status of different times for the same event. Essentially there was a sequential delay between each of the screen workstation. Each of the seven screens was roughly 20 seconds slower than the previous screen which were connected in series. This delay meant the last control screen was displaying the status of a fire, ventilation systems, evacuation information, two minutes after the fact. A software upgrade had created the delay which was resolved quickly by reverting to the old software until corrections were made.

This problem led to the following software:

**Case Study 9) Controlling Software Changes.** Recognizing changes can create additional challenges. The light rail system was carefully and expertly designed to integrate the fire and life safety systems, traction power control, train control and bus signal systems. This allowed verified fires to rapidly perform necessary steps without the need for slower human actions. However, upgrades to the software after commissioning required retesting of the fire and life safety systems to ensure these systems were not inadvertently compromised by the upgrades.

This was subsequently resolved by isolating the fire and life safety systems for which testing would disrupt normal operations, specifically the emergency fans. This allowed retesting of most systems as changes occurred during normal operations and eliminated closure of the tunnel for retests.

Software problems should be a major concern on the part of the AHJ/Owner. Splitting of system contracts among multiple contractors and equipment vendors would cause operational problems due to lack of consistency in systems configurations, equipment incompatibility, lack of cross-listing between the various manufacturers’ equipment, etc.

Since SCADA systems monitor and control multiple systems that often utilize different software and communications protocols and may be installed and serviced by different contractors, it is critical that a written management plan for long-term testing and maintenance be implemented. This ensures the data structure between the FACP and other systems such as PLC based controls remain compatible.

**CONCLUSION**

Clearly the use of fire and life safety systems contributes to the safer use of tunnels, and can prevent major economic impact created by long term tunnel closures, tunnel damage and litigation. However, it is obvious that great care needs to be taken in the design, installation, commissioning and periodic testing of these systems. Without an in depth understanding of their design intent and how the
proposed systems meet the basis of design as well as how they integrate with each other, problems can arise that negate the advantages and inadvertently put people at unexpected risk.

It is essential that the pre design, final design, specification and plan development be a joint effort between the various parties. At a minimum this should include the Owner, Operators, Emergency Responders, Fire Protection Engineer(s) and the agency that enforces the requirements for fire and life safety systems, i.e. the AHJ.

This cooperative effort will result in a robust, cost effective and SAFER tunnel where the fire and life safety systems that are selected, perform as expected.

REFERENCES:


KEYWORDS: Safety System, Sprinkler, Integration
Protective Design Guideline of Tunnels

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ABSTRACT

The security of tunnels against potential detonated explosions from within and outside the tunnel structure is a main challenge facing to owners and operators of tunnel systems, particularly those used for vehicle or rail traffic. This paper introduces a design practice recently developed for protecting underground structures from explosion. The protective design of tunnels consists of identification of the potential threats to the underground facility, evaluation of its vulnerability and risk level, analyzing the impact of internal and external threats on its assets and providing internal and/or external structural hardening measures, and finally cost-benefit analysis. Author has published a tunnel security design guideline in 2006 (Choi & Munfakh, 2006). Since the guideline has developed, author have found the guideline to be very practical and useful and the guideline has been implemented in many tunnel security design practice in U.S.A. As the blast protective design was being performed, however, up to date approach and methodology have been added. This current paper is an update of the previous design guideline published in 2006. The new proposed guideline is intended to clearly explain how to assess the risk and vulnerability, how to analyze the blast impact on the structures including post-blast failure identification, and to introduce the latest developed tunnel structure hardening measures.

KEYWORDS: protective design, risk assessment, blast analysis, coupled Euler-Lagrange analysis, post blast analysis, progressive failure of tunnel, tunnel blast protection measures

INTRODUCTION

Terrorism remains a constant, serious threat to the public transportation. A key area of concern that could threaten our national economy is an explosion that cripples one of our nation’s major tunnel thoroughfares. This has the potential to cause a substantial loss of life, a major disruption in our national economy, and a significant change in our confidence to use public transportation. Protective design of tunnels, especially passenger tunnels, becomes an important element of nation security due to their vital roles in modern transportation system.

Author has published a tunnel security design guideline in 2006 (Choi & Munfakh, 2006). Since that time the authors have found the method to be very practical and useful and the guideline has been implemented in many tunnel security design practice. As the blast protective design was being performed, however, up to date approach and methodology have been added into the guideline. This current paper is an update of the previous design guideline published in 2006. The new proposed guideline is intended to clearly explain how to assess the risk and vulnerability, how to analyze the blast impact on the structures including progressive failure potential identification, and to present the latest developed tunnel blast protection measures.

Figure 1 presents a proposed protective design steps. The new protective design of tunnels consists of four elements: (1) threat, vulnerability and asset criticality evaluation through a risk assessment, (2) blast analysis and post-blast stability analysis including evaluation of progressive failure potential, (3) development of tunnel blast protection measures and system countermeasures, and finally (4) cost – benefit analysis. The guideline proposed in this paper relies on credible information gathering and the use of proven methods that have been successfully applied to and accepted in the tunnel design.
practice in USA.

**Figure 1 Protective design steps for tunnel security (Choi, 2009)**

**THREAT AND VULNERABILITY/RISK ASSESSMENT**

The proposed threat and vulnerability risk assessment includes four stages: (1) identification of project assets and threats, (2) development of threat-asset matrix, (3) risk assessment, and (4) set priority. The purpose of the threat and vulnerability/risk assessment is (1) to provide safety and security guidelines to identify principal vulnerabilities of assets to various hazards and threats and (2) to provide input data to be employed for the subsequent blast analysis, expressed in terms of threat locations, design basis threats (charge weights), and tolerable tunnel damage level.

**Threat and Asset Identification**

The threat profiles for the given tunnel should be compelled enough to include the requirement to elevate the security program to include special counter terrorism design measures. This is in addition to design provisions for conventional security responses for traditional crimes against persons and property, which require routine response and security management. Project site development characteristics and threat assessment considerations that affect the project profiles are then, summarized. These characteristics are inherent in the project as a result of its critical transportation function, location, occupancy, and connection to adjacent transportation systems. Five major categories of the intentional threats to tunnel structures are vehicle bomb threat, waterborne threat, fire threat, cyber threat, and sabotage of mechanical, electrical and communication system.

**Development of Threat – Asset Matrix**

The threat-asset matrix identifies each asset and the corresponding general threat scenario that was evaluated and scored. This is accomplished by individually evaluating each asset on the basis of its location within the project, program of use, adjacent structures, occupancies, and activities. A typical threat – asset matrix is presented in Table 1. The matrix provides a comprehensive and compact means of conveying which assets are subject to compromise from which threats. The intent of this matrix is to identify, on an asset-by-asset basis, the particular threats to each asset. The matrix supports subsequent decision making regarding the vulnerability of an asset to a particular threat.

**Risk Assessment**

The next step is to quantify the risk to the various assets as a function of three factors including Criticality, Vulnerability, and Consequences. This approach follows the same basic approach as that used in conventional risk assessment and analysis.
Table 1 Threat – Asset Matrix

<table>
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<tbody>
<tr>
<td>Bored Tunnel</td>
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<td>x</td>
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<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Immersed Tube</td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
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<td>x</td>
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</tr>
<tr>
<td>Cut and Cover Section</td>
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<td></td>
<td>x</td>
<td>x</td>
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<td></td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Emergency Exit Shaft</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Cross Passageways</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Portals</td>
<td></td>
<td></td>
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<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
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<td>x</td>
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<tr>
<td>Stations</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Control Center</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Criticality
Criticality is a measure of the importance of the asset. Criticality identifies which assets within the tunnel system are relatively more important to protect from attack. A sample criticality scoring chart is presented in Table 2.

Table 2 Criticality scoring chart

<table>
<thead>
<tr>
<th>Category</th>
<th>Score</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed Population</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Emergency Response</td>
<td>Minor</td>
<td>Significant</td>
<td>Critical</td>
<td></td>
</tr>
<tr>
<td>Protection of Collateral Structures</td>
<td>Minor</td>
<td>Significant</td>
<td>Critical</td>
<td></td>
</tr>
<tr>
<td>Tunnel Operation Impact</td>
<td>Minor</td>
<td>Significant</td>
<td>Critical</td>
<td></td>
</tr>
<tr>
<td>Public Image</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Replacement Cost</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

Vulnerability
Vulnerability is a measure of how likely the asset is to be attacked successfully by a given threat. Vulnerability identifies which threats to which assets are relatively more likely to occur. A sample vulnerability scoring chart is presented in Table 3.

Table 3 Vulnerability scoring chart

<table>
<thead>
<tr>
<th>Category</th>
<th>Score</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of Access</td>
<td>Inaccessible</td>
<td>Moderately restricted</td>
<td>Wide open access</td>
<td></td>
</tr>
<tr>
<td>Level of Security Personnel</td>
<td>Controlled and protected with response force</td>
<td>Controlled and protected with no response force</td>
<td>Unprotected/ uncontrolled</td>
<td></td>
</tr>
<tr>
<td>Level of Publicity</td>
<td>Regional</td>
<td>Statewide</td>
<td>National</td>
<td></td>
</tr>
</tbody>
</table>
Consequences

Consequences are a measure of the effects if the given threat is successfully carried out against the asset. Consequences identify which threats at which assets are relatively more detrimental. A sample scoring chart for consequences is presented in Table 4.

<table>
<thead>
<tr>
<th>Category</th>
<th>Score</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatalities</td>
<td></td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Repair Cost</td>
<td></td>
<td>Minor</td>
<td>Moderate</td>
<td>Critical</td>
</tr>
<tr>
<td>Downtime</td>
<td></td>
<td>Minor</td>
<td>Moderate</td>
<td>Critical</td>
</tr>
</tbody>
</table>

Risk Calculations

For each asset-threat combination, the single measure of criticality, vulnerability and consequences is taken as the straight average of the attribute scores. Then, the risk can be calculated for the each asset-threat combination as follow:

\[ Risk = C_r \times V \times C_o \] (1)

where \( C_r \) is criticality, \( V \) is vulnerability, and \( C_o \) is consequences.

Prioritization

The results of the Risk calculation described in this section provided a comprehensive, systematic, and rational basis for thoroughly evaluating the risks associated with assets and deciding the most effective means for mitigating these risks. The results provide the road-map for developing mitigation strategy alternatives by threat scenario and asset. The risk score enables to prioritize the strengthening of assets and further blast protective design and construction.

BLAST AND POST BLAST ANALYSIS

Prediction of material damage under a dynamic loading is a complex function of several factors such as loading magnitude, loading rate and loading duration. If the material experiences the same magnitude of loading at a different loading rate, the response will be different. The current paper introduces a blast analysis method, which fully incorporates dynamic properties of materials as well as strain rate effects, so that a dynamic structural response could be predicted reliably when the structure was subjected to a blast loading.

Blast Analysis

The distinct behavior of an explosion in a tunnel was investigated by authors (Choi et al., 2003; Choi et al., 2006, Choi & Munfakh, 2006, Choi, 2009, Choi et al, 2010). The papers introduced a three dimensional coupled Euler-Lagrange nonlinear dynamic analysis for modeling tunnel explosion. Authors proposed conceptual evaluation charts for conceptual and practical explosion impact assessment, expressed in terms of effective strain of the concrete liner for various types of surrounding grounds, charge weights, standoff distances, and sizes of the tunnel (Choi et al., 2006). This approach provides a conceptual evaluation of the blast loading on a tunnel structure.

For the precise and reliable evaluation, engineers need to conduct blast analysis for the given tunnel structures. Proper assessment of the impact of explosions on the underground facilities requires
sophisticated analytical simulations and the application of numerical analyses that take into account several factors representing the explosion, the structure, and the ground and water. The following sections introduce three-dimensional blast analyses for various types of tunnel structures.

**Bored/Mined Tunnels**

In cases where a tunnel is located in significant depth or overlying structures exist above the tunnel alignment, bored or mined underground tunnel construction is typically the preferred. The bored tunnel structures are usually composed of concrete. Even though the ballast fill concrete and concrete walk benches provide some cushion against an interior blast, due to the brittle nature of concrete materials, the bored tunnel is likely to be very vulnerable to an interior blast as well as an external blast set from the shipping channel bed. When the tunnels are underneath the water body, cracking or failure of the concrete liner may allow inundation with water and resulting in high flooding potential in the transportation system if the tunnel is connected to underground transportation network. When the ground stability is not preserved, a failure of tunnel liner would impact adjacent surface and underground structures. Sample 3D blast analyses on the bored tunnels are presented in Figure 2.

![Figure 2 Three-dimensional blast analysis on bored tunnels](image)

When segmented precast concrete lining is used, the behavior of the lining is also of concern. Three dimensional blast analysis enables to model behavior of bolted segment to investigate the performance of the segments when they are subjected to internal blast loads and to recommend a proper dimension and number of bolts to be used. (Figure 3)

![Figure 3 Three-dimensional blast analysis on bolted Precast segment lining](image)
Cut-and-cover Tunnels
Shallow depth tunnels in land are frequently designed using the cut-and-cover method. This tunneling method involves braced, trench-type excavation and placement of fill materials over the finished structure. The excavation is typically rectangular in cross section in relatively shallow depth. It is likely that the cut-and-cover sections of the tunnels will be extremely vulnerable to an interior blast due to less confinement from surrounding ground. However, it is probable that the cut-and-cover sections will be less vulnerable to a surface blast due to the open-air nature of the blast and soil cover over the tunnel. For U-tunnel section, where the tunnel structure is open and not covered, the vulnerability will be extremely high due to relatively easy delivery method of explosives. (Figure 4)

![Figure 4 Three-dimensional blast analysis on cut-and-cover tunnels](image)

Immersed Tube
Immersed tube tunnels are employed to traverse a body of water. The tunnel construction method involves (1) construction of tunnel sections in an offsite casting or fabrication facility that are finished with bulkheads and transported to the tunnel site; (2) placement of the sections in a pre-excavated trench, jointing and connecting together and ballasting/anchoring; and (3) removal of temporary bulkheads and backfilling the excavation. The top of the tunnel should be at least 5 feet below the original bottom to allow for an adequate protective backfill. The typical immersed tubes consist of concrete liner, steel shell and concrete tube. The concrete liner and concrete tubes are load bearing elements, while the steel shell is usually not considered to be a load bearing element but rather acts as a water-proofing membrane. The joints between segments may be the most vulnerable if it is not covered with tremie concrete. Local breach of the main tunnel structures would induce complete inundation with water and cause flooding in the underground transportation system. Flooding may also introduce large quantities of sand, silt, gravel or shear zone debris. Significant lengths of tunnel can become filled with debris or backfill in a short period of time. For this reason, the immersed tube structures are considered to be the most vulnerable elements.

![Figure 5 Three-dimensional blast analysis on immersed tubes](image)

Underground Stations
The underground stations are constructed by either cut-and-cover method or bored/mined. Considering high level of access, exposed population and consequences, the station structures are likely to be very vulnerable to an interior blast. For the underground stations, hand-carried satchel bombs and suitcase bombs are the predominant mode of explosive attack, while subway storage yards, service facilities, and the shipping channels above the tunnels allow for the potential delivery of much
larger explosive/incendiary materials.

**Ventilation Shafts**
Ventilation shafts are typically reinforced concrete shafts extended from the land surface. At the interface of the shafts and the bored tunnel, they may be more vulnerable to damage because high stress concentrations may occur at these junctions. However, due to access restrictions, only a small amount of explosive is likely to be brought into the shafts, therefore an interior threat within the emergency exit shafts is not considered critical. A more critical threat would be one introduced to the external detonation that large amount of explosives are carried by vehicle.

**Cross Passageways**
The cross passageways may be vulnerable to damage because high stress concentrations may occur at the junctions with main tunnels and given the same amount of explosive charge, the resulting blast peak pressure in a cross passageway tunnel may be greater than that in the main tunnel due to its smaller cross-sectional geometry. However, from an operational standpoint, the cross passageways are not considered to be more critical than the main tunnel elements because of their greater degree of redundancy due to a number of cross passageways. Furthermore, local failure or collapse of one or more of the cross passageway tunnels may not necessarily affect the stability of the main tunnels or prevent their continuous use if the water inflow is controlled.

**Portal**
From a stability standpoint, the tunnel portal area is generally one of the critical locations due to the inherent slope stability problem and/or retaining structure failure. Tunnel portals are therefore considered to be particularly vulnerable during extreme events. Nevertheless, the consequences of a portal failure are generally considered to be less severe than those of main tunnel element failures because the repair can be done in an open space. The flooding is not an issue when a portal is damaged or collapses, so the repair time and associated costs are relatively low compared to the other parts of the tunnel. Furthermore, at the portal, the blast is less confined and the energy dissipates away rapidly than it will in the confined tunnel environment.

**Post Blast Analysis: Progressive Collapse and Flood Potential**
In addition to the evaluation of damage extents caused by the blast-induced loading, post-blast behavior should be analyzed to evaluate progressive type failure/collapse where continued failure may occur due to the structural weakening, load redistribution, excessive displacements, water inflow or running ground into the tunnel.

Progressive collapse of underground structures is of great concern, even if the underground structural elements are not completely damaged during the blast. They may be weakened or softened, at which point the normal loading imparted during operations would cause further damage or failure to the structures. The progressive failure analyses consider the structure in operation, subsequent to the blast loading. The post blast progressive collapse analysis is performed in such a way, where the damaged area(s) are removed and by applying load combinations to the structures. Figure 6 presents post blast progressive collapse analysis for a tunnel and complex underground structure. The segmental lined tunnel is loaded by surrounding ground and water pressure. The complex underground station is assumed to be fully loaded with trains on each track level, with the mezzanine level and platforms assumed to be fully occupied with the full live load and dead load expected.

The stability of the ground is also of concern with the breach failure of the liner when the stability of surrounding ground is not preserved. For a soft ground tunnels under the water, ground failure and subsequent flowing condition into the tunnel associated with the breached concrete liner failure is a more likely scenario. This ground failure and/or flowing condition may result in large water inflow because of the high water pressure and infinite water supply.
Damage Level

The damage levels for each blast analysis are assigned after evaluating the damaged area, determining the remedial construction activities that would be required to return the tunnel to its normal operating condition. Consequences including flooding potential, ground stability, and progressive failure or collapse are also considered in the designation of damage level.

The Transportation Research Board (TRB) publication, “Making Transportation Tunnels Safe and Secure” (TRB, 2006) proposed a level of damage and disruptive impact rating system for transportation tunnels. The damage levels are divided into six levels including severely catastrophic, catastrophic, critical, serious, marginal, and negligible.

In the protective design or strengthening of tunnel structures, it is reasonable to accept a moderate level of damage to the tunnel elements such that disruptions to operations would be limited to a short period of time. Such a level of damage acceptance may result in greater affordability of the tunnel construction cost.

BLAST PROTECTION MEASURES

During a blast loading, the structures make an attempt to balance the kinetic energy from the blast with the strain energy of the structural members. If the kinetic energy from the blast is greater than the total strain energy of a structural member, the structural member will be breached. The total strain energy is a function of the area under the stress-strain curve of a material used to make up that structural member. Thus, ductile materials can absorb more blast energy. Various products have been proposed in the market for blast protection of the structures. The most common products used in the practice are introduced here.

Steel Plates
Structural steel typically displays a linear stress-strain behavior up to the yield point, followed by a plastic deformation. Beyond the yield plateau, additional elongation is associated with an increase in stress (i.e., stress hardening) before reaching rupture. The strain at rupture for a typical structural steel is approximately 20 to 30 percent of its original length. This sizeable plastic deformation before rupturing makes steel favorable for blast protection design. In addition, because the blast loading takes place in a fraction of a second, the strain rate is much different than static loading. The strength of a steel plate with thickness less than 60 millimeter (2.5 inch) may increase up to 30 percent while the technical manual TM5-1300 recommends using a 10 percent increase in the strength of structural steel in blast design.

SPS (Sandwich Plate System)
Intelligent Engineering (IE) has developed and patented the Sandwich Plate System (SPS), in which two steel plates are bonded to form a sandwich with a compact polyurethane elastomer core. The elastomer provides continuous support to the steel plates and precludes local plate buckling and the
need for stiffeners. The flexural stiffness and strength of the sandwich plate is tailored to meet particular load requirements by selecting appropriate thicknesses for the sandwich elements. SPS consists of SPS plates that are fastened at the perimeter to supporting steel framing. The connection of the SPS plates to the supporting framing may be made through collapsible steel members to increase the plastic deformation and energy absorption.

Ductile Micro-Meshed Reinforced Concrete

High strength ductile concrete represents the combination of a high-performance concrete and a microreinforcement from microfine wire meshes. The wire meshes are made of steel, stainless steel or carbon steel. The micro-reinforcement is uniformly distributed all over the cross section which results in a homogenous composition of the composite material. It consists of multiple layers of meshes with variable mesh width (between 6 mm and 35 mm) which are 3-dimensionally connected. The strength of these materials are up to 200 N/mm² and ductility ratio is sometimes greater than 10. Production is based on the placement of the prefabricated micro-reinforcement and the infiltration of the concrete slurry. Between 1 and 10 volumetric percent of microreinforcement are embedded, typically, 6 volumetric percent. Commercially available brands are DUCON, DUCTAL and CORTUS.

Fiber reinforced polymers (FRPs)

Fiber reinforced polymers (FRPs) are composite materials made up of two main constituents: carbon fibers as reinforcing agent and a polymer matrix (e.g., epoxy) which holds the fibers together. FRPs have been used in structural retrofit applications in the areas prone to earthquakes. Recently, they have been tested and used in blast protection applications. The fibers in a sheet of FRP come in the form of woven or stitched fabric that is saturated on premise and bonded to a substrate using a specially formulated structural epoxy. The fibers can be oriented to enhance unidirectional or multidirectional mechanical properties. The fibers can be made of carbon, glass, or Kevlar. Light weight (approximately 1/5th of steel), high strength (at least twice as strong as steel), high stiffness, and ease in installation, made FRPs highly favorable for retrofit applications. Different manufacturers focusing on various applications of FRP (including soil reinforcement, blast mitigation, earthquake resistance, corrosion resistance) typically have proprietary design mix for polymer matrix and fibers. The fibers typically have very high strengths and polymer matrix adds ductility to the composite material. Although CFRP has almost 5 times higher strength than mild steel, its elongation is around 1.5 percent.

Polyurea

Polyurea is a type of elastomer (i.e., elastic polymer) derived from the reaction product of an isocyanate component and a synthetic resin blend component through step-growth polymerization. The isocyanate can be aromatic (ring structure) or aliphatic in nature. The resin blend is made up of amine-terminated polymer resins and may also contain additives. Polyurea is characterized by high elongation (elongation at rupture ~ 90 percent vs. 1.5 percent for CFRP), high tear strength (13.8 MPa or 2,000 psi). The resilience and large strain capacity of elastomers enable them to absorb blast energy and reversibly stretch within a significant range of deformation. Curing time ranges from minutes to hours, depending on the mix design. Polyurea is composed of 100 percent solids; so, no volatile organic compounds are present typically. Polyurea is much less sensitive to moisture than epoxy type polymers and can be sprayed on a surface using a multi-component spray gun. Different manufacturers have proprietary design mix for polyurea to enhance different physical properties. Aliphatic polyurea is UV resistant.

BlastWrap®

BlastWrap® made up of pockets filled with lightweight granular material. The pockets are approximately 6.45 cm² (= 3 inch²) and 2.54 cm (= 1 inch) wide. Pockets are filled with white granular material composed of perlite (i.e., a volcanic glass commonly used as loose-fill insulation in masonry construction), water, and salts. The granular material has a density of 0.09 g/cm³ (4.95 lb/ft³), as indicated on the manufacturer’s website (BlastGard®, 2008). Although not much literature is available on the product, the manufacturer claims that these low-density grains are frangible and designed to reduce blast pressure and impulse by irreversible processes, including drag, turbulence,
friction, viscosity, etc. The explosive shock wave ruptures the plastic packaging and breaks down the perlite mixture, filling the blast area with perlite dust and droplets of water released from the pulverized salts. The thickness of the product approximately 2.54 cm (1 inch) and multiple layers can be used for increased protection.

Security Countermeasures
The security countermeasures should be implemented in combination with the tunnel blast protection measures. Choi & Munfakh (2006) proposed three categories of system countermeasures such as (1) basic measures of safety and security, (2) measures deployed for an elevated threat (hazard) level in response to a specific threat condition, and (3) permanent enhancements to the tunnel structure or systems. Details of system countermeasures are discussed Authors’ previous paper (Choi & Munfakh, 2006).

COST BENEFIT ANALYSIS
The result of this cost benefit analysis is a ranked list that identifies the benefit of enacting each mitigation measures. The costs (in terms of capital expenditure, operation and maintenance, and disruption) are developed in a parallel effort and used with these results in an explicit cost-benefit analysis to identify the final list of mitigation measure to apply.

CONCLUSIONS
Tunnel safety and security require the systematic application of engineering, technology, and management tools to identify, analyze, and control hazards and vulnerabilities within operational, budget, and time constraints. This security can be enhanced through a comprehensive process ranging from vulnerability assessment to implementation of remedial measures. They encompass all of the integral factors that comprise a tunnel, including people, operating procedures, systems and controls, and the physical aspects of the tunnel components.

REFERENCES
Design Loads and Methods for Prestressed Open Cut Tunnels under Severe Accidental and Malicious Threats - Explosions

Assad Nawabi\textsuperscript{1,4}, Andreas Bach\textsuperscript{1,4}, Ingo Müllers\textsuperscript{1,4}, Alexander Stolz\textsuperscript{3,4}, Markus Nöldgen\textsuperscript{2}

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\textsuperscript{3}Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, Efringen-Kirchen, Germany
\textsuperscript{4}BRS-Design, www.brs-design.com

E-mail: abach@schuessler-plan.de

ABSTRACT

Failure of critical infrastructure, such as tunnels, causes severe economical and sociological loss. This aspect needs especially be investigated for explosions in tunnels which may cause disproportionate damage to a structure. Therefore the resistance of two representative prestressed open cut tunnels against three explosive scenarios has been investigated using 3D nonlinear finite element analysis. It could be shown that during to the dynamic excitation lifting and rebound of the slab occurs, in reason of the permanent loads acting on the structure. During the rebound the elastic limit of the structure is exceeded, leading to plastic deformation and plastic stresses in the reinforcement. However due to the robustness of the structure, only local damage is identified. This may be critical for tunnels exposed to groundwater where flooding needs to be avoided.

KEYWORDS: prestressed open cut tunnels, large spans, explosions, nonlinear dynamic analysis

INTRODUCTION

Tunnels are key elements in modern traffic networks often crossing rivers and city regions with a high traffic density and important, highly frequented buildings and infrastructures in close distance. Against this background economical and societal consequences of large scale accidents and malicious threats such as explosions are potentially very high. Furthermore a comparatively small damage to the structure might lead to a disproportionate effect for the tunnel such as a partial collapse evoking spontaneous flooding and/or progression of damage in the tunnel which may induce damage to structures on top of the tunnel as well.

With increasing traffic in transit regions the need for motorways with an extended transport capability over their life cycle duration is of high importance. Hence, tunnels width became significantly larger than they were in the past decades with up to six lanes per direction. The resulting spans of more than 25 m either need to be partitioned in several tubes which is rarely compatible with undisturbed traffic requirements or they need additional structural prestressing to strengthen the tunnel top slab. Furthermore the prestressing leads to an economic design with a reasonable reinforcement ratio and significantly reduced deformations. However, prestressed tunnel types show significant differences in constructional design and structural behavior which has to be considered for standard and severe fires and explosions.

The presented paper is dedicated to severe explosion in large span prestressed tunnel structures. Based on fully dynamic and nonlinear numerical simulations the structural collapse resistances of two different prestressed open cut tunnels were simulated for three different explosive scenarios.
STRUCTURE

A scheme of the analysed tunnel section is shown in figure 1. Due to the high width of the tunnel of 25 m, prestressing of the slab is necessary for an efficient and economic design. For the reduction of constraints, concrete hinges have been implemented at the outer corners of the tunnel.

Figure 1 system of tunnel section and characteristic crosssections A-G

The design of the section was made using 2D finite element analysis, which represents the state of practise for tunnel segments being uniform in longitudinal direction. A more comprehensive 3D finite element model of the tunnel segment with a length of 25 m has been used for the fully non-linear dynamic analysis. This allows for the redistribution of stresses in the section from regions with high loading to regions with lower loading along the length of the tunnel by the formation of yield patterns. This is essential for the modelling of the explosion process within the tunnel as the load varies severe along the length of the tunnel (see EXPLOSION IN TUNNEL). 2D analysis would be inadequate as the full plastic capacity of the section would not be utilized, the resistance would be calculated due to beam theory instead of shell theory, leading to over simplified results which may be too conservative within the inelastic regime of loading.

Figure 2 Finite Element models for the simulations : Left: Beam-model used for the design, Right: Shell-Modell for 3d non-linear Analysis

Loading for Tunnel Design

For the design of the tunnel considered loading cases are represented in figure 3. These have been chosen in accordance with DIN-Fachbericht [3] and are listed in table 1. The tunnel is covered with a soil layer ($g_e$ in figure 3) the height of the layer has been modified between 1 m and 2 m. Hence, two
structural models with different amounts of prestress and reinforcement have been designed and evaluated against explosive scenarios.

Figure 3  Load cases for the design of the tunnel, dead load (left) and live load (right).

<table>
<thead>
<tr>
<th>Type</th>
<th>dead load</th>
<th>live load</th>
<th>prestress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( g_E )</td>
<td>( g_{E,1} )</td>
<td>( g_{E,r} )</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 1  Characteristic loads and prestress (including a reduction of 20% due to creep and shrinkage of the concrete) of the two tunnel types.

The prestressing of the tunnel slab has been chosen in accordance to the necessary checks of the [4]. Hereby the load of the tendon has been changed until the decompression check was satisfied. The configuration of the tendon is represented in figure 4 and was identical for both section types.

Figure 4  Configuration of the tendon within the slab.

Material Properties

For the design of tunnel material properties have been used according to [2]. The material properties of the reinforcement, the prestress and the concrete for the non-linear calculations are represented in figure 5 and table 3.

Figure 5  Stress-Strain relationship for non-linear design [5]
Left: concrete, Middle: prestressed steel, Right: reinforcement steel (\( \sigma(\varepsilon) = -\sigma(\varepsilon) \))
<table>
<thead>
<tr>
<th>Material</th>
<th>Stress [N/mm²]</th>
<th>Strain [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>concrete</td>
<td>σc</td>
<td>εc</td>
</tr>
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<td></td>
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</tr>
<tr>
<td>tendon</td>
<td>σp</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Material properties used for the nonlinear analysis.

**Reinforcement of Crosssections**

The tunnels have been designed according to the DIN FB 101 and 102 [3] and [4]. For the characteristic crosssections (A-G from figure 1) the characteristic values (reinforcement ratio, height) are stated in table 6. Hereby μlow,l is equal to μup,l defining the lower and upper rate of the reinforcement (μ=a̅/h), hence symmetric reinforcement has been chosen for the entire tunnel for simplicity. The orthogonal reinforcement was set to 20% of the longitudinal reinforcement.

<table>
<thead>
<tr>
<th>Tunnel type</th>
<th>Crosssection</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>μlow,l=μup,l [%]</td>
<td>0.13</td>
<td>0.13</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>μlow,l=μup,l [%]</td>
<td>0.21</td>
<td>0.21</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.17</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Table 4 Properties of the characteristic crosssections (A-G).

The stiffness of the rotational and vertical springs was evaluated for the foundation (auger piles) to \( k_φ=975\) MN/m and \( k_v=315\) MN/m², see figure 1. For the whole tunnel the centroid of the steel reinforcement has been chosen to 10 cm from the edge of the sections.

**EXPLOSION IN TUNNELS**

For built infrastructure explosions may cause local and/or global damage to a structure, depending on the proportion and resistance of the structure and the proportion and dimensions of the explosion. In the worst case this may lead to partial or global collapse. For the design and calculation of structures for explosive loading, the following basics should be mentioned.

An explosion is caused by a sudden release of energy causing air propagation. Depending on the propagation of the energy in the adjacent material, it can be distinguished between two basic types of explosions known as deflagration and detonation, see [1]. Whereas the velocity of the shockwave propagation is subsonic for deflagrations and supersonic for detonations. Within this paper the authors solely concentrate on detonations, as generated by TNT.

An important factor to describe the dynamic properties of the wave propagation of the detonation is the so called scaled distance \( z \), defined by the distance \( R \) of the explosive device towards an element and the effective mass \( m_{eff} \) of the explosive device in TNT equivalent, defined by:

\[
z = \frac{R}{m_{eff}^{1/3}}
\]

A detonation causes the development of a shock front, which travels radial from the center of the explosion with overpressure \( p_{so} \), depending on the scaled distance \( z \). If this shockwave reacts with a
boundary, for example a wall, the shockwave will be reflected on the surface of the building, hereby the so called reflected overpressure $p_r$ is induced on the surface, see figure 1.

**Figure 6** Overpressure and reflected overpressure-time-history for free field detonation.

Depending on the overpressure and the atmospheric pressure the reflected pressure $p_r$ will be up to 8 times higher than the overpressure $p_{so}$ of the shockfront [1]. Casing pressures up to several thousands of KPa for a few milliseconds.

**Scenarios**

The location of the explosive has been chose in distance of 4.0 m from the wall and a height of 0.5 m. This leads to a minimum distance of 4.0 m to the outer tunnel wall, see figure 7. In total three scenarios with a different quantity of explosive material have been analysed, see table 5.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>car bomb</td>
<td>low</td>
<td>medium</td>
<td>high</td>
</tr>
<tr>
<td>z [m/kg$^{1/3}$]</td>
<td>0.71</td>
<td>0.56</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*Table 5* Scenarios considered for the numerical analysis.

$^1$For the scaled distance the effective mass has been evaluated as $m_{eff} = 1.8 \cdot m$ according to [6]

Mayrhofer showed that local phenomena, such as spalling and scabbing of the concrete caused by the wave propagation and high densities within the concrete can be neglected for a scaled distance $z > 0.5 \ m/kg^{1/3}$ [5]. Therefore the limit response of the structure will be dominated by flexural and shear behaviour for the defined scenario and can hence be evaluated using nonlinear 3D FE analysis.
LOAD-TIME-HISTORY

As it is necessary to shift the detonation from free field to the internal domain analytical or semi-empirical evaluation of the pressure time history becomes impossible. The beforehand spherical shockwave is reflected at the boundaries, tunnel walls and slabs. Therefore, the pressure time history is strongly influenced by the reflection characteristics of the propagation process. Hence the dynamic loading $p_{\text{exp},i}$ of the tunnel becomes instationary in time and space:

$$p_{\text{exp},\text{tunnel}} = f(x, y, z, t)$$

(2)

The load time history has been estimated using hydrocode simulations by the Ernst-Mach-Institut. As different software was used for the nonlinear analysis of the structure, the load time history needed to be transferred from one program to the other. Therefore for nine locations along the tunnel crosssection and thirteen sections of the tunnel length the pressure time history has been captured. Resulting totally in 117 tracking points with different load time history functions, see figure 7.

![Figure 7 Tracking points for the load time history for 0 m (grey) and 2.5 m (transparent) distance from the explosion for the right tunnel segment.](image)

As the load-time-histories was evaluated for 117 distributed points along the tunnel a three dimensional linearization function could be used for the total description of the tunnel loading at arbitrary points:

$$p_{\text{exp},\text{tunnel}}(x, y, z, t) \approx P_{\text{exp},\text{tunnel}}(x, y, z, t) = \sum_{i=1}^{117} w_i(x, y, z) \cdot f_i(t)$$

(3)

Hereby, the function $w_i$, with $0 \leq w_i \leq 1$, describes the contribution of the tracking point $i$ to the loading at point $(x, y, z)$ and $f_i$ describes the load time history at point $i$. For the weighting factors linear averaging has been used along the tunnel length.

For scenario three the pressure time history for a distance of 0 m is shown in figure 8. During the expansion of the shockwave in the tunnel tracking point 3 is firstly engrossed, due to the minimum distance to the explosion, followed by tracking point 0 and 1 with a similar distance. Tracking point 0 and 2 experience the highest stresses as these are located within the corners of the tunnel where reflections of the shockwave lead to stress concentrations.
Figure 8  Pressure time-history at tracking points 0-6 for 0 m distance from the explosive.

ANALYSIS

The finite element nonlinear analysis has been performed with a time step less than 0.1 ms. As the loading has a duration of approximate 3 ms more than 30 time steps are used for the dynamic load description. Material damping is taken indirectly into account by the nonlinear material description overall damping of the structure has conservatively not been included within the analysis.

Within the following the dynamic response on the local level, strains and displacement, and global level, damage will be represented. Plasticity will hereby be defined on the element level by the strain reached in the longitudinal reinforcement $\varepsilon_{i,s,\text{long}}$ or orthogonal reinforcement $\varepsilon_{i,s,\text{orth}}$ and the strain within the concrete $\varepsilon_{i,c}$ during the dynamic analysis, see equation 4.

$$\begin{align*}
\text{Plastic} & \quad \forall i \quad \varepsilon_{s,y} < \max \left( \frac{\varepsilon_{i,s,\text{long}}}{\varepsilon_{i,s,\text{orth}}} \right) < \varepsilon_{s,u} \quad \text{and} \quad |\varepsilon_{i,c}| < |\varepsilon_{c,u}| \\
\text{Damage} & \quad \forall i \quad \varepsilon_{s,u} < \max \left( \frac{\varepsilon_{i,s,\text{long}}}{\varepsilon_{i,s,\text{orth}}} \right) \quad \text{or} \quad |\varepsilon_{i,c}| > |\varepsilon_{c,u}|
\end{align*}$$

Figure 9 represents the maximum displacement directly over the explosive device, hereby negative displacement describes lifting of the slab. The following conclusion can be drawn from figure 9: The first peak of the oscillation of the tunnel occurs after 0.07 ms for minor dynamic loading and after 0.97 s for higher dynamic loading. Hence the response of the structure to the loading is either dynamic or impulsive after [6].
For all tunnel types and scenarios the maximum displacement of the tunnel in respect to its deformations under dead loads arises during the first rebound. This is remarkable as generally within the explosive design the first oscillation is sufficient for the determination of the load capacity of the structural element, for example within the widely used SDOF approach, see [7] or [8]. Hereby, the structural resistance is determined on energy equivalency and the non-linear resistance of the structural element by the dynamic analysis of a equivalent non-linear single degree of freedom system. Preloading and rebound is commonly neglected, as the dynamic performance is examined solely and the resistance curve calculated for one load direction. Within the considered case of this paper the structure is already loaded in opposite direction to the dynamic load, due to the pre loading the slab firstly experiences lifting and secondary rebound. This effect is essential as the rebound causes plastic deformation within the slab and therefore determines the capacity of the structure.

Figure 9  Vertical displacements of the slab for the two tunnel types and three scenarios.

Figure 10  Steel stresses in longitudinal and orthogonal direction for upside and downside reinforcement for damaged element of scenario 200 kg with 1m soil cover.

Figure 10 represent the stresses in the reinforcement at the midspan element for scenario 200 kg with 1 m soil cover. The beforehand described effect of lifting and rebound by the conversions of stresses can ones more be identified. Within the rebound the yield stress is reached within the longitudinal as well as in the orthogonal reinforcement. These stresses beyond the elastic limit lead to plastic stresses and plastic displacements as shown in figure 10 and 9.

The damage patterns of the tunnel types and scenarios are shown within figure 11, which lead to the following conclusions:
The structure shows a good load distribution after cracking and yielding as the plastified area is
spread widely along the tunnel. Damage of the structure occurs in the corners closest to the explosion and in the slab directly above the explosion. The damage in the corners is due to the high loading stresses caused by reflection of the shockwave. For the slab the damage is caused by the dynamic excitation leading to the beforehand described rebounding. Obvious as the explosive amount increases the damage increases as well. For the scenario 2 and 3 with a higher impact on the structure as scenario 1 the higher soil cover leads to a reduction of the damaged area. The same effect does not hold for scenario 1.

![Diagram](image)

**Figure 11** Damage patterns of the two tunnel types for the different scenarios according to equation (4).
CONCLUSIONS

Prestressed, large span, open cut tunnels have been analysed for three different explosive scenarios. The two tunnel hereby differentiate due to the different soil cover of 1m and 2m thickness. It could be shown that the first maximum deflection of the excitation, causing lifting or expansion of the tunnel slab, is uncritical as the slab is preloaded in opposite direction. During the following rebound the dynamic excitation and preload combines as they act in the same direction which leads to severe damage and plastic deformations. This is in contrast to ordinary protective design approaches such as the SDOF (Single Degree Of Freedom) approach as thereby opposite preloading and rebound is generally neglected. In addition it can be stated that three dimensional non-linear finite element analysis enables load distribution along the tunnel length which enables to utilize the necessary capacities of the tunnel segment, allowing an efficient design against sever threats. Further on it appears that the soil layer reduces for high loading the dynamic effects of the excitations and damage of the structures. This may be explained through the reduction of the impulsive impact caused by the shock wave as increase of the oscillating mass reduces the initial velocity.

The investigated scenarios of severe explosions led to partial damage or partial collapse of the structure. Due to the robustness of the structural system overall collapse can be prevented. However for tunnels in groundwater partial collapse may still lead to crucial flooding of the tunnel.

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RESCUE OPERATIONS IN UNDERGROUND MASS TRANSPORT SYSTEMS AT FIRES AND DELIBERATE ATTACKS

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*Mälardalen University ** Greater Stockholm Fire Brigade, Sweden

ABSTRACT
Fire and rescue operations in mass transport systems underground often constitute a great challenge for the first responders. In rush-hour traffic at important junctions thousands of people can be located at a relatively small area. At underground fires or deliberate attacks in these premises the need for assistance or rescue can be extensive and the possibilities to reach those in distress are limited. In case of deliberate attacks with explosives the risk for a second delayed attack, aimed at the first responders, has to be considered. The blast load and structural response can destroy important functions, used for evacuation, in the metro carriage and harm passengers in the exposed and adjacent carriages. This can increase the need for assistance from the fire and rescue services. In this paper the possibilities for the first responders to assist and rescue persons at the event of fire or explosion in a tunnel is discussed, based on the research results from the full scale tests performed within the METRO-project.

KEYWORDS: Tunnel, fire, explosion, fire and rescue operation

INTRODUCTION
The work presented in this paper is a part of the METRO-project [1], a Swedish research project about infrastructure protection. The focus of the project is on the protection of underground rail mass transport systems, e.g. tunnels and subway stations. Both fire and explosion hazards are studied. METRO is a multidisciplinary project where researchers from different disciplines cooperate with practitioners with the common goal to make underground rail mass transport systems safer in the future.

The results from the full scale METRO fire and explosion tests are presented and analyzed from a fire and rescue perspective. The analyzes and assumptions in this paper are based on a normally equipped and manned “standard” BA-rescue team in Stockholm Greater Fire Brigade. The conditions at a fire, accident or arson, are compared with the conditions that can be expected at a deliberate attack with explosives. The difficulties are highlighted and recommendations regarding fire and rescue operations are made both in areas concerning tactical approaches, suggested solutions at the scene of the accident and future need for research and development.

Four different areas have been chosen to analyze more thoroughly:

1. The experiences from, and effect on, the BA - rescue unit, for example regarding temperature and sight.
2. How do the images of the fires turn out in the IR camera? How easy is it to identify potential victims using the IR-image camera? How did the rescue “robot” – ROV (remote operated vehicle) with the IR image camera work in this environment?
3. The experiences of the use of the mobile PPV-ventilator, from a fire and rescue perspective.
4. Which circumstances in the environment may influence a possible fire and rescue operation?
A fire and rescue operation inside a tunnel involves many difficulties that alone or in combination influence the outcome of the fire and rescue operation. A fire or explosion, or in worst cases a combination of the two, inside a train tunnel is a complex situation where many persons can be in need of assistance. In mass-transport systems many persons can be located close or further away from the scene of the accident. Trains and metros carry many persons, with different possibilities to rescue themselves to a safe environment. An ageing population and increased demands for accessibility for disabled persons also represents a challenge for the fire and rescue services in case of a rescue operation. The evacuation route, the location for smoke extraction and the rescue services’ response route often co-exist in the tunnel tube. Long evacuation routes put more persons at risk if they are affected by the toxic smoke and fire and rescue operations with long response routes in high-risk environments make the transportation speed for the fire and rescue services slow if all safety measures are correctly addressed. Tunnel fire and rescue operations sometimes require special equipment that most fire and rescue services do not have access to. The Incident Commander (IC) in general work under an information shortage and the fire and rescue organization usually lack of experience of large fire or explosion situations underground.

BACKGROUND
In recent years a number of serious fires [2-7] have occurred in train tunnels. In some cases the consequences of these fires have been large in terms of loss of life and the accidents have shown the need of, but also the difficulties with, effective fire and rescue operations. In addition to the risk for injuries and fatalities fires in mass-transport systems will have a significant impact on the society since it decreases the confidence for the infrastructure itself. The economic losses not just strike the tunnel owner, the tunnel operator but also the public expenses and private interests.

At real life incidents or accidents the information about heat release rates (HRR), temperatures or toxicity only can be estimated based on the injuries and damages, investigated afterwards. The fire and rescue services can rarely relate their experiences to exact data and some phenomenon can not at all be paid attention to as the main aim is to save persons, property or the environment. Full scale fire tests are very expensive and demand a large organization. Few full scale fire tests have been performed and explosion tests, both in model and full scale, are often not public for security reasons. Full scale tests even more rarely include many disciplines and usually focus on strictly the fire dynamics or the effect of a specific fire technical installation, such as for example sprinkler or ventilation. Despite the expenses a few valuable full scale tests have been performed and contributed to the level on attainment worldwide [8-14]. Early tests did not include HRR measurements and many of them were based on pool fires, not vehicle fires. The possibilities for fire and rescue operation have seldom been investigated in the full scale tests and are first presented systematically in the Runehamar tests [15].

STRATEGY AND TACTICS AT FIRE AND RESCUE OPERATIONS IN TUNNELS
The IC can, with the help of the fire and rescue forces; either take an offensive strategy (fight the fire) or a defensive strategy (not fight the fire). This paper mainly discusses the circumstances where the aim is to fight the fire, but also try to identify the cases when this not is possible. In case of a deliberate attack with explosives, without a following fire, the strategy is offensive (rescue persons inside the tunnel) in most cases. Circumstances where the IC can make a decision to wait and see could be during risks for further explosions or if the construction first has to be reinforced to ensure a safe working environment for the first responders.

The experiences from the full scale fire tests are analyzed with respect to the five possible tactical approaches possible to use in case of a fire [16];

1. Fight the fire from inside the tunnel in order to save persons inside the tunnel.
2. Assist or rescue persons inside the tunnel and take them to a safe environment.
3. Control the air flow in the tunnel in order to save persons inside the tunnel or support the fire and rescue operation.
4. Fight the fire from a safe position to reduce the consequences of the fire.
5. Take care of persons that without assistance have rescued to a safe environment.

In case of an explosion the possible tactical approaches instead would be;

1. Secure the train and clear train and/or tunnel to make evacuation and rescue possible.
2. Assist or rescue persons inside the train or tunnel and take them to a safe environment.
3. Control the air flow in the tunnel in order to clear the tunnel from toxic gases and by this reduce the impact on persons inside the tunnel.
4. Take care of persons that without assistance have rescued to a safe environment.

In both cases the one or more of the tactical approaches can be applied in combination. With unlimited resources of course all tactical approaches can be used simultaneously, but in real life situations one of the IC’s main tasks is to prioritize the possible missions with respect to available resources.

FULL SCALE TESTS IN THE BRUNSBERG TUNNEL

The full scale fire and explosion tests within the METRO project were performed in the abandoned Brunsberg rail tunnel during September 2011. In total four tests, with each one week interval, were performed, see table 1. For the tests X1 commuter trains placed at the METRO project’s disposal by the Stockholm Public Transport were used. The first test performed was an ignition test underneath a not rebuilt X1 train, which also was used for the second full scale tests the week after. The third test was performed in an X1 train that had been rebuilt to correspond to a newer C20 metro train regarding surface, isolation and seats. The length of an X1 carriage is 24 meter, while two connected carriages is in total 49.95 meter. The two full scale fires were initiated by a small amount of petrol, imitating an arson attack. Left luggage was placed at 81% of the seats, with a mean weight of 4.44 kg. No consideration was taken to left luggage from standing passengers. The number and weights was based on an earlier field study performed in the Stockholm Metro [17]. The fourth and last test was an explosion tests, performed with a hand carried-sized charge placed at a seat. In this test two similar original X1 trains were connected and placed together inside the tunnel. The aim was to investigate the effect on the two trains, measure the pressure distribution, investigate the possibilities to perform a rescue operation and estimate the possible injuries at the passengers at different locations. The fire test was performed in cooperation between SP, Mälardalen University and Greater Stockholm Fire Brigade. The final explosion test was lead by FOI – the Swedish Defense Research Agency in collaboration with the three organizations mentioned above.

The old Brunsberg tunnel is 276 meters long and located next to an active track. The test area was closed and supervised during all tests and all traffic and activities at the nearby active track was totally suspended during the time for the explosion. The tunnel has a mean height of 6.9 m and a mean width of 6.4 meter at ground level. The surface roughness of the tunnel varies between 0.2 and 0.3 meter. A MGV L125 trailer mounted PPV ventilator, with the capacity of 217,000 m³/h (eq. to 60.3 m³/s), was placed at the east end of the tunnel in order to direct the smoke to make temperature and HRR measurements possible. The mean air velocity before ignition varied between 2.0 and 2.5 m/s. The PPV ventilator also made it possible for the fire and rescue services at all to be located, up-streams, close to the fire. The tunnel has a slight inclination from the west to east and the front of the train was placed 84 m from the east adit. The distance between the train side and the tunnel was 1.3 m on the left hand side and 1.9 m on the right hand side, seen from upstream side of the train.
The water supply was covered by two water pumps placed at the nearby lake at a distance of 115 meters from the eastern adit. The main pump was of type III (2400 l/min. at 10 bar) and a type II (1200 l/min. at 10 bar) as back up. The supply hoses had a diameter of 63 mm and the operating hoses 42 mm, with traditional fog-fighter nozzles with an approximate maximum flow of 300 l/min. The BA-rescue front team was equipped with one IR image camera and a helmet mounted video camera. 

In addition to the two BA-rescue teams a fire robot, also equipped with an ordinary video camera and an IR image camera was tested. The main aim of using the fire robot was to test the operation of the robot itself and to make images from downstream the tunnel facing upwards, from a position where the BA-rescue teams for safety reasons not could be located.

The five fire fighters who participated in the full-scale tests were between 25 and 45 years old. All have extensive experience in emergency services in general and BA-operations in particular. Two of the five fire fighters are instructors for BA-operations and two of them have requisite training for BA-rescue command. Water supply and operation of the mobile fan was covered by additional personnel.

Each test was documented by observers, placed outside the tunnel adit for visual observation and inside a fully equipped command vehicle, for overhearing the BA-rescue radio channels. The BA-rescue teams were running reporting air consumption, location and observation to the command vehicle and the fire fighters were equipped with pulsimeters. The locations and experiences were later compared to the actual recorded measurements in the tunnel, for example regarding temperature or heat radiation. During the fire tests the tunnel was equipped with 102 thermocouples, 9 plate thermometers for heat radiation measurements, 18 gas analyzers, 6 bi-directional probes for air velocity measurements and 4 laser detectors measuring the visibility inside the train. In addition to the measuring equipment cameras was placed both inside the train and in the tunnel - on the side of the train and up-stream the fire.

At the first fire ignition test the planned set up of the BA-operation was tested. The BA-rescue teams were also assigned to extinguish the fire in case of fire spread underneath the train, as the same train should be used in the second test. Only minor changes was made in the fire and rescue set up for the two following full scale fire tests. For safety reasons a full BA-rescue organization was set up, consisting of one BA-rescue team at the front as close as possible to the train, one BA safety team 75 meter behind, a BA-rescue commander outside the tunnel and an IC responsible for general decisions. A BA-team consists of two BA fire fighters. During the final explosion test a closed safety zone comprising the tunnel and 50 meter from each tunnel adit was decided for safety reasons. FOI – main responsible for the explosion tests – searched the train and the tunnel prior the test and kept guard outside the safety zone until the explosives had detonated. No fire followed the explosion. FOI personnel together with the fire and rescue services entered and secured the tunnel in order to make non-disturbed observations before the project photographers and the rest of the observers were allowed into the tunnel. The fire and rescue service’s experiences entering the scene of the explosion was filmed by a helmet-mounted camera for later analyzes.

RESULTS AND OBSERVATIONS
The temperatures and HRRs measured in the tunnel are presented in detail in other publications [18] and are here only presented as maximum values. The first ignition test did not affect the ceiling
temperature at all and no fire spread could be seen outside the area directly heated by the flames.

<table>
<thead>
<tr>
<th>Test</th>
<th>Type</th>
<th>Max HRR [MW]</th>
<th>Max temp. (above train) [°C]</th>
<th>Max temp. (downstream) [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ignition</td>
<td>0.5*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Fire</td>
<td>76.7</td>
<td>1073</td>
<td>1081</td>
</tr>
<tr>
<td>3</td>
<td>Fire</td>
<td>77.4</td>
<td>1118</td>
<td>980</td>
</tr>
<tr>
<td>4</td>
<td>Explosion</td>
<td>No fire</td>
<td>No fire</td>
<td>No fire</td>
</tr>
</tbody>
</table>

*HRR for actual heptanes pan measured in laboratory environment.[18]

The HRRs and the temperatures in test 2 and test 3 are similar and the biggest difference between the two tests was the time until a fully developed fire inside the train. For short description of tests, see table 1. Test 2 corresponded well to the earlier performed laboratory tests performed at the SP fire lab during the summer 2011 [19] and a fire with temperatures above 600 °C could be seen after approximately 3 minutes. The maximum HRR was measured after approximately 13 minutes. In test 3, with the rebuilt carriage with mainly incombustible surfaces and partitions that effectively prevented heat radiation between the main compartments the corresponding times were measured to 108 minutes for temperatures above 600 °C respectively 118 minutes for maximum HRR. The fire behavior, apart from the initial time to reach a fully developed fire, though has many similarities in maximum values and duration. Both fires declined to the size of a larger car fire in approximately an hour [18, 20]. The results clearly show that incombustible surfaces gives the passengers valuable extra time to evacuate as well as the fire and rescue services time to reach the fire while it is at a size possible to extinguish. With the resources available at a normal sized Swedish city fire and rescue service, i.e. a minimum of ten fire fighters in the second line of response, the fire represented in test 3 would have been extinguished successfully. At favorable circumstances (short response route, easy access) the fire could have been extinguished by the first line of response with fewer personnel after regular risk estimations.

Due to the air flow created by the mobile ventilator in order to direct the smoke in one direction the influence on the visibility at the location of the front BA-team a was limited. The BA-teams had a unique opportunity to study the fire development at a large train fire from a distance that at a real accident not would be possible to be located at, due to heat radiation from the fire and re-radiation from the smoke layer. Without ventilation, further away from the fire, the full tunnel cross-section instead would be filled with smoke [21]. The smoke would effectively prevent the BA-teams from seeing the fire through plain sight and the visualization would instead be reduced to the use of an IR-imaging camera.

In spite of the mobile ventilator some back-layering could be seen both in test 2 and test 3. The working environment, at ground level, was in all three fire tests close to normal conditions with no significant exposure of high temperature or heat radiation affecting the fire fighters. In test 2 the back-
layering under a short duration, at approximately 6 minutes from ignition, advanced fast to 50 meter upstream the fire and stretched to the eastern tunnel adit before the effect of the mobile ventilator was adjusted to direct the smoke in the east to west direction. During the fast progression of the back-layering the BA-teams retreated from their advanced position for safety reasons, but re-established the position after less than three minutes. In both test 2 and test 3 strong pulsations could be seen in the tunnel. These phenomena was first discovered in the Runehamar tests in 2003. The pulsations depend on the HRR, the effect of the ventilation (natural or mechanical) and the properties and length of the tunnel [22]. Outside the tunnel adit observations were made of light objects moving back and forward over a distance of approximately 20 meter. During the strongest pulsations brushwood outside the tunnel swung almost to the point that frail branches broke and loose equipment, paper and rubbish were thrown around. The pulsations affected the mobile ventilator and the ventilation motor’s changing number of revolutions, due to the changing counteracting resistance in the tunnel, could clearly be heard at the eastern adit.

In test 1 and 2 a ROV with mounted conventional and IR-imaging cameras was used to picture images downstream the fire. The ROV was also used to provide the project with images from angles where projections in high and low sensitive mode could be recorded for later evaluation. From the position downstream the fire, the burning train carriage as well as the BA-rescue teams upstream the fire, could be viewed in the camera. The filmed sequence shows that the sensitivity of the camera automatically switches to “low” when the flames from the fire appear in the viewfinder. The appearances of the BA-rescue team then was largely reduced. This perfectly normal function in the camera could obscure a potential victim if a BA-fire fighter is unaware of the camera's limitations. This shows that the pictures from the IR-image camera can be difficult to comprehend for the BA-rescue team and that the use of the IR-image camera can be reduced in situations where the search needs to be performed from a distance and the fire blocks the way. Earlier performed tests also showed that the tunnel environment further away from the fire, when the smoke temperature has declined and the smoke fills the entire tunnel cross-section [21, 23], shows very low thermal contrasts. Low thermal contrast will make it difficult for the BA-rescue team to evaluate the images from the IR-image camera and estimate borders and directions [23].
The communication between the remote control and the ROV worked well and pre-tests prior to test 1 showed no interference between the ROV radio communication and the measuring equipment. The low center of gravity turned out to make the ROV stable and it had no problems to cross water hoses or move next to the track on gravel and macadam. These tests results, regarding maneuver and control of the ROV, should be seen as preliminary and more extensive tests need to be carried out.

The mobile PPV ventilator used in the tests did well power to redirect the smoke in the desired direction. The ventilator was used in the range of 60-75% of its full capacity. The ventilator was affected by the pulsations and the back-layering and, in short duration, got over-powered before the right air flow could be set. The situation clearly showed that the ventilator more easily can withhold a flow if a counteracting pressure already has been established than to redirect a flow moving towards the ventilator. Pre-tests showed that the ventilator is more effective inside the tunnel or at the tunnel adit, than outside the tunnel with the air cone covering the tunnel opening [24]. The sound-level in the ventilator vicinity would though easily cause communication problems especially between the BA-rescue commander and the BA-rescue teams.

After test 4 – the explosion test – the first BA-team entered the east tunnel adit approximately two minutes after the detonation. The train was thereafter reached in an additional minute. The short response time in this test does not correspond to the conditions applicable at a real rescue operation after an explosion. In test 4 there was initially no forced mechanical air flow and the natural wind velocity in the tunnel was negligible. There was only a slight haze of smoke inside the tunnel, mainly due to dust, and no fire was observed. The IR-image camera showed a very low heat signature close to the former location of the explosive device. Major damage was observed on the first train carriage and slight damage to the connected rear carriage. The front carriage had de-railed and the roof had split open to both sides. The deformation obstructed the tunnel and made it difficult for the fire fighters to reach the second carriage. Tactical extrication can be complex in open air and the tunnel environment represents additional challenges for the fire and rescue services. In a real life situation it would have been very difficult and time consuming to transport cutting and heavy rescue equipment or injured passengers on stretchers past the obstructed parts in the tunnel.
The blast effectively put out all camera and lightning equipment in the carriages and a real rescue situation would require setting up of primarily lightning in order to effectively rescue passengers. The direct effect on the passengers could be divided into four types:

1. Over pressure (from shock wave)
2. Fragmentation (shrapnel and scattered pieces of primarily train interiors)
3. Impact (passengers thrown towards rigid surfaces)
4. Heat (from thermal wave)

Thermal wave effects can be considered relatively limited in non-military situations. The main types of injuries for the first responders to deal with in an underground train explosion would be passengers affected by shock wave or fragmentation. The human body can resist relatively high shock waves but are, for natural reasons, vulnerable to fragmentation. In cases where the rescue is delayed the risk of fatality due to lethal bleeding increases [25]. The pressure distributed to the second carriage was in a range which would be possible to survive. The second carriage would most likely represent a location where passengers with less effort and resources could be rescued [26]. Adjacent carriages, not blocked by the demolished carriage of origin, would also be easier to reach for the first responders and increase the possibilities for survival. An observation of importance is though that the over pressure in the tunnel, outside the carriages, caused a blocking of the doors in the second carriage, which would cause problems evacuating especially if the explosion is followed by a fire.

Under real circumstances, it is likely to take anything between ten minutes and one hour before the first BA-rescue team arrives at the scene of the fire in a train tunnel. The front transportation speed for a fire and rescue operation and full water hose lay-out, with respect to the Swedish Working Environment regulations [27], are between 0.1 and 0.2 m/s [24]. The maximum distance a fire and rescue operation can cover with consideration to the safety regulations mentioned above and air supply of compressed air is approximately 200-250 meters. To cover longer distances the BA-rescue teams need to move partly or fully without water supply, use longer lasting air supply for example oxygen systems and use transportation trolleys or vehicles. Oxygen systems for BA-rescue operation though cause other challenges to consider. In the tests the fire fighters physical condition was monitored regarding for example pulse and air consumption. The outcomes of the measurements is not discussed further as the tests, in respect to correspondence to real life conditions regarding strain, heat exposure and stress levels, not are applicable.

CONCLUSIONS
After the tests all involved fire fighters and engineers were interviewed and the results from the measurements, observations and interviews are summarized below;

1. The different surfaces of the train interior created totally different conditions and possibilities for both evacuation and fire and rescue operations.
2. For the conditions in test 2, with non rebuilt train interior and fast fire development, the fire and rescue services would most likely not be able to reach the train in time in order to extinguish the fire.
3. For the conditions in tests 3, with rebuilt train interior and slow fire development, the fire and rescue services would relatively easy be able to stop the fire developing to flash-over.

4. Even if an under ventilated fire inside the train could occur the fire environment in the tunnel itself could be considered well ventilated, with or without mechanical ventilation. In respect to this the requirement of safe water supply at all times should be discussed in national Swedish fire fighting. The common apprehension is not to move inside the tunnel without a filled water hose. This prevent the possibilities to send BA scout teams or BA-rescue teams that move without water and connect to mounted water hydrants inside the tunnel when the conditions require water supply.

5. The mobile high flow ventilator created a very favorable environment upstream the fire. The risk for increasing the HRR must though be taken into consideration as well as the conditions for evacuating passengers in case of re-direction of the flow inside the tunnel. The best location for mobile ventilation is at the tunnel adit or inside the tunnel.

6. The sound-level from the mobile ventilator could cause communication or working environment problems at the tunnel adit.

7. The use of IR-imaging in tunnels, both close to and further away from the fire, needs to be further evaluated. Education material and images would be of use for training of BA-rescue in tunnels.

8. Robots or ROVs for scouting and search beyond the fire scene are very useful and should be further developed.

9. There is need of development and evaluation of different types of search patterns for tunnels. Normal IR-image search methods used in compartment fires are not applicable.

10. The over pressure in the tunnel can make doors at adjacent carriages to stuck in closed position (test 4).

11. An explosion inside a train carriage in a tunnel can cause blocking effects that influences the fire and rescue operation.

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STUDIES OF EXPLOSIONS OCCURRING IN A METRO CARRIAGE IN A TUNNEL

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ABSTRACT

The paper presents a comparison between numerical modeling and explosion tests in model scale and full scale involving underground/commuter train carriages. The full-scale test was performed in an abandoned Swedish railway tunnel in September 2011. Relevant geometries and construction models of the metro carriage were exposed to closely controlled design explosions in the model scale experiments. The characteristics of the blast waves were measured at different locations. The final design of the full scale experiment was chosen based on the experiences from the model scale tests. The subjects studied were uncased explosive charges and their blast wave effects in the present complex geometry and the consequences on the structures. The results from the full scale test, the corresponding model scale tests and the numerical modelling work were compared and analyzed.

KEYWORDS: explosion, tunnel, metro carriage

INTRODUCTION

These studies were performed within the METRO project, which is a large three-year interdisciplinary research project, executed by a consortium of universities and research institutes in Sweden. The project was financed by several stakeholders in Sweden. The METRO-project is a joint research project aimed at improvement of the safety and security concepts of underground mass transport systems with regard to both structural and organizational measures. It is divided into several Work Packages. Work Package 5 (WP5) is intended to evaluate the interaction between an explosive charge and the structure and interior parts of a carriage, the interaction with the tunnel, and to supply more reliable data regarding construction sustainability in case of extraordinary strains and stresses. This paper seeks to analyze the correlations between numerical simulations, small-scale tests and the full-scale test. Some simplified models, which were as closely as possibly related to the tests, were calculated with the AutoDyn\textsuperscript{\textregistered} model. The small-scale tests were carried out at a test site of the Swedish Defence Research Agency, at Grindsjön, at a scale of 1:10 and the full-scale test was made in an abandoned railway tunnel at Brunsberg in Sweden.

METHOD

Small-scale tests and a full-scale test were carried out and compared to numerical simulations with correlative set-up. Experienced phenomena were discussed and illustrated with help of figures. Numerical modelling of the experiments was performed with the Ansys AutoDyn\textsuperscript{\textregistered} finite difference code [1]. Replica (Hopkinson-Cranz) scaling was used i.e. the linear scale was 1:10 the area scale 1:100 and the mass scale 1:1000. This is designed to give equality of the shock pressures at scaled and full distance, whereas time and impulse will be linearly scaled [2]. The colour of the graphs included
in the comparison figures is matching the colour of its name and its colour of the corresponding scale.

**LIMITATIONS**

This paper gives interpretations of the calculated and measured values for the simulations and tests presented. It does not necessarily mean that it is valid in all cases. The results of peak pressure measurements need to be discussed for each test individually. The precise amount of the explosive device used in the full-scale test and the comparable simulations NS 100-109 will not be mentioned.

**TESTS MADE**

The tests were designed to study the effect of an explosion in a metro carriage located inside a tunnel. These tests were designed to enable correlations to be made between them, in order to create valuable data for contingency planning and tactics of first responders.

**Numerical Simulations (NS)**

The numerical simulations were made with the numerical continuum dynamics code Ansys-AUTODYN®. The carriage and the tunnel were filled with air at normal temperature and pressure, modelled as an ideal gas with $C_p/C_v = 1.4$, density $1.3 \text{ kg/m}^3$ and internal energy $0.1925 \text{ MJ/kg}$. The shock wave was calculated on ambient air with a pressure of $100 \text{ kPa}$ (ab. 1000 millibar) which is relevant at sea level for an air temperature of $0 \degree \text{C}$. The explosive charge was modelled as a sphere of TNT, with data taken from AUTODYN’s material library. After a short run in 2D it was mapped into the 3D model as a gaseous sphere with 1 m radius, 0.3–0.5 milliseconds after the detonation was initiated. The calculation continued in 3D with an Euler-FCT processor. The mesh in the geometry model contained 2–3 million cubical elements. The tunnel ended after 30 m with a flow boundary that emulated an infinite continuation of the tunnel [3]. These characteristics were similar in all simulations. The numerical simulations can be divided into three set-up groups recognizable by the different range of calculation numbers used.

NS’s 1-79 were prepared for the comparison with the small-scale tests. In these simulations the metro carriage were modelled as a hollow box with a length of 24 m and a cross-section of $3 \times 3$ m located 1 m above the ground plane of the tunnel. The distance between the “gauge” (pressure registration) locations were $c/c = 3$ m originating from the detonation point in the centre of the carriage. A similar set-up was used in the small-scale tests, only with fewer gauge positions. Inside the carriage the total number of 20 seats were modelled as $1 \times 1$ m rigid plates and located with $c/c = 1.7$ m. The model used symmetry in two vertical planes, one in the tunnel length axis and the other one orthogonal to the length axis of the tunnel [3].

Figure 1 shows the design of the modelled carriages that included the explosive device. The left picture is a quarter of the simulated carriage for the small-scale tests NS 1-79 and the right side shows half of the simulation carriage for the full-scale tests NS 100-109.

![Figure 1: Design of the modelled carriages for NS1-79 and NS 100-109 [3]](image)
A total of 76 numerical simulations were made with different combinations of charges, venting areas, tunnel areas and the presence of an adjacent dummy carriage. The charge weight was chosen as 1, 5 or 10 kg TNT. The ventilated area in the carriage wall and ceiling was chosen as 2, 6, 18 or 45 m² which is not shown in Figure 1. The tunnel cross-section was chosen as either 5x5 or 7x7 m and a variation with an adjacent carriage present or not present was made as well. The calculations NS 70-79 were set-up with an initial opening of 2 m² that was widened to 18 m² after 20 ms. This was done in order to simulate the breaking up of walls and ceiling of the carriage [3]. The calculations with the numbers NS 100-109 were related to the set-up of the full-scale test (FS). They considered a more detailed shape of the train and tunnel. The changes included a horseshoe shaped tunnel with 38 m² cross-section area, a decreased clear height inside the carriage to 2.3 m, inserted openings for windows and doors and an eccentric arrangement of tracks and carriage inside the tunnel. The gauges were arranged similarly as in the full-scale test [3].

Small-Scale Explosion Tests of an Underground Carriage (SS)
The small-scale tests were performed in collaboration between the Swedish Defence Research Agency - FOI and the Mälardalen University. These tests were designed to approximately model the full-scale commuter train explosion test in Brunsberg at a scale of 1:10. A box made of a steel frame construction and 2 mm thick steel plates was fabricated with the dimensions 240x30x30 cm and was placed 10 cm above the ground at the centre of a 10 m long tunnel with a cross-section of 70x70 cm. The sides and the roof of the carriage model left an opening of 45 cm at the middle of the carriage which was covered by movable steel sheets in order to be able to use different venting areas at different tests. The seats of the train were modelled by 20 steel plates of 10x10 cm, welded to the model carriage's structure [4]. Three gauges (V3, V6 and V12) were installed at the centreline of the carriage model, V3 and V6 at floor level to measure the side-on pressure and V12 in centre of the end wall to measure the reflected pressure. Four further gauges (T0, T12, T18 and T24) were installed outside the carriage model at the centreline of the tunnel roof. T0 measured the reflected pressure and T12, T18 and T24 measured the side-on pressure further down the tunnel [4]. Figure 2 describes the placement of the gauges in detail. The tests were also documented with a high-speed camera that was placed 15 m from the explosion and recorded at a rate of 300 frames per second. The explosive device was mounted at the centre point of the carriage. The tunnel was made of concrete blocks, used as walls, covered with 25-30 mm thick steel plates above as tunnel roof [4]. The tests varied the size of the venting area (180 and 1800 cm²), with or without an adjacent carriage, and the explosive devices used had a mass of 1, 5 or 10 g. The 1 g charge consisted of only the Nonel blasting cap with RDX as explosive. The 5 and 10 g charges were made of Swedish Plastic Explosive (85% PETN + 15% mineral oil) ignited with a Nonel blasting cap [4].

In tests 12 to 16 the venting area was covered with 1 mm aluminum plates (weight ab. 28 g/dm²) in order to simulate the breaking up of the carriage walls and to keep the initial pressure wave confined inside the carriage [4].
Full-Scale Commuter Train Explosion Test at Brunsberg (FS)

The FS was carried out in an abandoned railway tunnel at Brunsberg close to Arvika (Sweden). Two 24 m long carriages were placed close to the middle of the 272 m long tunnel. The cross-section of the tunnel was shaped like a horseshoe and the walls consisted of rough rock formations covered with a concrete layer (grouting). The profile depth along the tunnel walls and the ceiling varied between 20 – 30 cm. The height of the cross-section at the location of the experiment was constantly at 6.6 m and the width varied between 6.2 m at the east end of the train to 5.6 m at its west end. The rail track was located eccentrically by 30 cm. The explosive device was made of a common explosive; it was of a size easily carried by hand and was placed in a soft bag on top of the seat that was located next to the middle doors inside carriage A (see Figure 3). Pressure gauges were installed inside and outside both carriages to collect the pressure wave data, and a high speed camera was placed at the easterly tunnel adit to catch pictures of the explosion. At the time of explosion all doors and windows were closed [5].

Four gauges were placed inside the carriages, three of them in carriage A (A1, A2 and A3) and one in carriage B (B4). Three further gauges were installed outside the carriages on the sleepers of the track (Out 5, Out 6 and Out 7). The distances to the charge were chosen as following: [5]

- A1: 3 m east of detonation, Side-on pressure at floor level of carriage
- A2: 5.5 m east of detonation, Side-on pressure at floor level of carriage
- A3: 9.5 m east of detonation, Reflected pressure at 0.85 m height above floor level
- B4: 24 m west of detonation, Side-on pressure at floor level of carriage
- Out 5: 24 m west of detonation, Side-on pressure at ground level of tunnel
- Out 6: 18 m east of detonation, Side-on pressure at ground level of tunnel
- Out 7: 24 m east of detonation, Side-on pressure at ground level of tunnel

Comparison of Results

Comparison between the numerical simulations

The numerical simulations were compared with each other in order to observe general phenomena of the pressure propagation caused by an explosion in an underground carriage. As described variations were made with the size of the charge, the size of the venting area, the tunnel cross-section and the presence of an adjacent carriage.

It was observed that strong reflections from the interior walls increased the impulse density in several steps with clearly visible plateaus. Outside the carriage the impulse density increased in only two significant steps with the level depending strongly on the size of the venting area. The first step is the initial part of the pressure wave escaping through the venting area, the second step is depending on the remaining part of the pressure wave inside the carriage that was reflected at the end of the carriage and then escapes into the tunnel while it passes the venting area the second time. A small venting area led to a high impulse density inside the carriage and a relatively low impulse density outside. A large venting area led to a weak reflection of the interior walls, and the impulse density inside the carriage reached the maximum without noticeable plateaus and stayed relatively small, but it also led to significantly increased impulse densities outside.

In order to make the simulation more realistic it had to be assumed that the carriage initially is closed...
when the explosion occurs and the breaking up of the carriage walls will take some time. This sequence of events will mean that a more realistic pressure propagation situation will be created, with a small initial venting area that opens up to a large venting area before the pressure pulse returns from the carriage ends. It is a combination of the worst parts of both scenarios mentioned above and will be considered in the comparison with the small-scale and the full-scale tests. The size of the tunnel cross-section influences the peak pressure and the impulse density significantly. A large cross-section decreases the pressure levels; a small cross-section increases the pressure. The pressure values change significantly due to the presence of a dummy carriage in small tunnel cross-sections, but not in large ones.

Comparison of numerical simulations (NS) with small-scale tests (SS)
The different scales between the numerical simulations and the small-scale tests will mean different sizes of charge and venting area. The first comparison was made between NS-26 with 1kg TNT and 2 m² venting area and SS-2 which used 1g of RDX and 1.8 dm² venting area. The difference in the size of the venting areas was negligible. Figure 4 shows the results of the numerical simulation NS-26 in black and the small-scale test SS-2 in grey. The first column presents the side-on pressure measurements at a distance of 6 m (0.6 m) from the explosive device. The second column presents the reflected pressure measurements at 12 m (1.2 m) distance from the point of detonation.

Figure 4: Comparison of NS-26 with 1kg TNT and 2 m² venting area and SS-2 including 1g of Plastic Explosive and 1.8 dm² venting area

The pressure-time graphs at both gauge positions are showing good agreement at first sight. Especially for the computations it can be seen that the impulse density increases in steps with clearly visible plateaus. The steps will be caused by the reflected shock wave passing the gauge again while the plateaus indicate the time needed for the shock wave to return. The impulse density graphs in the first column are showing good agreement within the first 50 ms (5 ms) but are drifting apart as time progresses. As the shock wave passes the measurement point at 6 m distance from the point of
detonation (#3 and V6) the first time, the propagation was not disturbed by any obstacles. After 200 ms (20 ms) the values of the SS-2 graph are 40% less than the NS-26 graph values. Comparing the impulse-time graphs of the second column where the gauge was located at the end of the carriage at 12 m (1.2 m) distance from the charge, they show reasonable agreement in shape but a difference in level right from the beginning. Since the gauge was located at the end of the carriage, the pressure wave had to pass several simulated seats before it came to the measurement point. Obstacles obviously interfere with the shock wave differently in the small-scale test and the numerical simulation. A likely explanation will be that there will be shock-front relaxation and energy losses from friction and turbulence that occur around the simulated seats, which are not accurately modelled in the numerical simulation.

Figure 5: Comparison of NS-64 (1kg TNT, 18 m² venting area and a tunnel cross-section of 7x7 m) and SS-4 (1g of RDX, 18 dm² venting area and no tunnel)

Figure 5 shows a comparison of the numerical simulation NS-64 and the small-scale test SS-4. Only the three gauge positions inside the carriage were taken in consideration since the tunnel was not present in SS-4. The difference to Figure 4 is the enlarged venting area which had an immediate influence on the pressure propagation. The first peak pressure of NS-26 #3 (6 m) in Figure 4 shows a value of 155 kPa with a 2 m² venting area and a value of 128 kPa with an 18 m² venting area in NS-64 #3 (6 m) in Figure 5. That means that the peak overpressure value of NS-26 #3 (6 m) is 55 kPa and the peak overpressure value for NS-64 #3 (6 m), is due to the enlarged opening, reduced by 50% to 28 kPa. The difference in the pressure wave propagation also appears significantly in the different shapes and maximum values of the impulse density graphs of Figure 4 in comparison to Figure 5. The comparisons of NS-64 and SS-4 (Figure 5) shows good agreement.
The differences between the simulations and the tests that created the results in Figure 5 and Figure 6 were mainly the size of the charge, which was enlarged from 1 to 5 kg (g), and the attempt to simulate the breaking up in the NS-72 by opening up the venting area from 2 to 18 m² after 20 ms and in the SS-15 by covering the 18 dm² venting area with loosely hanging aluminium plates. The Swedish Plastic Explosive used in the experiment consisted of 85% PETN and 15% mineral oil. PETN has a TNT-equivalent of 1.27 [2], so the energy releases compares well to the same amount of TNT. Since the breaking up of the walls takes some time it was expected that the first pressure peaks inside the carriage would be very distinctive. After detonation a great part of the shock wave remains inside and as it returns after reflection at the carriage ends, it dissipates into the tunnel through the enlarged opening. The comparisons of the pressure graphs NS-72 and SS-15 (Figure 6) show good agreement, besides significant differences in the first pressure peaks where the experimental impulse density rises dramatically over the calculated values. That might be explained by the different situation of the initial venting area. The NS-72 started with a 2 m² opening whereas the venting area of SS-15 was closed up with an aluminium plate which increased the pressure inside the carriage and caused two prominent peaks, the first on the way to the end of the carriage and the second on the way back after reflection. Those peaks are clearly visible in SS-15 V6 (0.6 m) after 1 and 4 ms.

Figure 7 illustrates the calculated values of NS-72 in form of the main shock waves 1(left) and 2 (right) which are passing the gauge positions #2, #3 and #5. Gauges #2 and #3 are giving side-on pressure values and gauge #5 a reflected pressure value which is expected to be more than double as high as a side-on pressure value at the same point. That explains the rising of the calculated pressure value from 260 kPa after 10 ms in gauge #3 to 310 kPa after 20 ms in gauge #5. The increase at gauge #2 shows slight increase of the pressure after 50 ms (visible also in SS-15 V3) which may be explained by reflections of the shock waves from roof, walls and other obstacles, causing an overlaying of pressure waves. It seems to be impossible to trace the shock wave 1 or 2 over longer
distances since it constantly interferes with obstacles, openings and other shock waves.

Figure 7: Illustration of shock wave travel

Comparison of the numerical simulation (NS) and full-scale test (FS)
Figure 8 and Figure 9 are presenting a comparison of calculated results from the NS-102 in black and measured results of the FS in grey. The peak pressure measurements of the FS leave some space for interpretation. Figure 8 includes the gauge positions inside the carriage.

Figure 8: Comparison of the gauges inside the carriage of NS-102 (Z kg TNT, initially 26 m² venting area and a tunnel cross-section of 38 m²) and FS (Z kg of Plastic Explosive, initially closed carriage and a tunnel cross-section of 38 m² with rough wall surfaces)

The pressure-time graph of FS A1 (3 m) displays two unexpected high peaks, one after 25 ms and one after 100 ms. An explanation for these peaks could be fragments or other particles hitting the gauge, since they were not protected. Gauge A3 was mounted in the wall that was dividing the driver’s cabin from the passenger compartments. The gauge lost its position since the wall was not resistant to the explosion. The peak pressure after 115 ms in the pressure-time graph FS A3 (9.5 m) is likely to be the gauge hitting an obstacle after losing the original position. Figure 9 includes the gauge positions outside the carriage. The pressure-time graphs of NS-102 show different initial amplitudes than the
graphs of the FS. This could be reasoned in an error at the modelling since the shock wave had to travel a long distance in a tunnel with a complicated geometry.

**Figure 9: Comparison of the gauges outside the carriage of NS-102 and FS**

**FURTHER DISCUSSION**

In all numerical simulations presented, TNT was chosen as explosive material. Within the correlations comparable scaled charge sizes were used.

Numerical simulations have limits in generating the conditions of the real surroundings. The simulations use a mesh of little boxes through the lateral faces of which the peak pressure is transmitted. Due to the steep peak pressure of an explosion and the limited resolution of the mesh, the value will get rounded and end up lower than in reality. This failure gets qualified with the distance to the detonation point due to the increasing duration of the pressure. A further limitation of the simulations is to model the realistic behaviour of materials that interfere with the propagation of the pressure wave. The simulated walls of the carriage were included as stiff borders which do not give way due to the pressure wave. During the small-scale tests it was observed that the explosions were bulging the carriage walls slightly. In SS-15 and SS-16 the walls, the ceiling and the floor of the carriage were bulging outwards for about 1.5 cm. That change in the shape of the model might have affected the results in the later tests. The numerical simulation (NS 102) uses a simplified shape of the full-scale test carriage and does not consider the rough tunnel walls. Furthermore the correct shape of the seats or their materials were neglected. The seats were simulated as stiff bulkheads that will cause significant turbulence as the initial shock wave passes by. This turbulence would make it more difficult for the gases behind the shock front to propagate through the carriage and decrease the values of the simulations.
CONCLUSION

- It is not possible to take pressure measurements from explosions as truth. There is always a need for interpretation. Several possible explanations for the observed differences between the values are given.
- The NS and SS correlate quite well since both set-ups are fairly equal, whereas for the values of the NS and the FS there appear differences which might be explained in the complexity of the set-up and the simplification of the NS. And turbulence is not well simulated by AutoDyn.
- Numerical simulations are a great help for understanding the pressure wave propagation and give a lot of information about the real scenario. But to reach reliable results it is crucial to enter a set-up as realistic as possible.
- Often computations can be used to investigate the limits of possible outcomes of the real situation by choosing different simplified set-ups of the problem. For instance the mesh size which is a compromise between the use of computing time and propagating errors, may not be possible to choose optimally.

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Safety and security of underground infrastructure – new concepts for evaluating and mitigating risks of tunnels

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ABSTRACT

Throughout the last couple of years an enormous amount of research projects have been carried out regarding the evaluation and mitigation of possible risks regarding underground infrastructure. Main focus of most of these R&D-activities has been the safety of the tunnel users, especially in the course of roads, due to the large and devastating fires in the Alp-tunnels. Thereby developed methods and concepts for the assessment and evaluation of possible risks have already been implemented in nationwide as well as EU-wide guidelines, not least because of more and more complex tunnel projects. As a result the tunnel related planning processes of the younger past have shown that the application and use of these concepts can have an enormous impact on underground facilities, up to being the formative influence on selected measures, concepts and even the choice of specific alternatives, e.g. regarding the selected construction method.

But from a societal point of view not only the safety of possible users should be part of the equation. Especially tunnels could have a primary role for the availability and functionality of an infrastructural network since on most occasions these buildings do have kind of a “bottleneck” function for the network as a whole, combined with high amounts of traffic. That said the temporary shut down or complete loss of such a facility could lead up to enormous problems, e.g. induced by elongations of travel estimates. Also the costs for renewal or rehabilitation of the structure have to be taken into account.

In 2006 the German Federal Ministry for Education and Research launched a research strategy called “Research for the civil security” wherein the project SKRIBT (“Protection of critical bridges and tunnels in a road network”) was founded. Within this project a method was developed for evaluating the level and degree of criticality regarding a specific road tunnel, in terms of security, safety, meaning for the network as a whole as well as costs induced by the scenario-specific impact. This method could also be applied for other infrastructural networks as well.

KEYWORDS: criticality of infrastructural networks, security and safety assessment, holistic approach

SECURITY RESEARCH IN GERMANY AND THE EU

Why doing research on security?

Throughout the last couple of years the evaluation and the assessment of tunnel safety has become more and more a defining and determining process regarding the planning and designing of infrastructural tunnels. This is particularly true when talking about road tunnels and their special situation following the big fires in the alp tunnels a few years ago. Since then, decisions made in terms of safety do not only have an influence on the tunnel equipment but also on the design of the tunnel itself, especially regarding its alignment, possible cross sections or the construction method to be used. For instance, when dealing with river crossing tunnels the safety related need for breakdown
bays within defined intervals will often push the decision about a possible construction method from bored tunnels to immersed tunnels, since the latter will come in more handy and economically more efficient: breakdown bays can easily be integrated while the cross section is temporarily widened, a procedure that would not work using shield machines for the boring process.

By integrating European specifications [1] into German guidelines such as the RABT (Guidelines for equipping and operating road tunnels) [2] already implemented technical and operational measures of tunnel-safety are complemented by the analytical approach of qualitative and quantitative risk assessment. This approach is primarily needed when dealing with tunnels that provide so called “special characteristics” but focuses solely on user safety. The security of the users and buildings as well as the safety of the construction itself is omitted. But nowadays operating authorities have to think more and more about securing societal assets leading directly to assessments regarding the impact of a single building on the network as a whole and thereby its robustness and resilience. Meanwhile our society also has to face new scenarios with possibly large impact on the structural assessment and – as a final implication – on the societal wealth. Thereby it is more or less irrelevant if these scenarios are induced by changes in climatic conditions, accidents with dangerous goods or criminal charges and asymmetric threats. Especially the latter ones have to be considered as an already valid danger for infrastructural buildings, at the latest since “almost” incidents like the one which occurred at the Holland tunnel in New York a few years ago. An analysis of the database TED (Terror event database), developed by the German Fraunhofer-Ernst-Mach-Institute for high speed dynamics (EMI) delivers at least 29 terroristic attacks on civil engineering structures in the last 10 years (Figure 1). Thwarted attacks are not included.

![Figure 1 Terroristic attacks to civil engineering structures within the last 10 years (courtesy by EMI).](image)

The quintessence can be phrased in the fashion of a risk analytical assessment: Even if the specific scenario provides a rather low probability of occurrence, an assessment of possible measures for avoidance and mitigation is reasonable and has to be considered as mandatory on some occasions. This becomes even truer when dealing with large extents of damage being associated with the specific scenario. On this account security research has become more and more eminent even in the EU, which has integrated a special security related research cluster in its 7th research framework program. Additionally national programs such as the German “Research for civil security” were launched all over the European community which also laid a focus on infrastructural networks.
The SKRIBT-project

In the course of the aforementioned high-tech research strategy of the German Federal Ministry for Education and Research the SKRIBT-project (Protection of critical bridges and tunnels in a road network) was founded with a strict focus on the road network and its boundary conditions. Within the project duration of almost 3,5 years the following 10 partners were focusing on road-related topics of safety and security: the German Federal Highway Research Institute (BASt), Hochtief PPP Solutions, SIEMENS, PTV AG, University of Stuttgart – Institute for Construction and Design of Light Structures, University of Würzburg – Institute for Clinical Psychology, Schuessler-Plan Ltd., Federal Office of Civil Protection and Disaster Assistance (BBK), Fraunhofer Ernst-Mach Institute for High Speed Dynamics and the Ruhr-University Bochum – Institute for Tunnelling and Construction Management.

Within the SKRIBT-project the partners took an all-hazard approach, where all possible natural and man-made disasters and their associated threats were included. Thereby, one of the main focuses was the development of a methodology for indentifying critical bridges and tunnels, which will be sketched on the following. Thereby it has to be considered that this paper will focus solely on tunnels and can only basic principles. Because of the sensitivity of the data that was generated in the course of the project the authors will also refer only about the methodological approach without naming or describing concrete projects or buildings.

METHODOLOGICAL APPROACH AND BOUNDARY CONDITIONS

For developing such a methodological approach all boundary conditions and all factors with influence on a structural assessment had to be determined, especially regarding possible feedbacks of building damages onto the network as a whole. Additionally, several definitions from other scientific disciplines had to be adopted for the construction and operation of tunnels.

Criticality of infrastructural buildings

Initially the definition of criticality is rather unrelated regarding infrastructural networks. Criticality and its basic terminology origins from the safety engineering of nuclear power plants and has a discrete meaning. Adopting this meaning to road tunnels leads to generating and defining an extent of relevance of a specific building for the integrity and functionality of the whole network. In addition the relevance of the assessed structure for the networks availability and functionality is determined. Naturally this overall assessment correlates with a structural assessment under regard of specific criterions such as the buildings structural integrity or serviceability, possible costs for the rehabilitation of a damaged structure and the overall duration needed for such a task. Thereby the criticality of an infrastructural building can be determined according to an overall assessment of all concerning criterions or – as a singular observation – with the focus on one specific parameter.

Criterions of a holistic assessment and their combination

In the course of the SKRIBT-project also so called “miscellaneous” criterions were considered besides the “classical” structural assessment criterions. This term subsumes all soft criterions such as the symbolic meaning of a building for the society. These criterions cannot be quantified adequately but might become a central factor within the assessment process: Buildings with a high symbolic meaning could become rather critical elements of the network although their influence on the networks functionality – for instance in terms of the traffic density buildings have to cope with – is on a lower level. This is even truer when dealing with asymmetric threats and therefore has to be integrated within the considerations. Furthermore the methodological approach has to grant the user with the possibility to prioritize selected criterions. E.g., one could possibly see a larger priority regarding the structural safety compared to user aspects or vice versa. In the course of a holistic assessment all mandatory criterions therefore have to be merged via a flexible and efficient algorithm within the scope of predominantly defined safety and security objectives.
That said the partners within SKRIBT indentified the following criterions and their accompanying indicators for all further considerations (Table 1):

**Table 1 Criterions, indicators and their units for a holistic assessment**

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Indicators</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRUCTURE</td>
<td>Extent of damage</td>
<td>[-]</td>
</tr>
<tr>
<td></td>
<td>Costs for rehabilitation</td>
<td>[€]</td>
</tr>
<tr>
<td></td>
<td>Duration of rehabilitation</td>
<td>[d]</td>
</tr>
<tr>
<td>USER</td>
<td>Fatalities</td>
<td>[-]</td>
</tr>
<tr>
<td></td>
<td>Probabilities</td>
<td>[-]</td>
</tr>
<tr>
<td></td>
<td>Estimated risk values</td>
<td>[f/n]</td>
</tr>
<tr>
<td>NETWORK</td>
<td>Travelling time elongations</td>
<td>[d]</td>
</tr>
<tr>
<td>MISCELLANEOUS</td>
<td>Symbolic meaning</td>
<td>[-]</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>[-]</td>
</tr>
</tbody>
</table>

**EXAMPLE OF A CRITICALITY ASSESSMENT**

**Assessment of the structural criticality**

As one can derive from table 1, the structural criticality of a tunnel is defined as a combination of possible damages due to a specific scenario as well as the duration and the thereby emerging costs for a rehabilitation of the damaged structure. For determining the extent of a possible damage the initial loads and impacts to the structure have to be defined and compared with the resistances of the various structural elements being harmed by the threat. This is followed by an assessment of the structural integrity of the building – a procedure to be carried out for all incidents and scenarios. By doing this a persistent extrapolation from the element-level up to the structure-level of the building takes place. Figure 2 shows an example for an immersed tunnel with damages due to high speed dynamical loads. On the left hand side a local damage induced by the blasting gases is shown while the right hand side displays the FEM-check up regarding the structural integrity of the tunnel.

![Figure 2 Exemplarily damage assessment: immersed tunnel with high speed dynamical loads](image)
The overall damage to the structure then has to be implemented within a 5-step scale which is based on the definitions of the Eurocode and the German DIN engineering standards. Prior to the SKRIBT-project there were no experiences or guidelines for the damage assessment and the design under the loads of blasting incidents in confined spaces. For a closer look into the developed methods and theories one might inquire [3].

At a first and quick glance it might seem reasonable to assume that all indicators of the criticality class “STRUCTURE” are linked to each other and do correlate to a certain extent. Costs and durations of structural rehabilitations naturally do depend on the damaged of the structure. But within the road networks four different types of tunnels can be found, with completely different construction methods (immersed tunnels, bored tunnels, cut-and-cover tunnel and drill-and-blast tunnels) and boundary conditions regarding the construction process in general and a possible rehabilitation in particular. Thereby it becomes possible that two different buildings have to be classified within the same damage class according to a specific scenario and its appending loads, but generate completely different costs and durations for rehabilitation due to their varying boundary conditions. On this account all indicators have to be considered discretely. While the duration can be estimated according to the construction principle or the cross section, accompanying costs have to be calculated according to the following formula:

\[ K_W = K_N \times G \times Z \times L \times A + V \]  

with  
- \( K_W \) = Costs for rehabilitation  
- \( K_N \) = Initial costs for construction  
- \( G \) = Basic factor for rehabilitation.  
- \( Z \) = Extent of destruction related to the tunnel as a whole  
- \( L \) = Length of destruction  
- \( A \) = Factor for dismantling / difficulty  
- \( V \) = Local measures for traffic safety and maintenance

One can comprehend that costs for rehabilitation are related to the initial costs for construction, which have to be allocated to the fiscal reference date. The “Basic factor for rehabilitation” is determined according to the specific construction method. For instance, in case of a fire accident in a drill and blast tunnel there will be no additional costs for temporarily securing and thereby a reduction of the initial costs by a certain factor has to considered. All other factors are self-explanatory.

**Assessment of the user criticality**

For assessing the user criticality an approach has to be chosen according to already existing guidelines for quantitative risk assessment (QRA), such as the German RABT 2006 or other national PIARC-related specifications. The authors are referring to publications like these and will not go more into detail regarding the procedure of QRA. Exemplarily the following figure 3 shows the results from a CFD simulation with chloride gas.

As a result such approaches will deliver progression probabilities for each specific incident as well as the number of fatalities which are caused within the assessed scenario. Probabilities of occurrence have to be set as 1,0 for all scenarios since for all asymmetric threats, such as terrorist attacks or other criminal charges, the determination of a valid value for such a probability is rather impossible due to the little extent and the low amount of elements within the basic population. Additionally to the already existing procedures of QRA, the partners of the SKRIBT-consortium developed a new procedure of implementing human behavioral aspects within evacuation and egress simulations.
Assessment of the network criticality

For assessing the network criticality regarding a specific building one has to analyze possible feedbacks from the surrounding network in case of a temporary or permanent breakdown or loss of the structure. Therefore the corresponding part of the network has to be simulated. Since all SKRIBT-related scenarios could possibly induce huge damages to the structures, combined with enormously extended down-times for the traffic, it is reasonable to simulate the structure after the traffic has already adapted to the new situation. This means that probable road users already know about the blocking of the preferred route and therefore are looking for possible bypasses within the surrounding infrastructural net. On this account elongations of travel times are occurring due to extensions of travel distances and the fact that mentioned bypass routes often are not able to cope with emerging overcapacities. Figure 3 exemplarily displays such a simulation.

In such manner calculated travel elongations, in combination with the specific duration for rehabilitation and a regional approach for costs for travel expenses, deliver a financial damage for the regional subnet. The network criticality itself is only defined by time losses.
Homogenization of the criterions and indicators

Because of the differences between the criterions and indicators, especially in terms of unit and dimension, and the overall heterogeneous situation of such a criticality assessment a homogenization of the generated values is needed before they can be combined to an overall classification of the building. On the one hand such a homogenization can be carried out via mathematical procedures and allocative functions and formulas. On the other hand it is possible to defined reference measuring units, for instance the initial construction costs for the complete building stock in comparison to scenario and building related costs for rehabilitation. The SKRIBT-partners aimed for developing a 5-step evaluation level for all criterions in accordance to the already implemented 5-step scale for classifying structural damages. Figure 4 illustrates such fictitious harmonization and classification. Here, the categorization of travel elongations according to a specific harmonization stock is displayed.

Combination of the assessed criterions and implementation of miscellaneous indicators

For analyzing the criticality assessment of the examined building a comprehensive aggregation over all commanding variables is needed. Thereby two different possibilities do exist: On the one hand a criticality assessment regarding one scenario but all criterions (horizontal approach) and on the other hand an assessment regarding one criterion but all scenarios (vertical approach). While the former will deliver an overview on how one scenario might affect the specific building, the latter one will give an idea about how the building performs criterion wise under the influence of the different scenarios. Both approaches can be summarized theoretically as follows:
**Horizontal** approach:

\[ KBGI_{i} = \alpha_{N} \cdot EBGI_{N} + \alpha_{B} \cdot EBGI_{B} + \alpha_{V} \cdot EBGI_{V} + \alpha_{SF} \cdot EBGI_{SF} \]  

(2)

with:
- \( KBGI_{i} \): Value of the criticality assessment for scenario \( i \)
- \( \alpha_{N} \): Weighting factor STRUCTURE
- \( EBGI_{N} \): Single Value STRUCTURE
- \( \alpha_{B} \): Weighting factor USER
- \( EBGI_{B} \): Single Value USER
- \( \alpha_{V} \): Weighting factor NETWORK
- \( EBGI_{V} \): Single Value Network
- \( \alpha_{SF} \): Weighting factor MISCALLENEOUS
- \( EBGI_{SF} \): Single Value MISCALLENEOUS

while:
\[ \alpha_{N} + \alpha_{B} + \alpha_{V} + \alpha_{SF} = 1.0 \]

**Vertical** approach:

\[ BGZG_{i} = \sum_{j=1}^{n} \beta_{ij} \cdot EBGI_{ij} \]  

(3)

with:
- \( BGZG_{i} \): Criticality assessment value for one commanding variable \( i \)
- \( \beta_{ij} \): Weighting factor scenario \( j \)
- \( EBGI_{ij} \): Single assessment value for scenario \( j \)
- \( n \): Amount of the overall assessed scenarios

while:
\[ \sum_{j=1}^{n} \beta_{ij} = 1.0 \]

Regarding the implementation and homogenization of miscellaneous factors there are natural borders on the following account:

- A direct link between scenarios and a factor like the symbolic meaning of a building is missing, since any dependency between the accompanying factors neither cannot be modeled with mathematical approaches nor estimated due to statistical analyses.
- Expertise is lacking regarding an impartial assessment of societal appreciation of infrastructural buildings, especially under local or national boundary conditions.

That said, such miscellaneous factors have to be excluded from the weighted assessment. Surely, it is still possible to include – for instance – the symbolic meaning of a specific building within the assessment process but the choice of valid and verifiable values for such factors is more “instinctive” than based on facts and statistics.

**CURRENT STATE OF KNOWLEDGE AND OUTLOOK**

The given explanations are sketching the methodological approach for indentifying critical infrastructural buildings such as developed in the course of the SKRIBT-project. This methodology enables its user to assess the criticality of new constructions as well as the existing stock regarding a specific amount of scenarios and their accompanying loads and threats. The overall approach has to be considered as holistic but still provides potential for optimization. One problem with such an approach appears with the fact that thusly calculated criticality values exist without reference values. A comparable problem is encountered when dealing with the results of QRAs: The societal level of acceptance, the question about the amount of the risk a society is willing to take cannot be answered by a research project but with a discourse that includes users, operating authorities and the government in an equal fashion. The same can be said about criticality levels of infrastructural buildings and possible threshold levels were actions have to be taken.

Nevertheless the sketched methodology provides the possibility to compare the infrastructural buildings of one nations stock for coming up with criticality rankings that include the full amount of accessible buildings. This provides the feasibility to prioritize a building stock regarding the realization of mitigation measures. For this application such approaches have to be considered conducive as well as more and more indispensable.
Regarding the scientific status quo additional analyses are needed, for instance regarding the homogenization of the indicator values and the thereby resulting fuzziness of the overall result. Possible approaches may either focus on the homogenization itself or on finding new ways of assessing the needed values. For instance a quantitative risk assessment methodology for structures and buildings as well as for the assessment of the net-wide feedback in case of a structural failure could be developed. Actually the German government plans a continuation of the research for civil security in general and the funding scheme of the SKRIBT-project in detail. In this context some of the aforementioned problems will be tackled.

REFERENCES


Influence of different tunnel ventilation systems on the dispersion of light and heavy gases due to car accidents

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KEYWORDS: numerical simulation, gases lighter & denser than air, gas powered vehicles, dispersion in tunnels, influence of ventilation

INTRODUCTION
Dispersion of light and heavy gases due to the accident of gas powered cars in confined spaces is an issue that has been rarely investigated. Hence there are some international restrictions on the use of gaseous fuels in underground construction like tunnels [1]. Accidental scenarios were reviewed in terms of duration of gas release and possible mass source. In particular the heavy gas propane (for LPG fuel) and the light gas methane (CNG and LNG) are subject of the study in comparison to the conventionally used gasoline fuel. The gas dispersion was simulated in dependence on different tunnel ventilation system. It is shown that this can significantly reduce the explosion risk and implicitly the hazard of gas powered cars in tunnels.

METHODOLOGY
For the evaluation of the hazards of gas powered cars different accident phases were considered. First, subsequently to an accident of a gas powered car in a tunnel different source scenarios were compared in relation to the gas storage conditions. Pressure liquefied petroleum gas (LPG) and cryogenic liquefied natural gas (LNG) were set in contrast to compressed natural gas (CNG) and conventional gasoline. The release scenarios included an opening of a pressure relief valve and the damage of the gas line with different sizes of the leak. The total mass released was compared to an equivalent amount of gasoline. Methane was used to represent LNG and CNG, and propane for LPG.

In a second step, the gas dispersion was modelled in correlation with different ventilation measures in tunnels. The impact of different ventilation modes (emergency mode and standard operating mode in addition to natural ventilation) on gas dilution is discussed. Furthermore the release was considered as an impinging jet, no additional dilution was achieved by a high jet momentum. The piston effect that is caused by moving vehicles was also excluded. Furthermore the importance of the temperature of the released gas was considered. As figure 1 and 2 show, the density difference to air at 20° has a significant influence on the gas behaviour and the released gas volume, especially for methane that is originally lighter than air but changes to heavy-gas behaviour when it is released with a cold temperature.

Figure 1     volume compared to 50kg gasoline

Figure 2     density difference of considered fuels
NUMERICAL METHOD

The gas release phase was calculated with the ProNuSs Software [2] for numerical simulation of accidental releases that is based on fluid dynamic equations.

The CFD simulations of the gas dispersion phase were conducted with the fire dynamics simulator (FDS) developed by NIST. The hydrodynamic Model of the FDS implements the Navier-Stokes-Equations adopted for thermally driven flow. This includes a decomposing of the pressure into a background component and a fluctuating part. Based on this assumption, the model is only appropriate for low-speed fluid flow. As the mass conservation can be expressed in terms of the individual gaseous species and as different mass species equations are solved numerically, the dispersion of gases can also be examined with the FDS. Turbulent flow is simulated with the Large Eddy Simulation (LES) turbulence model. This includes the use of the turbulent Schmidt number $Sc_t$ that describes the turbulent diffusion in terms of the dynamic viscosity $\mu_{LES}$. The default value in FDS that is deduced from experiments is $Sc_t=0.5$.

Further details about the numerical and physical principles of the software can be found in [3] and [4]. The use of CFD tools requires the need to verify its application to the physical problem. As the FDS was initially developed for fire induced scenarios, additional work for validation is needed. In terms of gases lighter than air validation work was already done by researchers like Floyd [5] Prasad et al. [6] and Zhang et al. [7]. ACE Consultants and Sandia [8] used the FDS to simulate Burro 8 field tests with LNG and stated that the correct temperature of the LNG pool was essential for the simulation.

As the physics of the release of buoyant gases are comparable with fire-driven fluid flow concerning the density, the dispersion of heavy gases has to be a topic of intensified consideration. Although FDS simulations of the dispersion of heavy gases were compared with experiments by Truchot [9], Pape and Mniszewski [10] as well as by Ryder et al. [11] additional validation work was conducted regarding the stratification of heavy gases. For this purpose, experimental measures of the gas build-up of carbon dioxide CO$_2$ (M=44g/mol) and the stratification of sulfur hexafluoride SF$_6$ (M=146g/mol) in a ventilated room were compared with FDS simulations.

The carbon dioxide experiment was conducted by Gilham et al. [12] in 1997. In a cube with a width of 2.44m (14.5m$^3$) carbon dioxide was released with a velocity of 5m/s through a DN 5mm nozzle. The gas concentrations at different heights of the room were measured. At the top of the room, no gas concentration was neither measured nor modelled. The figures in figure 3 show that the mesh size did not have a huge influence. It was shown that in case of a coarse mesh the correct modelling of the initial momentum was essential to reproduce the experimental gas build up in the simulation. Here, a variation of the turbulent Schmidt-number had a significant influence on the results. The best correspondence was achieved with a value of $Sc_t=0.8$. Higher values than the default value of 0.5 led to a more characteristic stratification of the gas, while with lower values than 0.5 there was nearly no stratification modelled. These results indicate that the lowering of the turbulent Schmidt-number cause a higher dilution of the heavy gas. For this reason, the following investigations were conducted with the default value to achieve conservative results.

The sulphur hexafluoride experiment was conducted by Ricciardi et al. [13] in 2008. Gas concentration was measured in a 36m$^3$ room, similarly to the previous experiment, at different heights. (0.5m, 1.5m, 2.5m). The SF$_6$-experiment differs as here the gas distribution was compared to different ventilation scenarios of 3 h$^{-1}$ and 8 h$^{-1}$, represented by an air inflow at the top of one side and an exhaust opening at the bottom of the opposite side. Due to the fact that the inflow momentum of SF$_6$ in the experiment was too high to rebuild it in the limited FDS model, for the simulation an initial gas concentration in the room was chosen. The comparison of the experiment (black) to FDS-simulation (grey), presented in figure 4 showed that the CFD-model is able to rebuild the stratification of the gas as well as the outflow behaviour through the lower exhaust opening. There are differences in the results given by the influence of the different mesh size, but as observed in figure 4, those are relatively small regarding the considered mesh sizes of $h=0.0625m$ and $h=0.25m$.

Because two experiments were conducted, each with a different density-ratio of the heavy gas to air, it was possible to check if the degree of density-ratio had an influence on the distribution of heavy
gases. Having observed that both gases, carbon dioxide (ratio of molecular weight = 1:1.5) and sulphur hexafluoride (ratio = 1:5) were able to rebuild the measured gas concentration, it follows that the FDS is able to model the heavy gas behaviour with a satisfying preciseness.

*Figure 3  simulation of carbon dioxide build-up*

*Figure 4  simulation of sulfur hexafluoride concentration*
RELEASE SCENARIOS

The release of CNG, LNG, LPG and gasoline depends significantly on the storage conditions of the fuel and on the position and size of the leak in the fuel line system. The size of the leak was studied for 1mm and 10mm diameter exemplarily. For CNG there are different fuel pressures, varying from 200bar at the tank down to 1 bar low pressure lines behind the fuel pressure reducing regulator. In contrary to the stored natural gas CNG, the other fuels considered, are stored as a liquid: LNG has to be kept cold and LPG has to be stored pressurized (8-12bar) to remain a liquid while gasoline is stored at ambient conditions. For the liquids gasoline and LNG the release was calculated by the Torricelli theorem for the height of 0.5m above ground.

To be able to compare the stored amount of fuel, the CNG, LNG and LPG were related to a 50 kg gasoline tank in terms of the lower heating value. This aims to compare the fuels nondependent of the technique to store, but to the mileage range per tank. Parameters like the efficiency of the combustion were neglected. Table 1 gives an overview of the considered mass and volume of fuel.

<table>
<thead>
<tr>
<th></th>
<th>Gasoline</th>
<th>CNG</th>
<th>LNG</th>
<th>LPG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower heating value [MJ/kg]</td>
<td>48</td>
<td>55.3</td>
<td>55.3</td>
<td>50.4</td>
</tr>
<tr>
<td>mass [kg]</td>
<td>50.00</td>
<td>43.40</td>
<td>43.40</td>
<td>47.61</td>
</tr>
<tr>
<td>volume [l]</td>
<td>66.67</td>
<td>261.44</td>
<td>102.88</td>
<td>84.56</td>
</tr>
</tbody>
</table>

An abrupt release of compressed natural gas at a high pressure (200bar) leads to an expansion of the gas with a decrease of the gas temperature, due to the Joule-Thomson-Effect. The rate of temperature decrease depends on the inversion temperature of the gas and ranges between 0.4 and 0.7 K per bar for natural gas. If a cooled liquid, like LNG is released, a part from the released liquid will evaporate rapidly (flash-evaporation), while the other part will remain liquid and build a pool. When heat from the environment is added and the LNG pool warms above its boiling point, more gas will evaporate at a temperature near the boiling point of -160°C. Similarly the LPG or autogas that consists of propane and butane will be released at a temperature between -42.1 °C (boiling point of propane) and -0.5°C (boiling point of butane). However, the liquid is stored pressurized and therefore spills out of the tank or the line much faster than LNG. In addition, the boiling point of LNG is lower and more heat needs to be ad for the vaporization process.

For the considered fuels related to 50kg gasoline, the efflux of the different fuels out of the tank in reference to the time is illustrated in figure 6. The boundary conditions were equal, e.g. the hydraulic head for the liquid fuels or the discharge coefficient. The figure clarifies that between the different fuels, there is a significant difference in time until the total mass is released. In particular, it lasts approximately 13 minutes longer to empty a tank of liquid natural gas than a tank of compressed natural gas, although the same amount is stored. The difference of released time between the pressurized liquid petroleum gas (LPG, storage 8 bar) and the compressed natural gas (CNG, 200bar) are only 3 minutes. However, the conventional fuel gasoline has a longer release time of 10 minutes, while the LNG has the longest release time of 15minutes due to its lower liquid density.

A rupture of a gas line behind the vaporizer was considered to have a pressure of 1bar. Besides, the fuels have already changed their phase to a gas. Figure 7 gives an overview over the different release
times for a constant mass flow through a leakage of 10mm, 2 and 1 diameter. It becomes obvious, that here is a difference of more than 20 minutes until the total mass is released. But in contrary to the leakage near the tank, the natural gas (liquefied or compressed, represented by methane) has a longer release time than gasoline due to its lesser gas density.

![Figure 6](image1.png) **Figure 6** time to release of the total mass through a hole in a line behind the vaporizer

In case of a leakage near the tank, for a considered leak size of 10mm diameter hence there are several minutes until a hazardous atmosphere is build up. For smaller diameters that time difference increases up to several hours. Specifically for DN 2, there is a difference of approximately 10 hours between the total release of gasoline and methane, and of 6 hours between the release of gasoline and propane. This shows that the potential to create an explosive atmosphere depends significantly on the release scenario, especially on the considered leak size, that has a proportional influence on the total released mass. The evaporation of LNG and LPG was calculated with the ProNuSs Software. The discharge coefficient was set to 0.62. It is important to know that the evaporation of gasoline is not or barely not boundary-layer regulated, so the influence of wind can be neglected and the only important factors are time, temperature and remaining mass in the pool as it is stated by Fingas [14]. The evaporation rate of gasoline was calculated for a temperature of 20°C, with equation 1 based on experiments derived by Okamoto [15].

\[ \nu_{20°C} \left[ \frac{kg}{m^2s} \right] = 0.000496 \exp(-5.13a) \]  \hspace{1cm} (1)

The weight loss fraction “a” is given by the ratio of the weight loss fraction to the initial weight of gasoline and represents the extend of degradation of gasoline. The amount of evaporated gasoline depends on the amount and size of the gasoline pool. As this is an unsteady process and there are many parameters that influence the spreading of the pool, the evaporation was calculated for a pool of 50 kg gasoline with a pool thickness of 5mm. The pool area remained constant during the evaporation process, whilst the thickness decreased with mass loss. As shown in figure 8, the evaporation of gasoline lasts much longer than the vaporization of the liquid petroleum gas and the liquid natural gas. In case of the considered mass of 50kg, it would last 60 hours until the whole content of the tank is evaporated. Even, a pool with a thickness of 0.5mm would last 10 times longer than LNG and LPG to evaporate completely.

![Figure 7](image2.png) **Figure 7** time to evaporation of a pool – equivalent to 50 kg gasoline
The time difference in the efflux of the tank and the duration of the evaporation is illustrated in figure 9. It becomes clear that due to the process of evaporation, it lasts much longer for the fluid content of the gasoline tank to transform into gas than the gaseous release of the other fuels.

![Figure 8](image)

**Figure 8** time for release – high pressure at the tank

**CFD-SIMULATION WITH THE FIRE DYNAMICS SIMULATOR**

The dispersion simulations with different mass sources were carried out within a 2-lane tunnel with a height of 5m and a width of 10m. The examined length of the tunnel was a section of 100m. The considered accident scenario is shown in figure 10. Here, the gas source was considered to be in the middle of the tunnel section, located under a car to avoid a dilution of the supplied gas by an initial source momentum. For this scenario, the mentioned influences of the correct initial momentum could be minimized. According to the previous considerations about the influence of storage conditions and release area, the gas distribution was simulated for different source rates (release of total content of the tank within a few seconds, release 1: 0.05kg/s and release 2: 0.0005kg/s) and different release temperatures, as they are listed up in table 2.

<table>
<thead>
<tr>
<th>total mass</th>
<th>mass flow rate $m_1$</th>
<th>mass flow rate $m_2$</th>
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</tr>
<tr>
<td>propane</td>
<td>47.61kg -42°C 0.05 kg/s -42°C 0.0005 kg/s -42°C</td>
<td></td>
</tr>
<tr>
<td>hexane</td>
<td>50.00kg 20°C 0.02 kg/s 20 °C 0.0005 kg/s 20°C</td>
<td></td>
</tr>
</tbody>
</table>

Methane ($M_{\text{CH}_4}=16.04$ g/mol) represented the natural gas, while propane ($M_{\text{C}_3\text{H}_8}=44.1$ g/mol) represented the autogas LPG. Hexane ($M_{\text{hexane}}=86.18$ g/mol) was chosen to represent gasoline, since it is a mixture of components with many different molecular weights. Because the objective of this study is the increased hazard of gas driven cars in comparison to the conventional fuel gasoline, for release 1 there was a decreased source of 0.02kg/s that also takes the extended evaporation of gasoline into account. Likewise the total amount of gasoline would not evaporate within a few seconds, but here was taken into account to compare it with the other fuels. The gas concentration was measured for the considered scenarios at different heights (0.5, 2.5 and 4.5) at 25m and 50m up and down the tunnel sides, as represented by the crosses in the figure. Concrete walls with a thickness of 50cm and more, according to the required grid, were considered as a surrounding to the tunnel area with the intention to enable an energy exchange with the cold gas.

![Figure 9](image)

**Figure 9** geometry of tunnel with concentration measurement point: top view
The mesh +/- 25 m around the gas source car was divided into rectangular cells with a height of 0.125 m, a width and a length of 0.25 m. In the remote part of the tunnel there was a coarse mesh with a length of 0.5 m. Because the FDS geometry is restricted the cars were represented by a rectangle.

The considered ventilation scenarios were modelled according to the classifications of longitudinal and transverse tunnel ventilation scenarios described in the Handbook of Tunnel Safety [17] and the NFPA 502 [18]. For the longitudinal ventilation a low velocity of 1 m/s was chosen to compare the gas distribution behaviour of the light and heavy gases in case of the normal operation mode that initially addresses the dilution and removal of pollutants. To represent the transversal ventilation, supply and single extraction points with a width of 0.5 m and a length of 1 m were placed every 4 meters at one lower side of the tunnel and beneath the ceiling on the opposite side. The considered inflow or outflow velocity of 1 m/s is conforming to an air change rate of 9 h⁻¹. Furthermore the influence of lesser velocities (e.g. 0.2 and 0.5 m/s) is tested. All observations are related to the particular explosive limits of the fuels in the gaseous phase.

As figure 15 for volume sources (total amount of tank) describes, the influence of the lower temperature could be neglected in case of propane which initially is a heavy gas. The negative buoyant effect was thus intensified by the lower release temperature, but did not have an influence on the gas distribution. In sharp contrast, the positive buoyant effect of methane was reversed by the lower release temperature. This led to a longer distribution time, however, the heavy gas behaviour of the cold methane was neutralized after a few seconds and the methane spread beneath the ceiling. Due to the higher density, the gasoline spread faster than the gaseous LPG, while the distribution of methane in case of the release of the total mass lasted up to 3 minutes longer, simulated at a distance of 50 m away from the accident. For mass release 2, no explosive cloud was built during the simulated release of 2000 seconds (circa half an hour).

In the longitudinal ventilation mode, the released gas clouds were pushed downwind. The cold methane showed the same behaviour with and without ventilation. Here, no distribution of the gases over the height was observed, as shown in figure 16. The heavy gases layered above the floor, while the light gas layered beneath the ceiling. No back layering was observed. An increased velocity from 1 to 5 m/s raised the heavy gas and leaded to an increased distribution over the height. Hence, no stratification for the heavy or light gas is observed.

In case of the mass release 1, an explosive cloud was built only a few meters downwind of the source. With a velocity of 1 m/s the full transverse ventilation system was capable to press a part of the heavy gases propane and hexane (represented gasoline) up to the ceiling in case of the release of the total content of the tank within a few seconds. There it was partially extracted from the tunnel section. This went ahead with a mixture of the gas over the whole tunnel area. This phenomenon was also observed for the light gas methane. However, due to the induced turbulence, the methane distributed also over the whole area in small, bordered clouds and did not build a homogenous layer beneath the ceiling. A slower velocity of 0.5 m/s showed this behaviour too, while at a velocity of 0.2 m/s no vortexing of the gas happened.

The mass source 1 of 0.05 kg/s (respectively 0.02 kg/s) leaded during the transversal ventilation mode with 1 m/s velocity as well to distributed gas clouds all over the tunnel section.
The full transverse emergency system with a multiple zone concept, where the air was exhausted in the accident zone (+/-25) and supplied in adjacent zones did not lead in the considered scenario to a constraint of the explosive gas in one zone. The higher velocities of 1m/s caused a homogenous distribution in explosive clouds all over the height for both heavy and light gas, as it was observed in the standard mode. Merely slow velocities of 0.2 m/s led to a stratification of the gases. In this case, the extraction of air at the top and the bottom in the exhaust zone led also to an extraction of the heavy respectively light gas.

A single point extraction of air at top and bottom in all zones with the velocity of 1m/s caused a stratification of the gas and thus an extraction of the heavy and light gas. For the steady release of m1, the same observations were made, but the distribution took longer.

For the semi transverse system, the air supply with 1 m/s at the top of the tunnel led to explosive clouds below the ceiling and above the floor, for both heavy and light gases. Figure (x) illustrates this.
behaviour for methane (CH₄) and gasoline (hexane). Propane (C₃H₈) showed the same behaviour. In case of extraction beneath the ceiling, the light gas was extracted but the heavy gases did not show any influences. In the contrary scenario, for extraction at the floor, no methane is exhausted through the bottom nodes.

HAZARD REDUCTION
The gas behaviour during different ventilation mode shows, that the kind of ventilation has a strong influence on the gas distribution when the total content of the tank is released as a gas. While the longitudinal ventilation mode displaces the hazard and pushes the explosive cloud upwind through the tunnel, the transverse ventilation mode is capable to vortex the heavy and light gases. This depends on the inflow velocities and consequently on the induced turbulence within the tunnel section, no matter if full transverse or semi transverse ventilation mode is used. The multiple zone concept does not constraint the gas cloud but also vortexes the gases. Only the exhaust modes are able to remove the gases and thus reduce the hazard of an explosion. Extraction below the ceiling or above the ground is essential to remove the light or heavy gases that are released in a cloud. For limited mass sources like m₁, the hazard can be minimized by the longitudinal ventilation. In contrast, for limited mass sources the transversal system does not cause a minimization of the hazard. The inflow velocity of the transversal ventilation nodes has a significant influence on the distribution behaviour.

DISCUSSION
While the NFPA 502 Standard for Road Tunnels, Bridges and Other Limited Access Highways [18] addresses in the Annex G alternative fuels like CNG and LPG, the Directive 2004/54/EC of the European Commission [19] does not include these fuels. The NFPA advises to evaluate each tunnel ventilation system on a case-by-case basis for the release of alternative fuels; however, the EC Directive only tackles smoke movement for the design of the ventilation system.

The conducted simulations showed that the LPG disperses similar to the conventional gasoline, although the time for mitigation differs little, due to the decreased heavy gas behaviour. The distribution of methane (natural gas) was observed as reversed to the heavy gas behaviour. Moreover the distribution without ventilation took a few minutes longer for the considered length of 50m away from the source. For both ventilation types, the turbulence or recirculation of the ventilation had an essential influence on the distribution behaviour. A high transversal velocity led to a spreading of the gases over the tunnel where an initial gas cloud broke apart in smaller ones that distributed along the tunnel length. It depends on the magnitude of the velocity if the gas can disperse opposed to its natural behaviour either at the top or the bottom of the tunnel.

Dilution by the ventilation system as proposed by the NFPA did not lead to mitigation in case of the total released content of a tank, but for smaller release rates indeed minimized the hazard zone a few meters around the damaged tank. There, for the considered ventilation scenarios, the longitudinal ventilation enabled the best dilution. Transversal ventilation has to be managed sensitive, to address both heavy and light gases. A fast response on the regulation of the ventilation system simultaneously with a detection of the released gas is essential to avoid uncontrolled distribution of small gas clouds in the tunnel.

CONCLUSION
It has shown that due to the pooling of the gasoline and the subsequent evaporation there were differences in the release behaviour of alternative fuels in contrast to the conventional one. Especially for a leak nearby the tank, gasoline provided a much longer time until it was evaporated completely and therefore a longer time until a hazard atmosphere inside the tunnel was created. In contrary, for a leak behind the vaporizer there were only some minutes differences in release time. Here, gasoline was released faster than the alternative fuels (up to 20min for a break of the line). The kind of ventilation system had a significant influence as well on the dilution in terms of a limited mass source as on the distribution and partition of one gas cloud.

ACKNOWLEDGEMENT
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REFERENCE
2. www.pronuss.eu. [Online]
Identification of Critical Tunnels in a Road Network

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Bergisch Gladbach, Germany

SUMMARY
Bridges and tunnels on highways and major roads are key elements of the Trans-European Road Transport Network. In order to improve the security of these infrastructures regarding man-made hazards a comprehensive overview about number and different types existing in the different European Member States is necessary. In order to get this overview a survey among road operators in Europe was conducted. The paper describes the comprehensive analysis carried out concerning relevant tunnel types in Europe and presents a method to identify possible critical tunnels in a road network. Finally an outlook of the currently executed detailed investigation of critical infrastructures on a major highway links is given.

KEYWORDS: road network, road tunnel, critical infrastructure, protection measure, infrastructure failure, man-made hazards

1 INTRODUCTION
The European road network is of major importance not only for the mobility of European citizens but also for the European economy. Even small disruptions due to traffic restrictions or failure of road network elements can lead to severe traffic interference resulting in potentially high economic costs and negative environmental impacts. Bridges and tunnels are key elements of the road network, particularly as they can act as functional bottleneck. Such infrastructure objects may therefore constitute attractive targets for man-made attacks, and attractiveness added to by their accessibility and great potential impact on human lives and economic activity.

In order to identify the most critical infrastructure objects in the European road network and to protect them with appropriate measures an overview about existing bridge and tunnel types in the different EU member states is essential. Due to different construction standards in the European countries especially before the introduction of the Eurocodes and because of different environmental conditions (e.g. climate, topography, geology) many different types of bridges and tunnels exist in the EU. The investigation concentrates on bridges and tunnels on major highways of the Trans European Road Network (TEN-T roads). Based on the results of a survey among European road operators relevant bridge and tunnel types could be identified and categorised by major construction specifications (e.g. length, material, etc.). Based on the identified relevant bridge and tunnel types a classification concerning parameters, important to assess an objects criticality, is done. This paper presents the tunnel results of the investigations. The bridge results have been presented at the 2011 IABSE-IASS Symposium [1]. The paper describes the comprehensive analysis carried out concerning tunnel types in Europe and presents a method for the identification of possible critical tunnels in a road network. Finally an outlook and first results of the currently executed detailed investigation of critical infrastructure failure on an example TENT-T highway link is given.

2 SURVEY AMONG EUROPEAN ROAD OPERATORS
2.1 Survey questionnaire
To identify the most common tunnel types in the EU, operators of Trans European Roads (TEN-T roads) were interviewed by means of a survey. To support this, different forms were developed to gather data about tunnel types in the different EU member states (Figure 1). The forms contain a big variety of tunnel types considered as relevant. The contacted road operators were also asked to add new
types if some types existing in their road network are not included in the initial forms. Additionally the road operators were asked to categorize their tunnel stock by type, number of tubes / cells and length (Figure 1).

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<thead>
<tr>
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</tr>
<tr>
<td>Immersed Tunnel</td>
</tr>
<tr>
<td>Cut and Cover Tunnel</td>
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<td>Partly Covered Tunnel / Gallery</td>
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</table>

Figure 1: Final Survey form for identification of relevant tunnel types (completed example for one country)

2.2 General survey results
For the survey 32 road operators from 19 European countries were contacted. The selection of member states was done based on availability of contact persons and TEN-T road network length. The organization of responsibility for road operation and technical infrastructure data differs between EU member states. In many countries the responsibilities for road infrastructures are still at government level whereas the network operation is in the hands of private companies. In some countries it is private operators that have technical data for the infrastructure in an area that they are responsible for. In countries with many different private road operators like e.g. France (18 companies), Spain (38 companies) and Italy (24 companies) only selected operators responsible for a considerable length of road network have been contacted for the survey.

In the end 17 operators (53%) from 14 countries (74%) replied and provided data about their tunnels on major roads/highways including TEN-T roads. Due to the good levels of feedback to the survey the gathered data may reasonably be seen as representative for the European road network.

The survey questionnaire asked for network length (Figure 2) and number of tunnels, each subdivided in total length/number and length of/number on TEN-T-roads. The questionnaire was accompanied by the form for relevant types (Figure 1).

The total European network length covered by the survey is about 26,400 km of TEN-T roads. Due to the different answers of the countries concerning other roads (some considered motorways / highways, some also secondary roads), only the TEN-T road network length is taken into consideration and shown by country in Figure 2. The data for some countries is for the complete network (e.g. Germany, Austria, and Sweden). For other countries (e.g. Italy and France) only part of the road network is considered because the operator answering the survey is only responsible for part of the road network.
2.3 Tunnel results
Stakeholders from 13 countries provided general data of overall 638 tunnels. In total 12 main tunnel types were identified as relevant in the EU (Figure 1). The tunnel types differ from one another regarding construction method/system (e.g. NATM tunnel) and cross section (e.g. 1 tube, 2 tubes). The following figures show the distribution concerning tunnel length (Figure 3) and tunnel type (Figure 4). The analysis is presented in the following chapter 3.
3 EUROPEAN TUNNEL TYPES

The reason for the classification regarding the parameters type and length was to identify limit values in order to determine which infrastructure - from a big stock of tunnels in a road network - are possible critical and must be investigated more in detail. From the analysis of all technical data gathered with the survey the following conclusions concerning European tunnel types may be drawn:

The most frequent tunnel types in Europe are NATM-tunnels (54%) and Cut and Cover tunnels (37%). The other tunnel types like TBM- and Immersed tunnel or Gallery are only built for special applications (e.g. river crossing, soft ground, etc.) if the standard solutions are technically not possible or if the construction method has economical advantages. This could be the case e.g. for very long tunnels in hard rock. Here the mechanised TBM tunnel could have cost advantages compared to the conventional NATM tunnel. Due to the potential extensive effects in case of damage or failure, tunnels under water (TBM (single shell) and Immersed Tunnel) are considered as sensitive and therefore as relevant concerning criticality.

Concerning tunnel length the short tunnels up to 500 m are dominant in the EU (56%). Tunnels longer than 1000 m (22%) are identified to be interesting concerning criticality. The reason why 1000 m has been chosen as a limit value is because of the regulations of the EC-tunnel directive [2]. Here a number of additional safety requirements must be investigated and considered if necessary for tunnels longer than 1000 m (e.g. ventilation system, emergency exits).

A summary of the classification of the relevant European tunnel types could be found in Table 1. The criteria for a classification concerning criticality mentioned here will be considered further in the development of a method to identify possible critical tunnels (cf. chapter 4).

Table 1: Classification of relevant European bridge and tunnel types based on all survey data collected

<table>
<thead>
<tr>
<th>Infrastructure</th>
<th>Parameter</th>
<th>Classification frequency</th>
<th>Classification criticality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel</td>
<td>Type</td>
<td>NATM and Cut &amp; Cover Tunnel</td>
<td>TBM and Immersed Tunnel</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>&lt; 500 m</td>
<td>&gt; 1000 m</td>
</tr>
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</table>
4 IDENTIFICATION OF CRITICAL TUNNELS

Based on the presented classification of relevant European tunnel types a method for the identification of possible critical infrastructure objects or better “for the exclusion of obvious not critical objects” has been developed. This method takes also traffic parameters into account because also a short tunnel could be critical in terms of a network perspective. The flowchart in Figure 5 gives an overview of the identification method for tunnels.

**Step 1A**
- **Traffic volume**
  - Very high DTV or Very high HGV percentage
  - No

**Step 1B**
- **Damage potential**
  - High DTV and High HGV percentage
  - Yes

**Step 2**
- **Economic consequences**
  - Long single tube tunnel or tunnel under water or under sensitive buildings
    - No
  - Long reconstruction time
    - Yes
  - High symbolic value (internationally known)
    - Yes

**Further detailed examination**

**Figure 5: Flowchart for the identification of possible critical tunnels**

DTV = Average daily traffic volume of whole cross section (both directions, all lanes)
HGV = Heavy goods vehicles > 3.5 t (Percentage of DTV)
The method applied is that of a „rough filter“ which should help to identify a limited number of possible critical objects from a large amount of tunnels. The method considers 4 important criteria (influence factors):

- **Criterion 1: Traffic volume**
- **Criterion 2: Damage potential**
- **Criterion 3: Economic impact**
- **Criterion 4: Probability**

The criteria are checked in a top-down procedure, beginning with the 1st (basic) criterion for importance of an object (Figure 5). If an object fulfills one of the criteria the object is retained for further study, the subsequent criteria need not be checked. The method considers different steps:

Step 1A consists of a basic check regarding the defined criteria. Only if the result of Step 1A is „yes“, the object specific relevance of the criterion is checked in Step 1B. Some possible criteria of object specific relevance are mentioned in the flowchart (Figure 5). More relevant criteria must be defined object specific by an engineer, who has knowledge of the infrastructure, i.e. someone who is responsible for the operation of a certain tunnel stock. If the result of Step 1B is also „yes“ the infrastructure is possibly critical and must be investigated in more detail in Step 2 which is not part of the method described in the flowchart. A possible method for Step 2 is described in sub-chapter 4.5.

The method for the identification of possible critical infrastructures (Step 1A, 1B) has already been evaluated with the available tunnel data from Germany, Austria, Italy, Denmark and Great Britain gathered with the survey (cf. chapter 3). The criteria threshold values (e.g. for traffic volume) must be adjusted according to the infrastructure stock and particularities of different EU member states. Unified criteria for whole Europe are very hard to define.

### 4.1 Criterion 1: Traffic volume

Traffic volume is a basic criterion. All infrastructures with a very high traffic volume (DTV - average daily traffic volume) are considered to be very important for the road connection and should be checked in detail. The same should be done with infrastructure which has a high heavy goods vehicle (HGV) volume. In order to identify only infrastructure with a high absolute number of HGV vehicles this check is included in Step 1B.

The 2nd traffic volume criterion is used to identify objects, which have a relatively high traffic volume (DTV) and additionally a high HGV percentage. Objects satisfying Step 1A (“yes”) the infrastructure is possibly critical and must be investigated in more detail in Step 2. Due to the “and” combination of the two parameters a Step 1B is not necessary for this 2nd traffic volume criterion.

The threshold value for criterion 1 must be chosen according to the traffic load of the investigated road network. This value could be very different in the EU member states. For example in Germany with a very high DTV on many highways a threshold value of 100,000 vehicles per day (both directions) and a HGV percentage of 20% could be feasible. For the 2nd traffic volume criterion 50,000 vehicles per day and a HGV percentage more than 15% have been proved to be realistic for Germany and some other EU member states.

### 4.2 Criterion 2: Damage potential

All long tunnels with bi-directional traffic (only one tube) should be investigated more in detail due to the possible negative impact on the road network if the tunnel is not available (no redundancy via a 2nd tube). The threshold value for a long tunnel could be set to 1000 m which comes from the EG Tunnel Directive [2]. Tunnels under water (river or completely in soft ground underground water) or directly under sensitive buildings are considered to be possibly critical and should be investigated more in detail. All immersed tunnels and TBM driven tunnels will fall under this criterion. With Step 1B tunnels crossing very small rivers, very deep under buildings or with a very low traffic volume (e.g. less than 10,000 vehicles/day) are excluded from a detailed investigation in Step 2. These tunnels could be considered as not critical concerning criterion 2 and will be checked further with criterion 3.
4.3 Criterion 3: Economic impact
Tunnels that are very hard to rebuild (i.e. have a long re-construction time) are considered to be potentially critical. If for this infrastructure operation or part operation (more than about 50% of the previous DTV) could be easily resumed with a provisional construction, this is considered as object specific not critical (Step 1B) and Step 2 need not to be executed. An example is a tunnel with 2 tubes: if one tube is blocked, traffic could still flow through the 2nd tube.
Due to the often missing information about reconstruction costs and the problem to define a threshold value for costs, this criterion has not been chosen for the estimation of economic impact.
Reconstruction time has been chosen instead. The threshold value for a long reconstruction time could be e.g. more than one year. Reconstruction time means in this context only the time for construction works and does not include damage assessment, tender procedure, awarding and design works.
Especially the necessary time for tender procedure and awarding differs from country to country. For the estimation of the reconstruction time of tunnels the construction time of the initial tunnel construction could be used.

4.4 Criterion 4: Probability
For the probability of attack only the symbolic value is considered as relevant. Only objects (mainly valid for bridges) internationally known should be considered as relevant. Tunnels with a symbolic value are considered as very rare. There is no Step 1B for infrastructures with a symbolic value, because it is a yes / no decision. The accessibility of the structure has not been chosen as relevant for this criterion, because most of the road infrastructure is easy accessible and is therefore a simple target for people with malicious intent. This was also result of the survey.

4.5 Procedure for a detailed examination (Step 2)
The steps for a detailed investigation of an objects criticality in a risk assessment could be as follows:
1. Determination of decisive scenarios for the tunnel (e.g. explosion and fire scenario)
2. Determination of the scenario probabilities (tools: fault- and event tree analysis)
3. Calculation of the direct consequences due to the chosen scenario
   a. Structural damage (tools: fire simulation, explosion impact calculation)
   b. Fatalities (tools: CFD models, pedestrian movement models)
4. Calculation of the indirect consequences due to the scenarios
   a. Network related effects of infrastructure failure (tool: traffic flow simulations)
   b. User costs due to additional travel time
   c. Other socio-economic consequences (e.g. environmental costs)
5. Calculation of the risk

The result of the risk calculation for different objects allows a comparison of objects and a possible ranking of tunnels according to criticality. If the level of acceptable risk could be defined (which is often a problem) the result of the risk calculation could be checked against this threshold value and allows a direct conclusions about the criticality of a single tunnel.

5 EXAMPLE TEN-T LINK
The method described in the previous chapter has been applied to an example TEN-T highway link based on the technical infrastructure data gathered with the survey. The Brenner Highway link (E45) from Munich (Germany) via Innsbruck (Austria) to Modena (Italy) crosses the Alps and has many bridges and tunnels (Figure 6). Concerning tunnels the majority of tunnels are short (<500 m) on the Brenner link. There are only 4 long tunnels between 500 and 1000 m on the Italian A22. Nearly all tunnels were built as NATM tunnel or gallery.
For the Brenner highway connection from Munich to Modena (E45) the results of Step 1A are as follows:

11 (of 22) tunnels must be investigated more in detail in Step 1B and/or Step 2:

- 4 tunnels due to Criterion 1
- 1 tunnel due to Criterion 3
- 6 tunnels due to Criterion 4

This shows that the method for the identification of possible critical tunnels could considerably reduce the number of tunnels to be investigated more in detail. The 6 tunnels with symbolic value (according to the local operator) have no international symbolic value and should therefore not be considered to be possible critical. Tunnels with a high symbolic value are generally considered to be very rare. The 4 tunnels due to Criterion 1 met the 2nd traffic volume criterion and could therefore be investigated directly with Step 2 of the method (detailed investigation). Thus there are 4 tunnels remaining which should be investigated more in detail in Step 2 of the method and one tunnel in Step 1B.

The application of Step 2 of the method for 2 example tunnels on the E45 is currently under examination. Results will be presented at the symposium.

6 CONCLUSIONS AND OUTLOOK

A large number of technical tunnel data has been gathered with the help of a survey among European road operators. The available data stock could be considered as representative for Europe because more than half of the European member states participated in the survey. Based on the technical data available the most relevant European tunnel types have been identified and classified. For the 12 relevant tunnel types the overall tunnel length and the construction method (e.g. NATM tunnel) have been identified as relevant for classification. Tunnel classification is subdivided into frequency and criticality.

Based on the presented classification of relevant European tunnel types a method for the identification of possible critical infrastructure has been developed and tested with example data from the survey. The proposed method to identify critical tunnels could be applied to every road network. It should help owners and operators to filter their tunnel stock and by this to focus on the decisive infrastructure of their road network. The method could be also helpful for the national implementation of the European directive 2008/114/EC [3]. The identified possible critical tunnels (Step 1A) must be investigated more in detail with the help of further object specific expert knowledge (Step 1B) or finally with a detailed risk assessment (Step 2). Depending on the outcome of this detailed analysis, the calculated risk and the conclusions concerning criticality, additional measures to improve the tunnels security could be implemented by the operator. The risk reducing influence or “effectiveness” of additional security measures could be investigated with the proposed procedure for detailed investigation (risk assessment) as well. The detailed investigation of 2 example tunnels with Step 2 of the method presented in this paper is currently under progress and will be finished end of 2011. Results of the detailed risk assessment will be presented at the symposium.
7 ACKNOWLEDGEMENT
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REFERENCES
SOME OF THE NFPA 130 IMPROVEMENTS PROPOSED FOR THE 2014 EDITION

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Mandatory NFPA Disclaimer - NFPA’s Regulations Governing Committee Projects, allows me, as a member of the Technical Committee (TC) to provide you with my personal opinion; it should also be known that my opinion does not necessarily represent the position of the TC or the Association and may not be considered to be or relied upon as such.

ABSTRACT: (Shortened)
The National Fire Protection Association (NFPA) Standard 130, entitled “Standard for Fixed Guideway Transit & Passenger Rail Systems” provides criteria to the transit and rail industry for the design of underground, at-grade and above ground (elevated) transit systems and their elements. The Technical Committee (TC) of NFPA 130 for the 2014 edition is taking on a number of significant issues, all of which have evolved since the previous edition published. First is the need for new and possibly expanded systems to locate stations and their respective tunnels deeper in order to go beneath existing infrastructure. A constant inquiry received over the years is that we must develop a uniform methodology for determining the Fire Heat Release Rates (FHRR) of fixed guideway and passenger rail vehicles. On-board fire suppression technologies for new and existing rail vehicles to fight the fire at its main source will be introduced. One of the more critical chapters of the standard will be reorganized and brought into line with the industry’s developmental process. Wire and cable requirements will be extracted from individual chapters (except the vehicles chapter) updated based on latest industry practices, and placed in one newly formed chapter. All of these improvements, plus others being considered will be included in the next edition.

1 INTRODUCTION

The National Fire Protection Association (NFPA) has developed two fire-life safety standards for tunnels. The rail tunnel standard is NFPA 130, “Standard for Fixed Guideway Transit and Passenger Rail Systems,” and the road tunnel standard is NFPA 502, “Standard for Road Tunnels, Bridges, and Other Limited Access Highways.” Both standards provide the minimum fire-life safety requirements for new construction as well as guidance for the rehabilitation of older tunnels and rail stations, with the ultimate goal of protecting human life. To keep up with an ever-evolving transportation industry both standards are updated every three (3) to five (5) years.

2 NFPA 130 DESCRIPTION

The “Standard for Fixed Guideway Transit and Passenger Rail Systems” document known as NFPA 130 is the only rail transit and passenger fire-life safety standard in the world. The Technical Committee’s (TC) scope as written:

“This Committee shall have primary responsibility for documents pertaining to fire safety requirements for underground, surface, and elevated fixed guideway transit and passenger rail systems including stations, trainways, emergency ventilation systems, vehicles, emergency procedures, communications and control systems and for life safety from fire and fire
protection in stations, trainways, and vehicles. Stations shall pertain to stations accommodating occupants of the fixed guideway transit and passenger rail systems and incidental occupancies in the stations.”

Because NFPA 130 is geared toward the movement of commuting passengers on transit and rail vehicles other categories, such as conventional freight, trolley coaches, circus trains, tourist trains, scenic, historic or excursion operations are not covered by this standard. Unless they do by sharing a common transportation corridor with a fixed guideway transit and/or passenger rail system, they potentially pose a threat to its fire-life safety. The other categories listed above historically utilize older and possibly out-of-service vehicles only to return to service to serve one or more of the non-inclusive categories. In most situations, these vehicles do not meet present day NFPA 130 vehicle fire hardening standards. For this, we normally request that a Fire Heat Release Rate Analysis (FHRR) of the non-inclusive category vehicle be performed. Should such a condition exist, the fixed guideway transit and/or passenger rail system property owner/operator would then have the option of implementing additional fire safety measures of which there are at least three available:

1) Increasing emergency ventilation capacities when it is determined through a fire analysis that the fire heat load of the non-included vehicle that it will be significantly higher than the design fire heat load of the “fixed guideway transit or passenger rail system” thus creating an untenable situation.

2) Holding back passengers in safe areas until the adverse condition passes, and

3) The introduction of tunnel and or station sprinklers and/or adding on-board misting systems.

2.1 Elements of the Standard

The 2010 edition of NFPA 130 consists of ten (10) technical chapters and seven (7) annexes.

2.1.1 Technical Chapters

- **Chapter 1 – Administration:** Provides the scope of the Standard and defines the applications under which this standard will relate.

- **Chapter 2 – Referenced Publications:** Lists all applicable publications referenced within NFPA 130 from the NFPA and other organizations such as the Air Movement and Control Association (AMCA), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the American Society of Testing Materials (ASTM), the Federal Aviation Regulations (FAR), and the Underwriters Laboratories (UL).

- **Chapter 3 – Definitions:** Lists all the terms as they apply to this standard and provides a listing of all relevant standard NFPA terms along with their definitions.

- **Chapter 4 – General:** Provides the characteristics of fire safety and defines the goals and objectives of NFPA 130.

- **Chapter 5 – Stations:** Provides requirements for below-grade, at-grade and elevated stations including civil works and construction materials, wiring and power, emergency egress, lighting, and fire protection including sprinklers and standpipes, etc. (where required).

- **Chapter 6 – Trainways:** Provides requirements for below-grade (tunnels), at-grade and elevated trainways including civil works and construction materials, wiring and power, emergency egress, traction power, and fire protection requirements for underground fuel storage tanks adjacent to or above subsurface trainways.

- **Chapter 7 – Emergency Ventilation Systems:** Provides requirements for the design of emergency ventilation systems, including but not limited to emergency fans, dampers, power and wiring, inflatable barriers and their operation and control (local and/or remote).
• **Chapter 8 – Vehicles:** provides requirements for vehicle construction, material and component testing, fire propagation resistance, ventilation, emergency egress, fire protection, testing and maintenance, and electrical elements including insulation, motors and their control, wiring, overload protection. (Note – Wiring and cables to remain in this chapter in the 2014 Edition as they pertain to Vehicles)

• **Chapter 9 – Emergency Procedures:** This chapter, one of the most important chapters in the standard, it was developed by first responders and property owners/operators to give guidance on proper and prompt response to an emergency event. Over the years, more lives have been lost due to slow response than to insufficient equipment to handle the event.

Having the proper emergency response precautions in place influences the day-to-day operations of any transit system. This chapter includes requirements for emergency planning and responses, planning of initial responses, roles of participating agencies (Authorities Having Jurisdiction (AHJs)), the role of the Central Supervising Station (also known as Operations Central Control), and requirements for training, drills and critiques. The components covered in this chapter apply to ALL types of systems, old and new.

• **Chapter 10 – Communications:** This chapter, newly added to the 2010 edition covers communications of all kinds that would exist in fixed guideway passenger and rail transit systems. The chapter includes requirements for radios, telephones and public address systems in stations during normal, day-to-day operations as well as in the event of an emergency.

The standard also defines the relationship between the Central Supervising Station and the at-the-scene Command Post throughout an emergency.

2.1.1 Annexes
The Annexes are included in NFPA 130 to provide clarification and supporting information to that which is included in the technical chapters of the standard. An annex does not contain enforceable requirements unless an owner/operator or AHJ adopts it for use as a safety guideline to be followed.

• **Annex A – Explanatory Material:** Provides supporting information for Chapter 1 – Administration;

• **Annex B – Ventilation:** Provides supporting information for design of emergency ventilation systems. This annex also identifies factors for consideration in maintaining a tenable environment.

• **Annex C – Emergency Egress:** Provides examples of emergency egress calculations to allow the designer to properly plan egress routes to areas of safety with the proper number and locations of stairways, escalators and elevators;

• **Annex D – Rail Vehicle Fires:** Provides information the hazards associated with burning vehicles and the impact on passengers evacuating from them;

• **Annex E – Fire Hazard Analysis Process:** Provides an expanded description understanding of the process required to conduct a fire hazard analysis for fixed guideway and passenger rail vehicles;

• **Annex F – Creepage Distance:** Provides the minimum creepage distance for transit vehicles; and

• **Annex G – Informational References:** Lists publications referenced in the Annexes.

2.2 Background of the Standard
In 1975, the NFPA established a Technical Committee to develop a standard for the rail industry to deal with the fire life-safety needs of Fixed Guideway Transit Systems. This need for a RAIL standard became evident when existing and new rail properties began to understand that dedicated rail guidelines did not exist at the time, and where the only guidelines that did were for buildings and structures. Members of the transportation industry quickly realized that rail was unlike buildings and
structures. Once the NFPA 130 Technical Committee was established, transit properties in Atlanta, Baltimore, Los Angeles, Pittsburgh and Washington had systems on the drawing board. This reinforced the need to develop a rail fire-life safety standard; NFPA 130 became that standard. Plans for some of the systems under consideration had progressed from design and were now ready to enter into construction; there no guidelines to follow. That is other than what designers had knowledge of from their experiences designing in the industry. Furthermore, it was determined that design methodologies that had been employed prior to World War II were no longer valid and that an overall overhaul of methodologies was needed to keep up with an evolving transit market. Older transit systems in Boston, Chicago and New York were all reaching their saturation levels that expansions became necessary however, there were no rail specific guidelines in-place to follow.

Because of this, the responsibility for design on the older rail systems fell to the “Authority Having Jurisdiction, the enforcer (“AHJ” as it is more commonly known) to make decisions; with this transit property owner/operators were obligated to make engineering judgments they felt were appropriate to resolve an apparent need. The AHJ had the responsibility for enforcing local rules and regulations in which a facility was located or one where a new system was being contemplated. However, while adhering to the existing rules and regulations (building codes), most AHJ’s, rightfully so were experienced in building and structures fire-life safety, however, they lacked experience in rail. Each owner/operator wanted their own systems designed and constructed at as low a cost as possible, as expeditiously as possible, and they did not want to incur any delays caused by the statutory approval process. At the time, there was no consistency of safety in design of rail systems available and thus each property owner/operator along with their respective designers, were designing to what they individually knew as being proper.

The standard and code development process within the NFPA, under which NFPA 130 falls, is comprised of volunteer representatives from every facet of the industry regardless of the document. Each member of the committee is impart its knowledge and experience to others; all members are volunteers that are from a wide range of property owners/operators, special experts (i.e. engineers/architects), enforcers (often AHJ’s, first responders, code enforcement organizations, etc.) to topic product manufacturers. NFPA 130’s Technical Committee consists of 30 Principal voting members plus their Alternates. To avoid the possibility of any one group controlling an outcome the 30-member committee have been proportioned whereupon all changes must be agreed to by consensus voting. The composition of the TC of NFPA 130 is as follows:

**Users - (U)**
- National Railroad Passengers Corporation (Amtrak)
- Port Authority Trans-Hudson (PATH)
- Metropolitan Transportation Authority (MTA) has two voting positions organized amongst three individual rail services:
  - Long Island Rail Road (LIRR)
  - Metro-North Railroad (MNR)
  - New York City Transit (NYCT)
- Washington Metropolitan Transit Area Authority (WMATA)
- Chicago Transit Authority (CTA)
- Toronto Transit Commission (TTC)
- Societe de Transport de Montreal (STM)
- Land Transit Authority of Singapore (STA)

**Enforcers - (E) (AHJs, etc.)**
- Seattle Fire Department
- Los Angeles County Fire Department

**Special Experts - (SEs)**
- Parsons Brinckerhoff, Inc.
- Hughes Associates
- AECOM
- ARUP
- LTK
- Lea + Elliot
- ITF Fire Cause Analysis

**Manufacturers - (M)**
- Bombardier

**Research/Testing Organizations - (RTs)**
- National Institute of Standards and Technology (NIST)
- United States Department of Transportation ((USDOT)/Volpe)

**Insurance - (I):**
- AON (formerly Schirmer Engineering)
A major incident occurred in December 1971, on the Montreal Metro System in Canada at the Henri-Bourassa Metro Station. The incident, where a train operator lost his life following a crash, where a number of parked train sets stored at the location were destroyed by fire, an outcome of the initial incident. The fire even consumed an above motor vehicle parking structure. For the firemen to put out the fire, the entire terminal was flooded covering all of the trains until the fire was extinguished. After an extensive investigation concluded, the results pointed towards a faulty brake system on the incident train-set. That throughout the initial stages of the fire, the incident train-set kept drawing power and continued to feed the fire until the terminals power was shut down. Having the terminals power shut down also compromised the emergency ventilation system that ventilated the facility. With the power off to the emergency fans, the fans failed to provide the needed critical velocity, as such the fire began backlayering with its heat and smoke. To make a bad situation even worse, the train’s tires were nitrogen filled and began exploding from the heat generated by the fire.

Montreal Transit provided their findings to the industry from which they could develop corrective recommendations to these deficiencies. Solutions, as part of this review effort led designers to develop methodologies to protect life and property. The concept of two sources of power to critical life-safety elements was set into motion such as two independent, separated protected power feeds to the emergency fans was developed. Additionally, introduced was a dependable fire standpipe system, rather than going to the extreme of flooding an entire station/terminal to extinguish a fire, it should be fed by two independent water supply sources; also, as we have found was that multiple fire districts could and would to respond to a fire. These fire districts in some cases used different hose fitting threads; the concept of having various fittings at each tie in point became an important factor.

The lessons learned as an outcome of the investigation led NFPA 130 to adopt a concept of dual feed/redundancies for to various fire-life safety systems such as fire standpipe system that shall be connected to two separate and independent water sources that must also have appropriate fire department fittings available at each tie-in point. That power to critical life safety mechanical systems, such as emergency ventilation must have two protected and available sources. The incident in Montreal triggered the thought process for which NFPA 130 was developed.

NFPA-130’s first edition was in 1983. However, it soon became evident that there was a need to update the standard on a regular basis, at intervals of approximately every three to five years or sooner if necessary based on the needs of the industry. Thus with the 1983 edition being the first, later editions were published 1986, 1988, 1990, 1993, 1995, 1997, 2000, 2003, 2007 and 2010; the next edition will be issued in August 2013 and dated 2014.

In 1988, the Technical Committee added the Automated Guideway Transit (AGT) component to the standard. This caused modifications to former Appendixes C (Emergency Egress) and D (Suggested Fire Test Procedures for Fire Risk Assessment).

A shift in thinking occurred for the 2000 edition, with a merging of “Passenger Rail Systems” with “Fixed Guideway Transit.” The standard’s name became “The Standard for Fixed Guideway Transit and Passenger Rail Systems.” With this, the standard began to cover a wider rail-transit oriented range of issues. Each subsequent edition of the standard brought enhancements, bringing the standard closer to the latest industry needs. The merging of the two separate functions caused significant changes to the body of the standard. For example, much of the former Chapter 2 (Stations – now Chapter 5) was modified to incorporate changes to the methodology for performing egress calculations, as stipulated in NFPA 101 “Life Safety Code, and added examples to its annex containing the new calculation methodology. Additionally, the Technical Committee made major changes to former Chapter 3 (Trainways – now Chapter 6) and former Chapter 4 (Emergency
Ventilation Systems – now Chapter 7). Chapters were modified to more effectively address emergency lighting and standpipes in stations and trainways, while expanding the requirements for emergency ventilation systems.

For the 2003 edition, the Technical Committee incorporated a number of technical revisions to the egress requirements and respective calculation methodologies for stations. Chapter 8 (Vehicles) was modified to incorporate a performance-based design approach to vehicle design. This changed the industry’s thinking on the traditional prescriptive (specified-based) vehicle design requirements. The 2003 version also incorporated conversions to SI (new metric) units throughout the document.

The 2007 edition of NFPA 130 saw revisions affecting station egress calculations, including incorporation of escalators into the calculation methodology; allowance for vehicle interior fire resistance; and power supply to tunnel ventilation systems. All guidelines associated with maintenance facilities were removed as those guidelines were contained in other codes and standards. Finally, the Technical Committee revised the vehicle performance-based design criteria to address the uniqueness of the rail vehicle as opposed to other transportation type vehicles.

Changes to the 2010 edition included provisions allowing elevators to be counted as means of egress elements, and revisions to escalators, doors, gates and turnstile-type fare equipment allowing them to be more appropriately used in egress calculations. Further, the Technical Committee modified Annex “A” by adding several fire scenarios to provide guidance on how to calculate other types of fires not originally included in the annex such as certain vehicle and station fire types.

2.3 Application of NFPA 130 in other Transit venues

NFPA 130 has been adopted as the rail standard to follow both in the US and internationally. Domestic locations include Atlanta, Baltimore, Dallas, Detroit, Los Angeles, New York City, Pittsburgh, Portland, Oregon, San Francisco, Seattle, St. Louis and Washington. Other countries include Argentina, Brazil, Canada (Montreal, Toronto and Vancouver), China, Copenhagen, Denmark, Guangzhou, Hong Kong, Istanbul, Izmir, London, San Juan, Shanghai, Singapore, Taipei, Taiwan, Turkey, and the United Kingdom. The adoption of NFPA 130 typically occurs when the transit system in a city requires significant modification and/or major expansion, as was the case in Boston, Camden, Chicago, Los Angeles, New York City, Newark, and San Francisco.

NFPA 130 has evolved to a well-recognized standard for fire-life safety of rail systems for rehabilitation of older transit systems and development of new transit systems, particularly in internationally. The NFPA 130 Technical Committee even has members from the international community including Australia, Canada and Singapore.

3 NFPA 130, 2014

Since the 2010 Edition published, the Technical Committee has assembled in excess of 200 recommendations from various sources. Some were tabled in previous years because they were not ready for action. Other recommendations are based on project-specific questions by engineers, architects, enforcers, owners/operators, etc. who require additional guidance from the standard.

Seven task groups were formed in order to effectively and efficiently respond to the 200 plus recommendations. The recommendations were divided and disseminated according to the task groups focus. In the cases where the assigned task group could not effectively act upon a recommendation, additional task groups were asked to assist in the development of a response. One task group is assigned the lead position. The seven task groups are as follows:

1) Manual of Style (NFPA procedural process for each edition) and uniformity of S.I. Units conversion
2) Emergency Exiting
3) Ventilation & FHRR
4) Vehicles
5) Facilities
6) Emergency Response, and
7) Wire & Cable.

For the 2014 Edition, five (5) key technical action items stand out over the others received:

a) Developing Criteria for Fire Profile Methodology for Rail Vehicles

It is planned that the 2014 Edition of the Standard will define a fire profile as the fire carbon monoxide, heat release, smoke and soot release rates expressed as a function of time from the initiation of the fire until at least the end of the time of tenability. The new Standard will require the designer to develop fire profiles for a number of common fire scenarios. A new Annex providing reference material on how to predict the fire profile for a given scenario will be provided. The material referenced includes spreadsheet calculations and two computer programs. All of these methodologies require doing ASTM-1354 cone calorimeter tests on samples of interior components including seats, floor coverings, wall and ceiling liners, etc. These tests predict critical heat flux for ignition; heat, soot and CO releases per unit area, etc. Ignition temperature for each component is measured separately. This data and the vehicle geometric properties are then used to predict the fire profile. All of these methodologies to predict fire profile have been validated in by scale or component tests. Full-scale tests (burning an entire vehicle were done in Sweden in September 2011; however, they have yet to be reported to the public.

a) Addressing the Deep Station Egress Issue

New rail projects tend to have to be built deeper to be routed under existing subsurface infrastructure. Enhanced egress techniques need to be developed for these deep tunnels and stations. Allowing elevators (albeit better protected) and escalators to be used more freely for egress would greatly help with the deep station egress issue. Providing additional and protected areas of safe refuge on platforms and/or in other areas of the station/facility would also help immensely. The more and more commonplace deep station has made it necessary for the NFPA 130 Technical Committee to step back and look more aggressively into these components as viable means of egress.

b) Reorganizing Chapter 6 – Trainways

The intent of reorganizing Chapter 6 – Trainways is to establish a more logical sequence for designers to follow, beginning with design, then construction and finally to operation.

From design through operation, the introduction of combustible materials into the trainway and related structures should be minimized or prevented. The provisions of Chapter 6 should provide riders/emergency responders with safe and efficient emergency egress/access from/to any trainway location. It should also afford the owner/operator with the ability to detect and respond to the fire-life safety incident in a timely fashion. The newly formulated Chapter 6 should with some easily resolved differences, simulate the organizational sequence set forth by Chapter 5 – Stations.

c) Developing a Completely New Chapter that Addresses all Wire and Cable Issues

The NFPA 130 Technical Committee formed a new task group (TG 7 – Wire & Cable) to deal with issues carried over from the NFPA 502 meeting in June 2010, where a majority of “Notice of Intent to Make a Motion” (NITMANS) were voted down by the NFPA Standards Council. In order to both meet the demands of the wire and cable industry and avoid the same NITMANS from being reinstated by the same proposer, the TG is organizing a new chapter that will respond to future issues on this matter. All wire and cable elements will be extracted from other chapters of the standard and be assembled into a new chapter.
d) Resolving the Issue of Station/Tunnel Sprinklers and On-board Vehicle Fire Suppression Systems (i.e., Misting)

One issue that has followed this document since its inaugural publication in 1983 is, whether or not to require sprinklers and/or misting systems in stations and on-board rail vehicles. As a first step, the Vehicle Task Group (TG-4) will propose that vehicles should contain on-board misting systems. This will only be recommended if vehicle fire modelling demonstrates the benefits of on-board misting systems, such as reducing the vehicle’s FHRR and/or eliminating the need for larger and higher capacity fan plants. The capital cost impact of this measure can be quite high for this reason, the standard will request that a cost benefit and life cycle cost analyses be performed before making any deployment decisions.

4 FUTURE EVOLUTION FOR THE 2017 EDITION

Codes and Standards are updated at least every three, but not more than every five years in order to meet the needs of the industry for which they are being prepared for. This is a National Fire Protection Association requirement.

For the 2017 Edition, the Technical Committee will:

- Further the development of a methodology for formulating the FHRR for vehicles; accomplished with the help of the NFPA - Fire Protection Research Foundation and the results of the Fire Testing performed in Sweden in 2011.
- Exploring additional methods for safe egress from deep station’s; owners and operators of new rail and transit systems are confronted with the long-term issue of having to go deeper into the earth to by-pass existing subsurface infrastructure. Passengers must consistently be reassured that they are safe and secure while down there. For the next issuance of the standard, modeling methodologies are being developed to allow designers to correlate modeling results wit real life situations and put them into place.
- Further develop concepts for stations and vehicle fire protection systems.
- Investigate and incorporate issues associated with the growing high-speed rail industry.
- Further investigation into the distances required between tunnel cross-passageways and protections required in each.

5 INTERNATIONAL ACCEPTANCE

NFPA 130 will continue to be a major force in the world, as it is the only comprehensive document that provides AHJs, owners/operators and designers with a basis for the safe and efficient design and construction of passenger rail and transit systems, whether new or old.

The ventilation guidelines provided in NFPA 130 are internationally accepted. Although not the target topic of this paper, there exists many differences between the emergency egress requirements of NFPA 130 and those used on projects outside the USA. These differences have sometimes resulted in the adoption of NFPA 130 by other countries in part, rather than in its entirety. The Technical Committee will continue to improve it to meet the growing needs of the industry, and keep it up-to-date and in line with the global market. The TC will incorporate criteria and recommendations as they are generated especially information as obtained from the international marketplace that can improve NFPA 130 and make it more widely accepted.

6 ACKNOWLEDGEMENT

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Safety of Dutch tunnels guaranteed by standard approach

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INTRODUCTION

We want to drive smoothly and safely, to protect our environment and to utilize space as efficiently as possible. Tunnels are therefore indispensable in the Dutch road network. These tunnels must be safe, they should enable us to maintain a steady traffic flow and they need to be realized as efficiently as possible. To achieve these goals, Rijkswaterstaat recently devised a Standard for Tunnel Technical Installations (TTI). This article will explain what the standard TTI encompasses, why it was developed and which approach has been used.

Problem outline: Background

Road tunnel construction projects in the Netherlands are increasingly delayed, resulting in much higher than budgeted costs. This subject is high on the political agenda due to its high impact on society.

CAUSE

One of the causes of this problem is that current legislation does not clearly state when a tunnel is safe enough. The decision-making process regarding opening of a tunnel has been decentralized which results in endless administrative discussions concerning the level of equipment that tunnels require to guarantee safety.

For a project this means striking a difficult balance between scope, time and money and responsibility to the stakeholders. The role of the private sector in finding this balance becomes greater due to the withdrawal of central government, which seems to concentrate more on the contract itself.

In addition, the increasingly greater role played by IT in the civil engineering sector combined with increasing complexity of tunnel systems seems to create problems in project execution. The ever-increasing requirements placed on both safety and traffic flow along with the associated demonstrability of these requirements pose a major challenge. Certainly as every tunnel is seen as a unique object, meaning that the wheel has to be reinvented every time.

SAFETY

Every year the Euro Tap conduct a joint survey on the safety of European tunnels. Time and again the Dutch tunnels earn a sufficient to a very high score. This is due to the following factors:

1. Dutch tunnels on major roads are always fitted with a dual carriageway.

2. Dutch tunnels always have several emergency exit doors (every 100 meter in ordinary tunnels and every 250 meter in drilled tunnels) and it’s made sure there is always sufficient information for travelers.
SOLUTION: STANDARDIZE AND UNIFY

So Dutch tunnels are safe. The cause of described problems is not the alleged lack of safety. What has to be considered is:

a) the absence of a uniform safety standard

b) each tunnel is seen as a unique object meaning that the wheel has to be reinvented every time.

By reviewing legislation and by standardizing functional requirements for the technical systems in tunnels the realization of new tunnels can be approached in a more structured way.

To provide a solution to these problems, a national tunnel director has been appointed within the ministry and tasked with implementing a structural change in the process of constructing road tunnels, by uniformizing the requirements and preconditions and standardizing the technical specifications and solutions for tunnel installations. In addition, the director is tasked with introducing results of these efforts where possible in the tunnel projects now under execution as well as existing tunnels.

Many parties participate in this process such as Rijkswaterstaat, local councils, emergency services, Building Societies etc. They all have worked together to try to find solutions for these problems and they have agreed on comprehensive cooperation and standardization. Results of this joint venture are recorded in a cooperation protocol.

The following questions played a central role in the discussions about standardizing:

- How far can one take standardization?
- What does standardization mean for the monopoly position of companies?
- How can we make sure that there is sufficient integral cooperation not only between client and contractor, but also between civil and electromechanical engineering.

Furthermore Rijkswaterstaat has closely coordinated the required level of equipment in tunnels with other participating parties such as the emergency services, the Ministry of Security and Justice, the Ministry of Home Affairs and the Platform Transport Safety.

THE STANDARD

All tunnels are unique. Length, width, number of tubes and traffic composition differ with each tunnel and in that respect it’s not possible to standardize tunnel design. However, usage and operation of tunnels as well as incident procedures (e.g. fires, accidents) are the same for every tunnel. Therefore it’s possible and highly recommended to standardize:

A) traffic flow and safety demands
B) the operational processes
STANDARDIZING OPERATIONAL PROCESSES

Regarding operational processes, first one has to consider which processes can be handled manually and which processes can be automated. This should be the same for every tunnel. Therefore it is highly advisable that both manual and automatic processes are standardized. At the same time the use of technical installations can be standardized along with the requirements that these installations must meet.

Assessment of operational processes has been made for a wide range of incidents. This includes: expected incidents such as congestion and bad weather, unexpected incidents such as broken down cars, collisions and lost cargo and major incidents such as calamities, major collisions, fires and incidents involving dangerous goods. See figure 1.

![Figure 1 Standard operational processes](image)

STANDARDISATION (ARCITECTURE)

The approach to uniformizing and standardizing has started with the definition of the tunnel system as part of the road network, taking into account organisation, operational processes and technology. For this system, main requirements (availability and safety) have been uniformized. Services and measures have been derived and the system architecture determined. For operationalization of the services, operational processes have been uniformized (See figure 2), associated roles defined and supporting technology determined (See figure 3 and 4).

This standard is suitable for all road tunnels and takes into account existing variations. The principle has been simplification of complexity, proven technology and best practices.

Architecture of the Standard is illustrated in figure 2.
The standard provides main requirements (where safety requirements have been made more strict), standard processes with the associated roles and a standard level of equipment for tunnels to guarantee safety. In addition to this standard equipment, one or more sets of options can be employed mainly related to availability of the tunnel system and not its safety.
CONSEQUENCES OF THE STANDARD

In addition to improving the administrative process and professionalizing project organisations, the standardization ensures that administrative discussion will not be held for every project, but will be held once generically. The standard will ensure a correct balance between safety, traffic flow and project delivery schedule.

ADVANTAGES OF THE STANDARD

Advantages include: fewer discussions with the stakeholders resulting in limitation of the execution risks, improved project control with predictable schedules and costs due to lowering of the risk profile, increased efficiency due to the repetition effect, more structured maintenance and change management, less susceptible to failure and improved familiarity for users (operators, emergency services and road users).

Standardization will ensure greater intrinsic safety of tunnels in the Netherlands.
The Standard applies only to tunnels that are yet to be designed and built. In principle it is not designed for existing tunnels but when parts of these tunnels need to be adjusted or replaced (for instance the operating software) an assessment will be made for each tunnel whether it might be more efficient to do so using the new standard equipment, especially when it’s possible to standardize the entire operating system at the same time.

In anticipation of the new law that will come into effect on July 1st 2012 the minister of Infrastructure and Environment has decreed that, whenever possible, the Standard must be applied to tunnels that are in the process of being built.

**Current situation (Fall 2011)**

- Tunnel legislation is under revision
- First version of the Standard TTI (Technical Standard Installation) is ready

It is expected that the revised Act (Warvw) will pass on July 1st 2012.

Warvw regulates:

1. The safety standard (0,1/N² per km tunnel tube per year for the group risk. N is the number of lethal victims per incident)
2. The Standard must be applied to major road tunnels

On the same date the Ministerial Regulation (Rarvw) which is currently under notification in Brussels is also expected to pass. Rarvw describes in detail how the Standard Operating Processes work and what Standard Equipment should be in every tunnel. It also includes a categorization. For example: Different requirements are placed on tunnels accessible to transport of all hazardous substances than on other tunnels.

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**KEYWORDS:** standard equipment, rijkswaterstaat, dutch tunnels, uniformizing, standardizing.
Current practice of Fire design for Road & Rail Tunnels in Austria

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KEYWORDS: Fire design, austria, standards & guidelines, structural modelling

1. INTRODUCTION

Following the disastrous accidents in the Channel Tunnel, in Mont Blanc Tunnel and in the Tauerntunnel a discussion about safety in tunnels was initiated all over Europe. On the one hand national guideline committees had to discuss the review and new definition of safety installations, on the other hand construction agencies more and more started to request evidence on the carrying capacity of tunnel structures against fire load. Since then intense efforts have been taken to evaluate the behaviour of tunnel structures against thermal loading. As a sample UPTUN, one of the largest scientific programs has been initiated by the European commission to deal with various aspects of tunnel fires.

Austria was one of the first European countries to establish standards and guidelines for a structured consideration of fire design for tunnels based on intensive studies, laboratory testing and field experiments. In order to satisfy the requirements of the now new standards and guidelines a calculation model was developed to allow the simulation of fire load onto tunnel lining structures and to demonstrate the ultimate carrying capacity under fire load. This model provides information about the carrying capacity by using standard engineering tools.

After nearly a decade of application of standards & guidelines and the calculation model a review of the past years is given along project history and an outlook into the next decade discusses the future challenges of fire design.

2. GENERAL APPROACH

The fire resistance requirements in Austria are in general set up to protect persons at surface. It is assumed, that for any type of tunnel the tunnel structure will maintain its stability for a period of time sufficient to allow self evacuation and evacuation assisted by emergency services. While other aspects as the disturbance of the tunnel operations, the likely tunnel reconstruction cost after a tunnel fire and other factors could be considered, the main target remains to prevent life threat to persons. On the surface the main target is to allow at least a safe evacuation of the zone which could be in danger in case of lining collapse. If required a proof of the necessary time to achieve such evacuation is necessary.

The necessity to provide sufficient stability of tunnel structures to allow self evacuation and emergency services supported evacuation goes along with these requirements. The necessary provisions to allow self evacuation like safety installations and ventilation are not part of the fire design for structures.

3. ROAD TUNNELS

3.1 European Standards

On European level the directive [4] defines the baseline and minimum requirements for the safety of tunnels within the transeuropean road network. In the annex I under paragraph 2.7 it says:

“The main structure of all tunnels where a local collapse of the structure could have catastrophic consequences, e.g. immersed tunnels or tunnels which can cause the collapse of important
neighbouring structures, shall ensure a sufficient level of fire resistance”

While these requirements and explanations broadly explain the target of fire design of tunnel linings they do not set up definitive assumptions for the design. A more specific source with respect to fire design can be found from the World Road Association-PIARC which is shown in the figure below:

3.2 Austrian Standards

The main design guidance for road tunnels in Austria is given in the RVS (Richtlinien und Vorschriften für das Straßenwesen). This compendium of guidelines also covers the requirements for fire design in RVS 09.01.45 [1]. The concept is based on the characterization of all road tunnels into different tunnel categories varying with traffic magnitude, traffic mixture and road design aspects. These categories are not only used for the fire design but also for ventilation and other safety aspects of road tunnels.

In a first step the evaluation of the hazard category is required which is based on a risk analyses. Dependent on the operational conditions of the tunnel either a simplified risk analyses [2] or a detailed risk analyses [3] is required for the definition of the category. Both methods develop a characteristic value for frequency equivalent “H” and damage equivalent “S”. Along this procedure various factors are considered. Geometrical data as length, cross section and gradient, traffic type and volumes, ventilation system and safety installations are considered among others. The resulting risk equivalent is defined to

\[
R = H \times S
\]

And from the risk equivalent (Risikoäquivalentwert) the hazard category (Gefährdungsklasse) can be defined:

<table>
<thead>
<tr>
<th>Riskoäquivalentwert</th>
<th>Gefährdungsklasse</th>
</tr>
</thead>
<tbody>
<tr>
<td>untere Grenze</td>
<td>obere Grenze</td>
</tr>
<tr>
<td>-</td>
<td>2 \cdot 10^{-2}</td>
</tr>
<tr>
<td>&gt; 2 \cdot 10^{-2}</td>
<td>1 \cdot 10^{-1}</td>
</tr>
<tr>
<td>&gt; 1 \cdot 10^{-1}</td>
<td>5 \cdot 10^{-1}</td>
</tr>
<tr>
<td>&gt; 5 \cdot 10^{-1}</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2: Definition of hazard category (Gefährdungsklasse)

Having defined the hazard category in RVS 09.01.45 [1] the requirements for fire resistance can be evaluated.

First the tunnel category has to be defined either for the entire tunnel length or for representative sections. The tunnel category describes the expected damage to surface. RVS 09.01.45 defines 5 categories A to E. Category A represents a section with no infrastructure on surface or a rock tunnel with sufficient overburden so that a lining collapse will not cause any disturbance of surface. Category E on the contrary describes a tunnel section with a definitive risk for day break if the lining structure fails and where possible evacuation times at surface would exceed 180 minutes. A matrix formed by the hazard category (Gefährdungsklasse) and the tunnel category (Tunnelkategorie) defines
then the required protection level.

<table>
<thead>
<tr>
<th>Tunnelkategorie</th>
<th>Gefährdungsklassen I + II</th>
<th>Gefährdungsklasse III</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>1*</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>E</td>
<td>3**</td>
<td>3**</td>
</tr>
</tbody>
</table>

*) jedoch 0, wenn rasche Sanierbarkeit nachgewiesen wird und nur kurzezeigtige Sperren zu erwarten sind

**) Die Anforderungen des Schutzniveaus 3 sind Mindestanforderungen, die objektspezifisch zu ergänzen sind

Table 3: Definition of protection level (Schutzniveau)

A further table in RVS 09.01.45 [1] finally defines the required fire resistance:

<table>
<thead>
<tr>
<th>SN</th>
<th>Mindestanforderungen an die Tragsicherheit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Brandwiderstand 30 Minuten (R 30) auf Basis ETK</td>
</tr>
<tr>
<td>1</td>
<td>30 min Brandeinwirkungsdauer Nachweis gem. ÖNORM EN auf Basis der Temperatur Zeitkurven</td>
</tr>
<tr>
<td>2</td>
<td>90 min Brandeinwirkungsdauer Nachweis gem. ÖNORM EN auf Basis der Temperatur Zeitkurven</td>
</tr>
<tr>
<td>3</td>
<td>120 min Brandeinwirkungsdauer Nachweis gem. ÖNORM EN auf Basis der Temperatur Zeitkurven Nach 120 min Brandeinwirkungsdauer einschließlich Abkühlphase Sicherheit normgemäß</td>
</tr>
</tbody>
</table>

Table 4: Definition of fire resistance requirements

For protection level 2 (SN) it is for example required to maintain the structural liability of the lining for a period of 90 minutes, unless an evaluation of the required evacuation time on surface does not sum up to a longer time period.

In order to standardize the assumptions for the thermal gradient within the cross section the same graph as used for the Rail tunnels can be applied for the design of road tunnels.

3.2.1 New Tunnels

For the design of new tunnel structures the application of the requirements of the RVS 09.01.45 [1] for fire design may add up project cost but does not challenge the project design. The common strategy is to apply PP-fibre concrete to prevent spalling and to increase concrete cover for reinforcement. A dimensioning for the temperature loading is mandatory.

3.2.2 Existing Tunnels

The upgrade of existing tunnels to satisfy the fire design requirements requires tailor-made technical solutions and a detailed material selection to produce the best possible technical and economic solution. “Kaisermühlentunnel” in Vienna, the tunnel with the highest traffic figures in Austria, is a good sample to demonstrate the difficulties which had to be overcome to make this tunnel fit for the fire safety requirements.

4. RAIL TUNNELS

4.1 European Standards

The TSI “Technical Specification for Interoperability” [8] define the minimum requirements for fire resistance of tunnels within the European network:

“The integrity of the structure shall be maintained in the event of fire for a period of time sufficiently long to permit self-rescue and evacuation of passengers and staff and the intervention of rescue services without the risk of structural collapse. The fire performance of the finished tunnel surface, whether in situ rock or concrete lining, has to be assessed. It shall withstand the temperature of fire for a particular duration of time. The specified “temperature-time curve” (EUREKA curve) is given in the following figure. It is to be used for the design of concrete structures.”
While these two paragraphs are currently undergoing a broad discussion to amend the wording for a more precise definition the basic requirements are understood. Based on these phrases the Austrian standard has been developed.

### 4.2 Austrian Tunnels

ÖBB, the Austrian rail operator, has developed its own standard [5] for fire design of rail tunnels. While the fire load is simulated by a time temperature curve with a peak level temperature of 1200°C the classification of the surface infrastructure defines the required resistance time for the tunnel structure.

All rail tunnels with mixed rail traffic (goods and passengers) have to be designed in accordance to this RVE guideline. The principles are based on European Community regulations. Similar to the road design guideline the surface infrastructure is categorized and results in different protection levels with different requirements for the tunnel structure.

<table>
<thead>
<tr>
<th>Schutzniveau</th>
<th>Anforderung aus der Oberflächenutzung, Auswirkungen auf die Oberfläche</th>
<th>Anforderungen an das Tunnelbauwerk</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 0.1</td>
<td>Keine Auswirkungen auf die Oberfläche</td>
<td>Die Tragsicherheit der Konstruktion muss für die definierte Temperaturbelastung nicht nachweisbar sein, die Standsicherheit des Hohlraumes muss gegeben sein. Es werden für die definierte Temperaturbelastung keine Anforderungen an die Gebrauchstauglichkeit gestellt.</td>
</tr>
<tr>
<td></td>
<td>Die Anforderungen aus der Oberflächenutzung können maßgebend sein (z.B. Bebau-ungen). Es ist aber mit keiner Auswirkung auf die Oberfläche zu rechnen (standsicherer Hohlraum).</td>
<td></td>
</tr>
<tr>
<td>SN 0.2</td>
<td>Auswirkungen auf die Oberfläche</td>
<td>Die Tragsicherheit der Konstruktion muss für die definierte Temperaturbelastung nicht nachweisbar sein. Es werden für die definierte Temperaturbelastung keine Anforderungen an die Gebrauchstauglichkeit gestellt.</td>
</tr>
<tr>
<td></td>
<td>Die Anforderungen aus der Oberflächenutzung sind auf Bestandsdauer sichergestellt nicht maßgebend.</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Sample for definition of protection level and fire resistance requirements

Again the definition of protection levels finally defines the fire resistance requirements. The target is to guarantee sufficient time for self evacuation and evacuation by emergency services from the tunnel and if required evacuation of any surface structure in danger.

#### 4.2.1 New Tunnels

As for road tunnels the common strategy is to apply PP-fibre concrete with increased concrete cover for reinforcement in order to prevent spalling and to maintain the structural integrity sufficiently long in accordance to the requirements of the guideline [5].

#### 4.2.2 Existing Tunnels

The upgrade of existing railway tunnels is not standard procedure today and so far not required by EU law. While for road tunnels the national Austrian law already gives a deadline to fulfil the requirements of the guideline up to the year 2029 no definition for rail tunnels currently is given.

### 5. APPLICATION HISTORY

#### 5.1 Lainzer Tunnel – Rail Tunnel

The Lainzer Tunnel is a major railway tunnel project within the boundaries of Vienna city. It is part of the high speed rail network and provides the access to the Vienna main railway station, currently under construction. Due to rail traffic and the limited rail capacity connecting the west and east side of Vienna the Lainzer Tunnel was designed and its approval process was commenced at the end of the last century. At this time the catastrophic rail and road tunnel accidents showing significant damage to tunnel linings commenced a broad discussion on the fire resistance of tunnels structures especially when built under developed environment and infrastructure. This public discussion also influenced the statutory approval procedures for the Lainzer Tunnel. It was therefore necessary to find a response accepted by the public.
5.1.1 Definitions / Classification

As can be seen the tunnel underpasses residential built up areas for a significant length and further follows the existing rail entrance to the city in order to stay below own grounds. The tunnel is situated within soft ground, below groundwater table and shows varying overburden from 8 to 20m above ground. The tunnel concept was developed already in the early 90’s of last century and at that time it was decided to construct a twin track tunnel rather than today’s approach which would apply two single tube tunnels.

In accordance to the guideline the definition of protections levels required a fire resistance of 180 minutes, sufficient for evacuation on the surface. For this time period the tunnel structure shall be capable to maintain its structural integrity.

5.1.2 Design consequences

The solution to the fire resistance requirements over a time period of 180 minutes was found in the application of PP-fibre concrete. In accordance to the ÖBB guideline and the findings of the various fire tests PP-fibre concrete showed to prevent spalling and to maintain the thickness of the lining.
throughout a fire scenario. A design method based on [9] had to be found which allowed to consider the changing material properties with temperature and to consider the stresses being built up by the temperature within the cross sections.

5.1.3 Application history

Today the tunnel construction has nearly been completed and the finishing works will allow to open the tunnel in 2012. During the design and construction of this tunnel all aspects of design and construction have been addressed. Solutions for design issues like the changing material properties within a cross section and varying in time, the optimized design of the concrete mixture, the required concrete cover for reinforcement and other aspects have been developed.

5.2 Kaisermühlen Tunnel – Road Tunnel

The Kaisermühlen Tunnel in Vienna represents the tunnel structure with the highest traffic figures in Austria. It was originally constructed as a noise reduction measure in the 1980’s and extended in the late 1980’s whereby this extension was designed to carry residential and commercial structures on top. While the structure itself shows little deficiencies the age of the tunnel installations now require refurbishment. In parallel to the design of the refurbishment of the installations the Austrian law [10] requires to consider fire resistance requirements if significant modification of the tunnel system is planned.

5.2.1 Definitions / Classification

As described above part of the Kaisermühlentunnel has residential and commercial buildings on top which can be seen in the map below:

![Figure 4: Plan overview „Kaisermühlentunnel“](image)

![Figure 5: detailed Plan with buildings on „Kaisermühlentunnel“](image)
In consequence to the design guideline [1] the required fire resistance in accordance to the classification give 90 and 120 minutes for which the structure must maintain its structural integrity. In a separate study in close cooperation with the tunnel operation center both time assumptions have been shown to be sufficient for evacuation.

5.2.2 Design consequences

As the original design did not consider today’s findings the plain concrete is in danger of spalling and the strong reinforcement shows only concrete covers of 30-40mm. Further assuming that spalling could occur after some 20 minutes the reinforcement would soon after such spalling loose its physical properties and in consequence leads to structural collapse. However, the required time span of 120 minutes under buildings cannot be achieved without additional measures.

The design approach for existing tunnels differs from application of fire design to new tunnels. The tunnel already exists and in most cases provides restrictions. Cross sections normally do not allow additional thick layers, existing installations require consideration and in most cases a compromise between the requirements of fire design and other design regulations has to be found.

In the case of the Kaisermühlen Tunnel the entire installation on the tunnel ceiling would be removed so that any existing measure for fire protection could be applied, although the existing room for installations between the clearance line and the ceiling would be reduced. A detailed study including the options of various fire protection mortars, fire protection panels, PP-fiber shotcrete and water mist systems concluded that the application of PP-fiber shotcrete at the ceiling and the use of colored PP-fiber SSC (self compacting concrete) for the walls would be the optimized solution.

5.2.3 Application history

Currently the statutory approval procedures are ongoing and should be finished by 2012 allowing the construction to start 2013 / 2014. Together with the fire protection the entire installation and ventilation system will be changed. In this case any option in the selection of the fire protection method was theoretically possible. On the ground of similarity of material and economical grounds shotcrete for the ceiling and concrete for the walls has been chosen.

6 LARGE SCALE FIRE TESTING

As the literature research on published knowledge of the behaviour of tunnel linings against fire did
not provide the requested information the ÖBB together with other public institutions provided budget for research work. Experts concluded to perform large scale fire tests to investigate the behaviour of linings in case of heat exposure. Two large scale testing regimes have been funded.

6.1 Plate Tests

In order to test various concrete mixtures, various content of PP-fibres and various boundary conditions including prestressed specimen a series of plate tests has been performed to allow statistically appropriate definitions and to study the effect of spalling.

The detailed results of the tests and the findings are summarized in [11].

6.2 Scale Tests

For validation of the assumptions and conclusions derived form [11] and for validation of the design model FLAMDOCS [7] large scale tests have been performed for the Lainzer Tunnel structure. The top segment of the tunnel lining was constructed in scale and tested against fire load. In addition a distributed single load of 400kN was applied in the crown of the lining.
The applied fire load was set in accordance to the ÖBB guideline [5] and applied by two industrial oil burners. The lining showed the expected results and only after the cooling of the structure for a limited area 1-2cm of the concrete dropped off.

With the design model FLAMDOCS the structure has been designed to maintain its structural integrity up to 180 minutes. In order not to endanger persons and neighbouring construction the tests have been extended up to 150 minutes monitoring temperatures within the concrete and also deformations. The structural did not fail and no spalling occurred during the tests. All assumptions have been verified and influenced the later definition of standards.

7 FLAMDOCS

In consequence to the findings parallel to the testing a calculation model was developed to allow dimensioning if reinforced concrete structures in case of high temperature loading. The aim was to develop a model without the need of application of numerical methods in order to use standards software tools like frame models. Two fundamental aspects have been developed in [7]:

The time dependent and non linear temperature gradient within a reinforced concrete structure is translated into equivalent loads to be applied on the frame model. The stiffness of the system is reduced accordingly. In addition the non linear temperature gradient within the cross section causes different material properties within the cross section for every layer.

The changing material properties within the cross section and with progressing time change the load carrying capacity of the cross section. The progressing time is simulated by the consideration of time steps, where the system integrity is verified for time steps during the fire events. The variation of the material properties within the cross section is considered and results in a M/N interaction diagram.
which allows to verify the structural integrity for every time step.

This model or similar variations are nowadays used for the design of tunnel structures for the load case tunnel fire.

7 CONCLUSION

The catastrophic fire accidents in European Tunnels have changed the public perception of danger in tunnels caused by fire. While fire resistance was purely a matter of material resistance since then the structural resistance is of major interest in case of tunnel fire. All new built tunnels are designed to satisfy these requirements and provide definitely a higher level of safety. Due to the large number of existing tunnels significant investment will be required to upgrade already existing tunnels not fit for the purpose of tunnel fire.

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298
ABSTRACT

In Canada, there is currently no specific regulation for road tunnels; there are no standards that are equivalent to the American NFPA 502 [7] or the European Directive [8] on Trans European tunnels (April 29th, 2004). However, regulations for railway tunnels, such as the one in use for Montreal’s subway network, do exist. Due to this limitation the feasibility studies carried out by the team were based on a performance approach rather than a prescriptive approach with the goals of the studies being to understand the existing conditions of the tunnel systems and infrastructure and to make the necessary recommendations for their upgrade based on an increase in the safety of their performance.

In the text that follows, the methodology suggested by the owner will first be explained, followed by how the CRINIFLEX was developed in relation with the specific functions of the tunnels. We will then explain how the CRINIFLEX was linked with the existing conditions of the tunnel infrastructure. This is followed by a discussion on how the CRINIFLEX was used to evaluate the improvements recommended by the team. Finally it will be explained how the method developed by the team can be used in an objective and rational process for comparing improvements and holistic solutions that reduce the risk for both the users and the owner.

KEYWORDS: Refurbishment, upgrading, Specific Hazard Investigations, performance approach, functional analysis, risk factors, design fire

INTRODUCTION

Over the past 10 years, the author has had the opportunity to participate in many urban tunnel infrastructure rehabilitation and improvement projects in the Montreal region, both as a designer and a project manager. The engineering process applied in these projects allowed him to develop an understanding of the issues associated with user safety and with the technical aspects of urban tunnel rehabilitation. Projects he has worked on include the Notre-Dame-de-Grâce, Atwater and Côte-de-Liesse tunnels as well as the Louis-Hippolyte-La Fontaine tunnel that crosses the St-Lawrence River (1.6 km) and the Ville-Marie and Viger Tunnel Complex in the city’s downtown core (6.6 km).

Two years ago, Mr Dubois joined the engineering firm CIMA+ as project manager in charge of two feasibility studies for the refurbishment and upgrading needs of two major tunnels: the Louis-Hippolyte-La Fontaine Tunnel and the Ville-Marie and Viger Tunnel Complex. It is for this reason that in 2010, he visited Nordic tunnels in Europe (Öresund Tunnel in Copenhagen and various tunnels in Stockholm) and attended the 4th International Symposium on Tunnel Safety and Security (ISTSS) [1] in Frankfurt. In November 2010, he attended the CETU conference on Human and Organizational Factors in Road Tunnel Safety in Lyon [2]. This conference gave him an opportunity to visit the Grand Lyon and Mont-Blanc tunnels.
The knowledge gained from these visits, meetings, discussions and collaborations with many specialists and international experts, as well as his understanding of technical publications issued by PIARC [3-4], UPTUN [5], CETU [6] and others, have allowed his team to develop a unique approach to road tunnel rehabilitation for the current feasibility studies, based on Specific Hazard Investigations implemented in Europe.

**UNIQUE APPROACH**

In the absence of legislation and standards in Canada, the team referred to the best international practices to develop a unique approach to the feasibility studies for the tunnels that combines several methods of analysis. These methods include:

1. The approach used by the Quebec Transport Ministry [9] (MTQ) for undertaking road works projects;
2. Functional analysis as described by the "Association Française de Normalisation" (AFNOR) [10];
4. The CETU [6] approach, including the Specific Hazard Investigation;
5. The best practices arising from PIARC [3-4]; NFPA 502 [7]; UPTUN [5], etc.

The feasibility study is the first step in the life cycle of a MTQ project, and all methods of analysis used by the team reflected this. The end result of the study is therefore not a detailed design, but an outline of potential solutions to increase safety in the performance of the tunnel systems.

In the functional analysis, each of the tunnel’s functions is identified in order to create the “CRINIFLEX”; a French term derived from the words “CRItère” (criteria), “NIveau” (level) and “FLEXibilité” (flexibility). The CRINIFLEX is what is used to determine the tunnel’s current performance. The existing conditions are then evaluated in accordance with the Highway and Rail Transit Tunnel Inspection Manual’s method. Therefore, a relationship is established between the current state of the tunnel’s operation and maintenance systems and their performance level based on their original design (from 1967). The CRINIFLEX is done for emergency functions and a performance level is evaluated. This allowed ensuring the objectivity in the assessment of the tunnel’s actual performance. The functions are then grouped together, and the priorities for refurbishment are established to produce a diagnosis for the tunnel. This diagnosis corresponds to the global analysis performed by the owner, in this case the MTQ, with regards to the existing conditions; the team’s adapted methodology reflected the CETU approach [6].

Following the CETU approach [6], a Worst Case Scenario is developed to establish the level of risk of the existing conditions with the aim of elaborating holistic and multidisciplinary solutions that would decrease the level of risk. A comparative grid is developed in order to compare the performances of the different holistic solutions and retain those with the most impact.

Throughout the approach, a link is preserved between the different analysis tools and a connection maintained between the owner’s perception of the tunnel’s performance and the team’s judgment.

**MINISTERIAL APPROACH TO UNDERTAKING ROAD WORKS PROJECTS**

In Quebec, the progression of a road works project is established by the Transport Ministry [9]. This progression entails the completion of the following stages:

<table>
<thead>
<tr>
<th>Control-Point</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Control-Point - 0: Needs study</td>
</tr>
<tr>
<td>2.</td>
<td>Control-Point - 1: Feasibility study</td>
</tr>
<tr>
<td>3.</td>
<td>Control-Point - 2: Preliminary design</td>
</tr>
<tr>
<td>4.</td>
<td>Control-Point - 3: Definitive design</td>
</tr>
<tr>
<td>5.</td>
<td>Control-Point - 4: Preliminary plans and specifications</td>
</tr>
<tr>
<td>6.</td>
<td>Control-Point - 5: Definitive plans and specifications</td>
</tr>
<tr>
<td>7.</td>
<td>Control-Point - 6: Construction</td>
</tr>
<tr>
<td>8.</td>
<td>Control-Point - 7: Project assessment</td>
</tr>
</tbody>
</table>
Figure 1 below presents the various project stages and steps to achieve, as established by the MTQ [9].

![Diagram of a project life cycle](image)

**Figure 1 – A project life cycle, according to the Ministry’s process flow [9]**

Stages 1 and 2, the Feasibility study, include the analysis of refurbishing existing tunnels. In general, a Feasibility study includes the following activities:
- Assessment of the current conditions;
- Study of the infrastructure’s rehabilitation needs;
- Identification of possible improvements to be made;
- Development of solutions.

**OBJECTIVES OF THE STUDY:**

The general objectives of the current feasibility studies as prescribed by the MTQ are:
1. To identify and analyze current and foreseeable problems affecting the tunnel infrastructure and to determine their cause(s);
2. To determine other needs, not necessarily linked to an infrastructure problem (improvements, upgrades, meeting standards etc.);
3. To determine the current and precise state of the tunnel infrastructure (including all systems and subsystems);
4. To develop on respective issues, for all infrastructure components (including systems), in order to demonstrate each problem, each requirement and/or each mandatory intervention;
5. To develop solutions to resolve the problems and meet all requirements.

From these general objectives, the project management team defined the following four (4) specific objectives with regards to the tunnel’s rehabilitation, namely determining:

1. The existing condition of the infrastructure (with the assistance of the tunnel’s operator);
2. The potential risks in case of incidents;
3. The security level for users in case of incidents;
4. The consequences of a potential major incident.

**ANALYSIS TOOLS SUGGESTED BY THE OWNER**

At the start of the feasibility study, the owner/operator recommended the use of the following tools:
1. Value analysis which includes a functional analysis workshop with the tunnel’s operator;
2. Risk management which includes:
   a. Risk analysis – Identifying hazards and evaluating risk;
   b. Risk evaluation – Risk level and analysis of options;
   c. Risk management and reduction – In accordance with procedures, decision making and implementation.
ADAPTED METHODOLOGY

As previously mentioned, a prescriptive approach does not apply to road tunnels in Canada. Therefore, the project management team developed an adapted methodology based on the specific European study on hazards performed by the “Centre d’Etude des Tunnels” (CETU) [6] in France. The CETU’s [6] study is considered a legal approach in France, while in Quebec it is an engineering approach. Figure 2 below demonstrates correlation between CETU’s [6] approach and the adapted methodology, referred to as the North American approach.

**FIRST STEP: NEEDS STUDY**

CETU’s approach [6] consists in the studies of the tunnel’s current situation including:
1. A global analysis by the tunnel owner or operator;
2. Existing conditions;
3. Upgrade studies;
4. Reference condition.
In the adapted North American approach, the first step includes:
1. Global analysis by the owner/operator using the functional analysis tool (CRINIFLEX) to acknowledge the existing conditions;
2. Determining the existing conditions by engineering discipline (structural, ventilation, electrical, mechanical, drainage);
3. Identifying the needs and improvements by engineering discipline;
4. Analysis and diagnosis of the tunnel’s components;
5. Development of the CRINIFLEX and assessment of the components using the HRTTIM [11], creating a provisional reference state.

This first step is crucial, as it establishes a detailed knowledge of the infrastructure in place and evaluates its current condition versus its original design.

At this stage, the analysis of the tunnel’s infrastructure is based on the following criteria:
1. The condition of components according to an assessment based on HRTTIM [11] (see table 1);
2. The ability of the components to meet current standards and best practices. This analysis is done using the CRINIFLEX (see explanation of this tool below);
3. The identification of rehabilitation requirements and improvements of existing components, as well and non-existing components to implement;
4. The costs assessment of repairs and possible improvements.

The results of this analysis constitute the provisional reference state that determines the priorities for action. It is essential that the owner/operator participate during the creation of the CRINIFLEX, as this is the equivalent in the North American approach of the global analysis that is recommended by the CETU in France [6].

**TOOL: CONDITION OF TUNNEL COMPONENTS BASED ON HRTTIM [11]**

The use of a proven and adapted methodology for assessing tunnel infrastructure is considered essential, since most methodologies in the infrastructure field are specific and non-multidisciplinary.

Use of the HRTTIM [11] is a North American addition to the European CETU [6] approach. Components are evaluated according to their current condition, based on a scale from 0 to 9. A numerical classification is attributed to each component of the tunnel, "0" corresponding to critical condition, and "9" corresponding to a recently completed work, as shown in table 1.

*Table 1 – Grading the elements of the tunnel [11]*

<table>
<thead>
<tr>
<th>“9”</th>
<th>Newly completed construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>“8”</td>
<td>Excellent condition</td>
</tr>
<tr>
<td>“7”</td>
<td>Good condition</td>
</tr>
<tr>
<td>“6”</td>
<td>Shading between “5” and “7”</td>
</tr>
<tr>
<td>“5”</td>
<td>Fair condition</td>
</tr>
<tr>
<td>“4”</td>
<td>Shading between “3” and “5”</td>
</tr>
<tr>
<td>“3”</td>
<td>Poor condition</td>
</tr>
<tr>
<td>“2”</td>
<td>Serious condition</td>
</tr>
<tr>
<td>“1”</td>
<td>Critical condition</td>
</tr>
<tr>
<td>“0”</td>
<td>Critical condition</td>
</tr>
</tbody>
</table>

*No defects found.*

*No rehabilitation is necessary.*

*Minor rehabilitation is required and is functioning as it was designed originally.*

*Major rehabilitation required and is not functioning as it was designed originally.*

*Major rehabilitation is required immediately to keep structure open to traffic.*

*Immediate closure is required. Study recommended to be performed to determine the feasibility of rehabilitating the structure.*

*Structure is closed and is beyond rehabilitation.*
TOOL: CRINIFLEX

As previously mentioned, the CRINIFLEX is created from a functional analysis, as described by the "Association Française de Normalisation” (AFNOR) [10]. A functional model of the tunnel is first established (see figure 3). A functional analysis entails defining the following:

1. The purpose of the tunnel’s operation;
2. The functions the tunnel must accomplish (e.g.: lighting, ventilation, etc.);
3. The quantifiable and measurable performance criteria to satisfy;
4. The specific target levels that each criteria must achieve;
5. The degree of flexibility, specifying the negotiability of each criteria and level;
6. The grade on a scale of 1 to 10, specifying to what degree the criteria is being met by the tunnel systems in their current state.

The end result is the CRINIFLEX which quantifies what the CETU [6] calls the functional description of the tunnel in Booklet 2 of its “Guide to Road Tunnel Safety Documentation” [6].

The functional analysis is ideally conducted in a joint workshop with the tunnel owner or operator allowing them to express their opinions on the tunnel’s current performance. The performance criteria also allow the owner/operator to specify which standards, codes and good practices (such as those of PIARC [3, 4], NFPA 502 [7], European Directive [8], etc.) are to base the performance analysis on.

Figure 3 illustrates an example of a functional model for tunnel, under AFNOR [10].

COMBINING THE HRTTIM METHOD AND THE CRINIFLEX

Once the functional analysis is completed by each discipline, the CRINIFLEX functions and criteria are consolidated and grouped together by tunnel component, and the individual components are rated from 0 to 9 according to their current condition using the HRTTIM [11] method. Figure 4 below provides an example this exercise’s result.

This combined method allows for priorities to be established based on the infrastructure’s condition. The component’s rating verifies its ability to function in relation to its original design. If a component’s rating is low the cost to rehabilitate it is estimated (conservation $). A new grade of the CRINIFLEX criteria is then determined to find out if the component’s performance improves with this investment. If there is no improvement in performance (grade after conservation), a recommendation for improvement must be made to the owner/operator. If there is an improvement, refurbishing is evaluated according to improvement level.
For an existing tunnel, this methodology allows relatively easy evaluation of priorities, in order to achieve objectives such as safety and circulation improvement for users, and protection of goods and infrastructure.

Table 2 - Example of element evaluation

<table>
<thead>
<tr>
<th>Component</th>
<th>CRINIFLEX</th>
<th>ASSESSMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive protection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walls and ceiling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passing 120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>minutes of exposure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>to fire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp of in-situ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>concrete surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥380°C (716°F)</td>
<td>F0 1</td>
<td>4</td>
</tr>
<tr>
<td>Protecting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>the facilities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire resistance of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>the structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NFPA 502: 1200°C</td>
<td>F0 1</td>
<td>1</td>
</tr>
<tr>
<td>Protecting the</td>
<td></td>
<td></td>
</tr>
<tr>
<td>facilities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protection of the</td>
<td></td>
<td></td>
</tr>
<tr>
<td>structure against</td>
<td></td>
<td></td>
</tr>
<tr>
<td>accidents</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Esthetics</td>
<td>F1 3</td>
<td>6</td>
</tr>
</tbody>
</table>

The above table shows an example of an analysis for passive fire protective on walls and ceiling and reveals the following:

1. Flexibility is F0 for temperature requirements and F1 for aesthetics, meaning thermal protection is a necessity while there is leniency on the quality of its aesthetic;
2. Current performance grades range from 1 to 3, meaning that currently the criteria and levels are not being met by the performance of the system;
3. The condition ratings of components (tiles on the walls and ceilings) is "4" which corresponds to a deteriorated state in the HRTTIM [11] method;
4. Following a rehabilitation of the tiles to their original design state (without the addition of an improved passive protection) the aesthetic criteria is the only aspect with an improved grade (10);
5. The recommendation of the engineer is to add a passive protective coating to increase performance.

This analysis is carried out for every tunnel component in all engineering disciplines: structural, mechanical, ventilation, electrical, signage, lighting, communication, automation, operations and others.
From these analyses a summary of all recommendations is presented to the owner/operator, before beginning the solutions study. This summary includes rationales and recommendations, both for required rehabilitation and needed improvements. Recommendations are ranked by priority, as defined in Table 3.

**Table 3 - Definitions of priorities**

<table>
<thead>
<tr>
<th>Priority</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unsafe or non-existent elements. Short-term rehabilitation required.</td>
</tr>
<tr>
<td>2 + mitigating measure</td>
<td>Mitigating measures that improve safety during major incidents.</td>
</tr>
<tr>
<td>2</td>
<td>Elements at the end of their life span. Short-term rehabilitation required.</td>
</tr>
<tr>
<td>3</td>
<td>Complementary work to priorities 1 and 2.</td>
</tr>
<tr>
<td>4</td>
<td>All other (non-priority) elements. (Medium-term).</td>
</tr>
</tbody>
</table>

This analysis method of elements completes the first stage of the North American approach of repair of existing tunnels. The next stage joins the analysis of the dangers based on the Specific Hazards Investigation elaborated by the CETU [6].

**SECOND STEP: SOLUTIONS STUDY**

The second step of CETU’s [6] approach is the production of the safety dossier which includes:

1. Traffic survey;
2. Specific hazards investigations;
3. Analyses of operations;
4. Events management:
   a. Emergency response plan and instructions;
   b. Description of the feedback procedure;
   c. Reports of incidents and accidents;
   d. List and analysis of safety exercises.

The first three items are easily integrated to the solutions study, as they are part of the engineering process. However, elements related to event management are internal procedures managed by the tunnel operator. These are very important aspects in improving tunnel performance and reducing risk. Each tunnel is managed differently and according to circumstance. The analysis process must address the presence or absence of safety response procedures and specific hazards studies of the tunnel’s current state, before implementing upgrades.

Analyses, studies, findings and recommendations at this stage of the feasibility study must be accompanied by the operator’s comments resulting from technical meetings, mandate to insure integration by the operator of the parameters affecting the level of current risk.

**SPECIFIC HAZARD INVESTIGATIONS OF EXISTING SITUATION**

This stage rests on the elaboration of a worst case scenario and the establishment of the tunnel’s equipments and systems performance in emergency mode. This allows to establish and quantify in percentage (%), the current performance as well as to identify the risk factors and the needs in improvement with the aim of decreasing the level of current risk.

The Specific Hazards Investigation of the current situation thus allows to test a realistic worst case scenario to validate the robustness of equipments, systems and procedures of the tunnel’s operation, especially as regards to the users evacuation, the ventilation system and the protection of the infrastructure.
This methodology is based on the booklet 4 “Specific Hazard Investigation”, by the CETU [6]. The investigation is conducted in accordance with the following plan:

- Chapter 1: Overview of the tunnel and its environment
- Chapter 2: Functional description of the tunnel
- Chapter 3: Identification of hazards and choice of the scenarios
- Chapter 4: Examination of the scenarios
- Chapter 5: Summary

The contents of chapters 1 and 2 according to the methodology of the CETU [6] were treated in the first stage of the North American approach: the needs study. This allows to begin immediately with the chapter 3 "Identification of hazards and choice of the scenarios" by adding the following analyses:

- Traffic survey and traffic rules
- Operating description: organization and facilities
- Emergency response plan and instructions

It is suitable; if available from the operator, to realize an analysis of the feedback procedure, report of incident and accidents, list and analysis of safety exercises which will help in the identification of hazards and choice of the scenarios. The specific hazard investigation use models of smoke movement and user behavior. For smoke movement, the use of both 1D and 3D models are helpful to understand the particularity of each tunnel. Models for user behavior are in great relation with smoke movement and numerous parameters affect often their unpredictable behavior. Both analysis are preponderating factor in the specific hazard investigation.

The developed North American approach thus retained from the Specific Hazards Investigation, most of the analyses suggested by the CETU [6]. Afterward, the North American approach pursues the use of the CRINIFLEX to express the current performance of the tunnel in a simple and clear way. A multicriteria table is elaborated for this evaluation.

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>WEIGHT (%)</th>
<th>CURRENT GRADE</th>
<th>IMPROVED GRADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: SAFEGUARD USERS &amp; PERSONNEL</td>
<td>50</td>
<td>x/50</td>
<td>+ x %</td>
</tr>
<tr>
<td>A-1 – Safety</td>
<td>20</td>
<td>x/20</td>
<td>+ x %</td>
</tr>
<tr>
<td>A-2 – Evacuation time in an emergency</td>
<td>15</td>
<td>x/15</td>
<td>+ x %</td>
</tr>
<tr>
<td>A-3 – Access to emergency exits</td>
<td>10</td>
<td>x/10</td>
<td>+ x %</td>
</tr>
<tr>
<td>A-4 – User comfort</td>
<td>5</td>
<td>x/5</td>
<td>+ x %</td>
</tr>
<tr>
<td>B: ENSURE FREE FLOW TRAFFIC</td>
<td>30</td>
<td>x/30</td>
<td>+ x %</td>
</tr>
<tr>
<td>B-1 – Roadway capacity and traffic management</td>
<td>10</td>
<td>x/10</td>
<td>+ x %</td>
</tr>
<tr>
<td>B-2 – Ability to communicate with users &amp; personnel</td>
<td>10</td>
<td>x/10</td>
<td>+ x %</td>
</tr>
<tr>
<td>B-3 – Operation</td>
<td>5</td>
<td>x/5</td>
<td>+ x %</td>
</tr>
<tr>
<td>B-4 – Maintenance</td>
<td>5</td>
<td>x/5</td>
<td>+ x %</td>
</tr>
<tr>
<td>C: PROTECTING THE INFRASTRUCTURE</td>
<td>20</td>
<td>x/20</td>
<td>+ x %</td>
</tr>
<tr>
<td>C-1 – Ensure the protection of the facilities &amp; infrastructure</td>
<td>20</td>
<td>x/20</td>
<td>+ x %</td>
</tr>
</tbody>
</table>

The Specific Hazards Investigation of the current situation allowed to justify the improvements suggested during the previous stage. Let us remind that these improvements were suggested according to criteria connected with the state of elements and necessity of repair of these elements. The Specific Hazards Investigation of the current situation highlights a second level of intervention necessity: the reduction of the risk in emergency situation. Indeed, the consequences analysis of a major incident such as fire of trucks according to the current performance, allows presenting to the owner / operator, the improvements necessity of the infrastructures and also of the procedures in emergency situation.
By using the CRINIFLEX elaborated in the previous stage, it is possible to estimate for each of the
technical criteria, the grade of performance after improvement. This innovative methodology allows
the design team to quantify the improvements for each of the disciplines from the detailed knowledge
acquired during the stage of needs study. The stages of this evaluation are as follow:

1. Assignment of each technical criteria of the CRINIFLEX to the evaluation criterion of the
   multicriteria table;
2. For each of the engineering disciplines, selection of the technical criteria in connection with
   the identified improvements;
3. Assignment of a new grade of performance according to the judgment of the engineer
   designer;
4. Compilation of the results by disciplines and if required, by type of improvement according to
   the multicriteria table such as presented in the Table 4;
5. Synthesis of the results and the presentation according to the multicriteria table.

CONCLUSIONS AND RECOMMENDATIONS

The North American approach to refurbishing of existing tunnels based on European specific hazard
investigation introduces an original methodology to evaluate the actual performance of the different
components and systems of the tunnel. This evaluation is done according to a performance approach.
The methodology tries to quantify the level of existing performance in relation with codes, rules,
goods practices that are determined by the owner/operator at the beginning of the study. The
CRINIFLEX is the tool to carry out this detail analysis.

In a second step, the Specific Hazard Investigation highlights the best improvements on a
cost/benefice scale to recommend to the owner/operator a refurbishing program. The Specific Hazard
Investigation is first conduct with the existing situation. Several improvement scenarios are then
developed by the team. Those scenarios represent different levels of improvement of the
infrastructures and they address as well issues related to risk management.

The next step is to do the engineering based on the solution chosen by the owner.

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Some Effects on Natural Ventilation System for Subway Tunnel Fires

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ABSTRACT

A series of experiments, using in a 1:15 model tunnel, were designed in accordance with the Froude conservation approach to investigate the influential parameters on temperature distributions in tunnel fires with natural ventilation. The effect of parameters such as fire size, shaft length and height were investigated. The natural ventilation system was depicted by introducing four vertical shafts spaced at 4 m in the ceiling of tunnel. Propane gas, located on the floor of the tunnel, was used to simulate the fire source. The fire source produced heat release rates in the range of 3.44 kW to 12 kW. The smoke temperature distributions along the tunnel ceiling and in the vertical direction along the tunnel length were measured using K-type thermocouples trees. Based on the fire plume theory, a dimensionless temperature was defined and it was found that the fire size did not have a major effect on the dimensionless temperature. Despite the shaft sizes did not significantly affect the distribution of the temperature in the near-field of the fire, they influenced the temperature values. The temperatures dropped with the increase of the shaft size. Based on the one-dimensional theory and rational assumptions, two formulas were developed to predict the ceiling longitudinal temperature distribution in tunnel fires with natural ventilation.

KEYWORDS: tunnel fires, natural ventilation, model scale experiments, Froude modeling.

INTRODUCTION

Natural ventilation schemes with openings on the roof can be utilized in subway tunnels to provide both normal and emergency ventilation. Compared to the traditional ventilation schemes, the natural ventilation mode could offer savings in capital investment dollars on the large ventilation plants. Moreover, natural ventilation systems could significantly help reduce the production of greenhouse gas emission or carbon footprint. However, utmost care should be given during the design of subway tunnel natural ventilation systems as to how to control smoke movement in order to ensure the safety of evacuees.

In recent years a great deal of research was conducted to investigate tunnel fires with forced ventilation systems. Concepts such as “critical ventilation”, “smoke backlayering length”, etc., were developed as results of enormous research work [1-5]. On the other hand, the natural ventilation scheme was not the subject of much of the research work. Smoke diffusion characteristics under a natural ventilation system were investigated [6-9]. Using a reduced-scale experimental approach, Yuan [6] investigated ceiling temperature distribution and smoke extraction through a natural ventilation shaft. Yuan [7] applied the Computational Fluid Dynamics technique (CFD) to investigate the maximum shaft interval distances to ensure tenable conditions in tunnels. Through the full-scale experiments and CFD technique, Wang [8, 9] researched the smoke diffusion characteristics in tunnel fire with natural ventilation.

In this study the effects of the fire size and shaft size on longitudinal ceiling temperature and vertical temperature were examined. A series of experiments were conducted on a model tunnel to understand
the smoke diffusion properties in tunnel fires with natural ventilation. Based on the analysis of the experimental data, formulas to predict ceiling temperature distribution were developed.

**REDUCED-SCALE EXPERIMENTS**

**Model tunnel and experiment setup**

A reduced-scale tunnel (1:15 scale) was used in this study. The tunnel model was 17 m long, 0.32 m high and 0.7 m wide. The boundaries of the tunnel were made of cement boards with a thickness of 10 mm. In order to be able to observe smoke diffusion in the tunnel, 4 glass windows were constructed on one side wall of the tunnel. To simulate the natural ventilation system, 4 cuboid shafts, made of gypsum board, were introduced on the tunnel ceiling in the middle of the width dimension. The shafts were arranged at interval distances of 4 m. To investigate the effect of the shaft size on smoke diffusion, 6 different shaft sizes, as shown in the Table 1, were used in the study. A schematic layout of the reduced-scale tunnel is shown in Figure 1a.

![Figure 1](image1.jpg)

**Figure 1** Layout of the reduced-scale tunnel

The porous bed burner of 178 mm diameter, used to simulate the fire source, was placed on the middle of the tunnel floor. Propane gas was used as the fuel source (Figure 1b). The produced heat release rates were regulated using a rotameter and a manometer. Different fire sizes in the range of 3.2 kW to 14.5 kW were used to investigate the effect of fire size on the tunnel fire dynamics. This range of heat release rates corresponded to a range of 2.8 MW to 12.6 MW at full scale.

To examine the smoke diffusion along the tunnel ceiling and the smoke temperature distributions under the ceiling, K-type thermocouples trees were used. A horizontal thermocouple tree was placed 10 mm under the tunnel ceiling. Five vertical thermocouples trees, five thermocouples per each tree, were installed at different tunnel cross-section. The five thermocouples were placed at distances from the ceiling of 10 mm, 60 mm, 110 mm, 160 mm, and 210 mm. One vertical tree was placed at the fire location, two were installed upstream of the fire and two vertical trees were placed downstream of the fire. All measurement points were set along the tunnel centerline. The sketch of the arrangement of thermocouples is shown in Figure 2.

![Figure 2](image2.jpg)

**Figure 2** Sketch of thermocouples arrangement
A hotwire anemometer was used to measure smoke temperature and smoke volume flow through the shafts. Four anemometers were used in the two shafts surrounding the fire. The volumetric flow of the smoke through these shafts was then calculated multiplying the shaft area and the average airflow velocities.

More than 100 tests were conducted to examine several influential parameters. The examined parameters included: fire size, fire location, shaft size (height and length), and tunnel grade. This paper presents the twelve tests conducted to investigate the effect of the three parameters; fire size, shaft height and shaft length on fire dynamics in a naturally ventilated tunnels. The test conditions of the 12 experiments are summarized in Table 1.

### Table 1 Test conditions

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Shaft Length (mm)</th>
<th>Shaft height (mm)</th>
<th>HRR (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>667</td>
<td>267</td>
<td>3.90</td>
</tr>
<tr>
<td>2</td>
<td>667</td>
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</tr>
<tr>
<td>4</td>
<td>667</td>
<td>267</td>
<td>7.84</td>
</tr>
<tr>
<td>5</td>
<td>667</td>
<td>267</td>
<td>11.90</td>
</tr>
<tr>
<td>6</td>
<td>533</td>
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</tr>
<tr>
<td>10</td>
<td>667</td>
<td>133</td>
<td>12.20</td>
</tr>
<tr>
<td>11</td>
<td>667</td>
<td>400</td>
<td>5.96</td>
</tr>
<tr>
<td>12</td>
<td>667</td>
<td>400</td>
<td>11.70</td>
</tr>
</tbody>
</table>

### Scaling Law

The Froude number conservation is usually adopted as a scaling technique in reduced-tunnel fire experiments to relate the model to the full-scale.

\[
F_r = \frac{V^2}{gL}
\]  

where \( g \) is the gravitational acceleration, \( V \) and \( L \) are the characteristic values of velocity and length, respectively. From the Froude number conservation, the relationships for the heat release rate, \( Q \), smoke velocity, \( V \), and smoke temperature, \( T \), of the model tunnel (subscript \( M \)) and full-scale tunnel (subscript \( F \)) can be expressed as follows:

\[
Q_M = Q_F (L_M / L_F)^{5/2} \\
V_M = V_F (L_M / L_F)^{1/2} \\
T_M = T_F
\]  

### RESULTS AND DISCUSSIONS

The following sections of the paper present the results of 12 experiments conducted to investigate the effect of three parameters; namely, fire size, shaft height and shaft length on the smoke diffusion in naturally ventilated tunnels.
Effect of fire size on temperature distribution

The maximum temperature rise of the smoke, $\Delta T_{\text{max}}$, can be expressed in terms of the dimensionless heat release rate, $Q^*$, and the ambient temperature, $T_0$, as follows [10]:

$$\frac{\Delta T_{\text{max}}}{T_0} \propto Q^{2/3}$$

where:

$$Q^* = \frac{Q}{\rho_0 C_p T_0 H g H}$$

where $\rho_0$ is the ambient temperature ($\text{kg/m}^3$), $H$ is the height of the tunnel ($\text{m}$), $C_p$ is the specific heat ($\text{J/kg K}$). In order to facilitate the investigation of the effect of heat release rate on the temperature distribution, the temperature rise is defined in a non dimensionless form as follows:

$$\Delta T^* = \frac{\Delta T}{Q^{2/3} T_0}$$

In this paper, the effect of heat release rate (fire size) on the temperature distribution was investigated for a shaft size of 667 mm in length, 167 mm in width, and 267 mm in height. The fire size ranged from 3.9 kW to 11.9 kW (Tests 1 through 5 in Table 1). In order to simplify descriptions, the model tunnel was virtually divided into two regions: the tunnel section containing the fire source was defined as the “fire section” and the rest of the tunnel was defined as the “non-fire section”. The ceiling longitudinal dimensionless temperature rise was plotted against the longitudinal distance from the fire source as shown in Figure 3. Figure 3 shows that for the five different fire sizes, the temperatures under the ceiling in the longitudinal direction are almost the same except for the thermocouple tree above the fire source. For small fire sizes, the flame did not impinge on the tunnel ceiling and therefore the temperature of the thermocouple above the fire source represented the centerline plume temperature. However, for the larger fire sizes, the flame impinged on the tunnel ceiling and the measured temperature represented the flame temperature.

![Figure 3](image)

**Figure 3** Effect of HRR on ceiling longitudinal temperature distribution

Figure 4 shows the vertical dimensionless temperature rise plotted against the distance from the ceiling for the five different fire sizes. Similar to the ceiling temperature distribution, Figure 4 shows that the vertical temperature distributions trends. Except for the thermocouple close to the ceiling, the dimensionless temperature did not change with the change in fire size.
From the above analysis, the changes in the fire size (heat release rate) did not have significant effect on the dimensionless smoke temperature rise vertical and ceiling distributions.

**Effect of shaft length on temperature distribution**

Three shaft lengths were used to investigate the effect of the shaft length on the smoke diffusion characteristics. Three lengths were: 667 mm (Tests 5), 533 mm (Tests 6), and 800 mm (Tests 8). The dimensionless temperature $\Delta T^*$ defined in the previous sections was plotted against the distance from the fire source (Figure 5) and against the distance from the ceiling (Figure 6).

The effect of the shaft length on the ceiling longitudinal temperature distributions is shown in Figure 5. It can be seen from Figure 5 that the dimensionless ceiling temperatures were almost the same in the fire section of the tunnel for the three shaft lengths. However, for a given distance from the fire source, the dimensionless ceiling temperature decreased with the increase in the shaft length in the non-fire section. This could be attributed to the longer shafts having the advantage of better extracting smoke while having insignificant effect on fire plume entrainment.

The effect of the shaft length on vertical temperature distributions is shown in Figure 6. The figure shows that the shaft length has a similar effect on the vertical temperature distribution as its effect on the ceiling longitudinal temperature.
Effect of shaft height on temperature distribution

The effect of the shaft height on the ceiling longitudinal temperature and vertical distributions are shown in Figures 7 and 8. Three shaft heights were investigated: 267 mm (Tests 5), 133 mm (Test 10), and 400 mm (Test 12).

Figure 7 shows that the shaft height had the same effect on the ceiling longitudinal temperature distribution as that of the shaft length both for the fire and non-fire sections. The increase in the shaft height improved the efficiency of smoke extraction due to the increase in pressure difference across the height of the shaft.

The effect of the shaft height on vertical temperature distributions is shown in Figure 8. From the figure, it can be observed that the shaft height has the same effect on the vertical temperature as the effect on the longitudinal temperature. Comparing the two figures, Figure 6 and Figure 8, shows the increasing the shaft length had more effect in reducing the vertical temperatures than that due to the increasing in the height of shaft. This is true, especially, for points closing to the ceiling (in the smoke layer). As such, the changes in the shaft length are more effective in extracting hot smoke and reducing the temperature in the tunnel than changes in the height of the shaft.
Longitudinal temperature decays

Karlsson and Quintiere [10] used the one-dimensional smoke diffusion theory to develop the following formula for the determination of the longitudinal temperature decay, $\Delta T_x$, in terms of reference temperature, $\Delta T_{\text{ref}}$, the distance from a reference point, $x$, and a constant value for a specific tunnel, $\alpha$:

$$\Delta T_x = \Delta T_{\text{ref}} e^{-\alpha x} \quad (5)$$

In order to ensure the proper application of Eq. 5, it is critical to select a reference temperature at a tunnel section at which the temperature is homogenous and can be treated as a one dimensional problem. In this paper, the ceiling temperature at a distance from the fire source of 0.6 m was selected as the reference temperature, $\Delta T_{\text{ref}}$, to investigate the longitudinal temperature decay characteristics.

As the smoke was extracted through the first ventilation shaft, the temperature of the smoke sharply decreased. As such, Eq. 5 cannot be directly used at and right after the first shaft. Another reference temperature, $\Delta T_{\text{ref}}$, should then be defined in order to investigate the temperature decays in the non-fire section after the first shaft. The ceiling temperature at a distance of 2.8 m from the fire source was selected as the reference temperature $\Delta T_{\text{ref}}$ of the non-fire section. The temperature decays in non-fire section can be expressed as:

$$\Delta T_x = \Delta T_{\text{ref}} e^{-\beta x} \quad (6)$$

where $\beta$ is a constant of the temperature decay in the non-fire section just after the first shaft. From Eq. 3, the reference temperature in the fire section can be expressed as:

$$\Delta T_{\text{ref}} = aQ^{2/3}T_0 \quad (7)$$

From the analysis of the experimental data, the value of the coefficient $a$ is about 1.68. Combining Eq. 5 and Eq. 7, the longitudinal ceiling temperature decay can be determined as follows:

$$\Delta T_x = aQ^{2/3}T_0 e^{-\alpha x} \quad (8)$$

If the effect of the shaft on the ceiling temperature was to be ignored, the reference temperature at the
non-fire section can be expressed as $\Delta T_{ref} e^{-\alpha(2.8-0.6)}$. Considering the effect of the shaft, the reference temperature, $\Delta T_{ref}$, can be determined from:

$$
\Delta T_{ref} = \Delta T_{ref} e^{-\alpha(2.8-0.6)} - \Delta T_{ref}
$$

(9)

$$
= ae^{-\alpha(2.8-0.6)} Q^{2/3} T_o - bl^m h^n Q^{2/3} T_o
$$

where $b$, $m$ and $n$ are constants; $l$ and $h$ are the length and height of the shaft, respectively. Eq. 9 will result in the temperature difference $\Delta T_{ref}$ to be zero, when shaft length and height equal 0 (no shaft case).

From the experimental data analysis, the constants; $b$, $m$ and $n$ were determined to be: $\frac{4}{7}$, $\frac{2}{3}$ and $\frac{1}{3}$, respectively. Therefore, the smoke temperature decay along the tunnel ceiling in the non-fire section can be expressed as follows:

$$
\Delta T_c = (ae^{-\alpha(2.8-0.6)} - bl^m h^n)Q^{2/3} T_o e^{-\alpha x}
$$

(10)

**Summary of the ceiling longitudinal temperature**

The distance from the fire source can be used to replace the distance from the reference position. As such, the smoke temperature distributions along the tunnel ceiling for tunnel fires with natural ventilation can be expressed as:

$$
\Delta T_x = aQ^{2/3} T_o e^{-\alpha(x-0.6)} \quad \text{for fire section}
$$

(11)

$$
\Delta T_x = (ae^{-\alpha(2.8-0.6)} - bl^m h^n)Q^{2/3} T_o e^{-\beta(x-2.8)} \quad \text{for non-fire section}
$$

(12)

Eq.11 and Eq.12 can be re-written in a non-dimensional form as follows:

$$
\Delta T^*_{x} = \frac{\Delta T_x}{aQ^{2/3} T_o e^{0.6x}} = e^{-\alpha x}
$$

(13)

for fire section

and

$$
\Delta T^*_{x} = \frac{\Delta T_x}{(ae^{-\alpha(2.8-0.6)} - bl^m h^n)Q^{2/3} T_o e^{2.8\beta}} = e^{-\beta x}
$$

(14)

for non-fire section

The experimental data of all tests and the prediction of the developed formulas of equations 11 and 12 are summarized and plotted in Figure 9. It is found that the longitudinal smoke temperatures can be well correlated with the equation.
CONCLUSIONS

In this paper, the model scale experiments were carried out to investigate the tunnel fires with natural ventilation. Based on the fire plume theory, a dimensionless temperature $\Delta T^*$ was defined to predict the temperature distributions in the tunnel.

From the experimental data, the change in the fire size, for a fixed shaft size, does not have significant effect on the dimensionless temperature distributions in the tunnel. Moreover, the shaft size has no effect on the dimensionless temperature distributions in the fire section. However, the decrease in the shaft length or height will cause increase of the dimensionless temperature in the non-fire section.

Based on the one-dimensional theory and using two different reference temperatures, the ceiling temperature decay can be expressed as exponential functions of the distance from a reference location for the two regions, the fire section and the non-fire section.

REFERENCE

External conditions have a significant impact on the air flow in tunnels using transverse ventilation for smoke extraction.

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ABSTRACT
In 2008 the City of Stockholm Traffic Administration conducted a series of full scale tests, with heat and smoke generation equivalent to that from a fire in a small car, in one of their urban tunnels with transverse ventilation. The primary goal of the tests was to verify how the ventilation system worked and also to provide an opportunity for the local fire brigade and consultants in this field to see what one could expect in a similar situation. A total of four different tests were carried out at two different locations in the tunnel. Methanol was chosen as fuel and the smoke was produced from smoke machines. The ventilation conditions were set according to a pre-set function to simulate both low and high traffic conditions and the fire ventilation was activated 10 minutes after ignition of the simulated car fire. The result of the tests illustrated a variety of phenomena where the external conditions and the general design of the tunnel had a significant impact on the air flow. These aspects determined the direction of airflow in the tunnel regardless of the pre-set ventilation settings. The ventilation settings for the different traffic cases had a significant impact on the stratification of smoke in the event of a fire.

KEYWORDS: Transverse ventilation, tunnel, stratification, external conditions, fire and smoke tests.

INTRODUCTION
During the past decade one of the City of Stockholm Traffic Administration tunnels, called the Klara tunnel, has been under scrutiny concerning its fire and life safety due to its age, neglected maintenance and as part the overall systematization of fire protection in Swedish tunnels. Throughout 2003 and 2004 a series of analyses were performed to establish the present tunnel status and identify urgent needs for the tunnel [1-3]. In the following years some of the most important issues were dealt with and in 2008 it was possible to make a full scale commissioning test with heat and smoke [4, 5].

The primary goal of the test series was to verify whether the transverse ventilation system would be able to make an effective smoke extraction. It was also an opportunity to draw conclusions regarding what the local fire brigade and consultants in this field could expect in a similar situation. It should also be noted that in order for a good evacuation to be carried out, it was necessary that the ventilation system functioned as intended.

DESCRIPTION AND DESIGN OF THE TUNNEL
The tunnel was built in the mid to late 70s and consists of two connected sections: the first section is 500 m with two lanes and the second section is a 350 meters one lane section. The ceiling height of the tunnel is only 3 – 3.5 m. The gradient in the tunnel is not more than a few percent except where the two lane and single lane sections meet, where a short on and off ramp connects the tunnel to the surface. The traffic intensity is approximately 35,000 vehicles per day. The ventilation system is transversal and consists of 15 fans, 8 of which are exhaust fans and 7 are inlet fans distributed in 3 ventilation rooms in and around the tunnel (see figures 1 and 2). The performance of the fans ranges
from 65 m³/s to 75 m³/s and they are rated to withstand a temperature of 250 °C for up to two hours. The inlet openings are located near the pavement and run almost along the entire tunnel on one side, the exhaust fans ventilate through a gap between the wall and ceiling on the opposite side of the tunnel from the inlet.

For fire detection, a line detection cable is mounted flush with the tunnel ceiling throughout the entire length of the tunnel. The tunnel has sprinklers, a dry deluge system, but the validation of performance of this system was not included in the test series presented here.

Figure 1 Ventilation rooms and escape routes.

Figure 2 Drawing of the ventilation concept.
OUTCOME OF RISK ANALYSIS OF KLARA TUNNEL
The analyses that were carried out in 2003 – 2004 [1-3] showed a variety of problems that had to be recognized and dealt with. Some were more urgent then others and improvements were made the following years, including (but not limited to):

- Lengthening of the walls between the parallel tubs at all three exits to prevent smoke from spreading to the other tube depending on the external wind effects from the tunnel entrances [1].
- Renovation and reinstallation of the sprinklers that had been out of order for some years [2].
- Renovation of both the inlet and exhaust fans to make them more temperature resistant, thereby promoting a better environmental ventilation, more energy efficiency and increased overall automation of the ventilation system in case of fire.
- Increased visibility of the exit doors [2].

EXPERIMENTAL SETUP
The consultant firm WSP was commissioned to verify the current ventilation strategies that are applied. SP Technical Research Institute of Sweden, Department of Fire Technology coordinated the tests, rigged the material and documented the observations made [4-5]. The smoke tests were carried out at two different locations in the tunnel. The two sites were located in the same tube with approximately 500 m separation, with the major difference being that the first position was in the two-lane section while the second position was in the single-lane section, see figure 3.

The tests were set up to produce heat and smoke equivalent to a fire in a small car, barely 1.5 MW. Methanol was chosen as fuel to produce as clean a fire as possible and thereby minimize the impact on the tunnel. The fire source consisted of twelve square containers (0.5 m × 0.5 m), each with 10 L of methanol. The smoke was produced from smoke machines, the type used in theaters, but with a thicker smoke, see figure 4. The external conditions the night of the test were 1 m/s southwest wind with a temperature starting at 16 °C decreasing to 13 °C during the night.

![Diagram of test sites](image-url)
SCENARIO CONFIGURATION
A total of four different tests were carried out for four different scenario configurations, see Table 1. The ventilation cases for the first two tests were made for low traffic condition. The third test was designed to replicate high traffic conditions. The fourth test was conducted with a manual ventilation setting [4]. The ventilation conditions were set according to a pre-set function (case 1) and activated the fire ventilation after 10 minutes after ignition (case 2).

In the ventilation case for fire ventilation all eight exhaust fans are activated at 100 % and none of the inlet fans are used. It takes about 1.5 – 2 minutes to ramp up to maximum capacity. The low traffic condition was set to one exhaust and one inlet fan at 25 % each, just enough to produce some turbulence. The high traffic condition was set to four exhaust and four inlet fans at 75 % each, which is normal for this tunnel during high traffic, provided there is no congestion. During congestion the fans are working at almost full capacity to maintain the environmental quality standard requirements that is 400 µg/m³ per hour. In the special case (test 4), all inlet fans were set at 15 % and all exhaust fans at 75 %, to study the different phenomena that occur. The first and last tests were run with cold smoke to study the flow conditions in the tunnel, without the impact of thermal expansion caused by fire. The smoke machines followed a pre-set program of smoke production, i.e. they did not start simultaneously, but with a lag time. This was done so that at least one smoke machine would be producing smoke throughout the whole length of the test. The same smoke generation method was used in all tests.
Table 1  Scenario configuration set-up.

<table>
<thead>
<tr>
<th>Test</th>
<th>Location</th>
<th>Fire</th>
<th>Smoke</th>
<th>Ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>No</td>
<td>Yes</td>
<td>1) Low traffic</td>
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<td>2) Fire ventilation</td>
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<td>1) Low traffic</td>
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<td></td>
<td></td>
<td>2) Fire ventilation</td>
</tr>
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<td>Yes</td>
<td>1) High traffic</td>
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<td>Yes</td>
<td>1) Special case</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2) Fire ventilation</td>
</tr>
</tbody>
</table>

a) Location of fire and/or smoke generation

TEST 1
Only smoke was used in Test 1, i.e. no fire. At the beginning of the test the air velocity was approximately 1 m/s from Herkules Street (Herkulesgatan) towards Svea Road (Sveavägen). The air flow was in the opposite direction to what was anticipated and a chimney effect occurred in the tunnel, and the ventilation case employed for this test was unable to either reverse or prevent this phenomenon. The smoke carried by the airflow was first held centrally in the tunnel as a plug (see Figure 5, to the left), then it filled up most of the tunnel cross section (see Figure 5, to the right). No smoke was observed upstream of the smoke machines.

![Figure 5](image.png)  
*Figure 5  Left: Test 1, 2 s after ignition; Right: Test 1, 46 s after ignition.*

After 10 minutes, the ventilation was set to fire ventilation (case 2). The air velocity at this time was about 3 m/s, in the same direction as before. The main difference near the smoke production after the ventilation was changed to fire ventilation (case 2) was the increased air speed in the tunnel, which led to a depletion of the smoke. This may also have been due to the exhaust ventilation, but this could not be observed near the smoke production.

TEST 2
Both fire and smoke were used in this test. At 15 seconds after the start of the test both all the containers with methanol had been ignited and smoke production was started, see Figure 6. In the first minutes it was sometimes difficult to see downstream but generally a good stratification of the smoke occurred. Just before and after fire ventilation (case 2) was set (around 10 minutes) there was good smoke stratification over virtually the whole tunnel section, after about 15 minutes into the test the ventilation situation become more and more turbulent and a thin presence of smoke covered almost the entire cross section downstream of the tunnel.
In this test, it was also monitored how well the fire detection cable responded to the heat. Despite the extra isolation slabs in the ceiling (see Figure 6), fire detection was made at 2 minutes after ignition.

![Figure 6](image1)

*Figure 6  Picture of the fire and isolation slabs.*

**TEST 3**

In this test the fire and smoke started as in Test 2 but the initial ventilation case was set to simulate the high traffic scenario. In this case, far more turbulent conditions in the tunnel were seen immediately after ignition and the stratification observed in the second test did not appear in Test 3. The smoke filled the entire tunnel cross section and the smoke front moved like a wall at the speed of 1m/s. The flow direction of the smoke was still towards Svea Road (Sveavägen) but there was a short back layering effect before being directed forward by the main air flow. A few minutes after fire ventilation case was set (12-15 minutes) the smoke started to thin out upstream of the fire and began to stratify near the fire. Near the end of the test (16-19 minutes) the air velocity had increased to about 2.6 m/s and stratification had deteriorated once more. The smoke extended further downstream and thinned out more at this point.

![Figure 7](image2)

*Figure 7  Picture of the smoke in Test 3, a few seconds after it had past the camera.*
TEST 4
Test 4 was conducted at the second site (see Figure 3) and was performed with only smoke, i.e. without heat. The smoke followed the air flow that was in the direction of the traffic at 1.1 m/s, i.e. as opposed to the case observed in test 1 to 3 when the air flow at the test site (first site in Figure 3) was against the direction of the traffic. Observations made in this test showed that the smoke rapidly filled up the entire cross section and one could see that the smoke was extracted near the ceiling. Another phenomenon observed was that the smoke stopped abruptly in its advancement, stood still and was extracted. This was probably due to an air flow towards Svea Road (Sveavägen), but this has not been studied in detail and cannot be verified.

RESULT SUMMARY
The external conditions had a significant impact on the air flow in the tunnel which contained a transverse ventilation system. The fire and smoke tests showed a variety of phenomena of which some are particularly important to note:

- The external conditions and the general design of the tunnel determined the direction of airflow in the tunnel regardless of the pre-set ventilation settings. Note that the prevailing wind conditions were 1 m/s southwest with a temperature starting at 16 °C decreasing to 13 °C during the night.
- The inlet fans had a significant impact on the stratification in the event of a fire in the tunnel. At the high traffic case the air flow from the ventilation destroyed stratification and visibility deteriorated significantly.
- The air speed was in general 1m/s opposite the simulated traffic direction in test 1 – 3 and increased up to 2.5 – 3 m/s after fire ventilation was set.
- In test 1 - 3 the smoke accumulated at the same spot in the tunnel, i.e. where the Svea Road (Sveavägen) access ramp meets the Mästersamuelsgatan (Mästersamuelsgatan) lane in the tunnel. This was the point where the smoke was extracted by the exhaust fans. This was not studied in detail but several participants saw this phenomenon and the general conclusion was that it must have been due to the fact that the exhaust fans built up the greatest negative pressure at this location. This, together with the external conditions, e.g. the wind, developed a flow in the tunnel in the opposite direction to the direction of the inflowing air from the ventilation system.
DISCUSSION
There are several different parameters and conditions that can affect the flow situation in a tunnel: external wind, flow created by the traffic, buoyancy effects due to temperature and height differences, balance of the ventilation system, etc.

Several authors have studied the effect of external wind on the flow of air and its velocity inside a tunnel [6-9]. The wind direction during the test series, outside of the tunnel, was almost straight towards the tunnel entrance at the Herkules Street entrance, see Figure 3. According to Nyman and Sandberg this would lead to a velocity inside the tunnel which is 70% of the outside velocity [9]. This would create an air velocity of approximately 0.7 m/s leading from Herkules Street towards Svea Road. An airflow towards Svea Road could also be confirmed during the tests. The curved tunnel at the end of the tunnel, close to Master Samuels Street complicates the situation, since at that tunnel entrance the wind was also ostensibly towards the entrance, although not as straight as at Herkules Street.

The height of the road varies along the tunnel. The lowest point is actually at the test site for Tests 1-3. If this is defined as height “zero”, the three tunnel entrances are at heights: 1.8 m (Herkules Street), 6.8 m (Svea Road) and 4.8 m (Master Samuels Street). This height difference could potentially have had an effect on the exhaust flow out of the tunnel through the entrance at Svea Road.

The position of Test 4 (see Figure 3) was at approximately the same height as the entrance at Master Samules Street and the maximum height of the road between these two positions was 1 m higher. Note that in Test 4, when the ventilation flow at the test site was from Master Samuels Street, only smoke and no heat was used. The ventilation system and wind may in this case have had a compounding impact on the ventilation flow to give the resulting flow. On the other hand, the smoke stopped abruptly a distance from the smoke production. The reason for this flow behavior may be a combination of the air flow from Herkules Street and an unbalanced exhaust flow. As mentioned in PIARCs report “Systems and equipment for fire and smoke control in road tunnels” [10], control of the longitudinal airflow is as important a design criterion as the extraction flow rates and must be carefully studied.

CONCLUSIONS
The question of how we can maintain good comfort ventilation without risking destruction of stratification early in an emerging fire event during high traffic conditions is an important one to answer. What could happen if we have even less favorable wind conditions (higher wind velocities), an even higher fire load or the production of higher volumes of toxic smoke?

The results of the tests presented here provide important information concerning the function of the ventilation system under the conditions experienced then. For future renovations and new tunnels we must take into consideration the factor that external conditions may differ considerably between different seasons and on different days. This can then have a significant effect on the flow direction, the stratification of smoke and visibility in the tunnel. More work is needed to develop contingency plans for different traffic flows and weather conditions. Further, it is necessary to look into how we can increase smoke extraction using the ventilation system installed, or improve efficiency of smoke extraction during an incident. Finally, an investigation of the utility of the active fire suppression system installed would provide important insight into the benefit of such installations as input to cost-benefit calculations when making decisions about future installations.

REFERENCES
Swedish).
Dynamics of natural air flow inside subway tunnels

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ABSTRACT

Terrorist attacks and major fires in subway tunnels lead into catastrophic circumstances. Large numbers of casualties and deaths could be the result. As fire tunnels develop very rapidly and contaminate the breathable air for subway passengers there is very limited time for reaction and rescue. Knowledge about the actual air flow direction of certain tunnel sections provides a prediction of affected and non-affected tunnel sections and stations that can influence the operational plans for fire fighters and rescue forces. An automatic evacuation guiding system can use this data as input in order to indicate save and unsafe evacuation routes.

Previous scientific work has proved the existence of a natural air flow in subway tunnels which is independent on the well known piston effect produced by trains. Field work has shown, that the characteristics of the natural background air flow in subway tunnels are related to the overground weather conditions. The understanding of classical climatology helps to set up a prediction model, to make a prediction of the natural air flow inside the tunnels. Data analyses from an actual research project could build up such a prediction model successfully.

KEYWORDS: subway climatology, natural airflow, spreading of CBRNE gases and smoke, terrorist attack, tunnel ventilation, prediction model

INTRODUCTION

Since subway tunnels have very few connections to the outer atmosphere, the climate factors which determines the natural air flow inside a subway system, are different from the classical climatology. The relatively young research field of “Subway Climatology” was developed in the late 90s of the last century [1]. Before, the general assumption was that air movement in subway tunnels is mainly triggered by the train piston effect [2]. Measurements, done by the workgroup “Cave & Subway Climatology” of the Ruhr-University Bochum (www.ubahn-klimatologie.de), showed clearly that wind speed and direction in tunnels are related to the outer atmosphere conditions [3&4]. During catastrophic circumstances like terrorist attacks with toxic gas or dramatic tunnel fire caused by accidents, usually the train traffic stops immediately in order to reduce victims [5]. Knowledge about the natural air flow is very valuable in such a dramatic situation to point out evacuation areas as well as rescue ways to coordinate emergency operations.
SUBWAY CLIMATE

Climatic factors in subway tunnels
The Environment of subway tunnels develops a specific climatic system which is different from the classical ideas of the climate system. The energy budget as driven factor for the climate systems differs in subway tunnels:

- **Incoming Energy**
  - no shortwave solar radiation or long wave atmospheric back radiation
  - soil heat flux is significant higher due to higher surface volume ratio
  - groundwater in urban agglomeration can be 4 K warmer than in its rural surroundings [6], therefore soil heat flux will be higher
  - trains, technical equipment like lightning or cooling of electric rooms, and other cause a large amount of anthropogenic energy flux
  - passengers themselves release latent and sensible heat

- **Outgoing Energy**
  - no radiational cooling
  - highly reduced sensible heat transfer from warm tunnel air to cooler outer atmosphere
  - subway and station walls, floors and ceilings are made from impenetrable materials therefore latent heat transfer is nearly impossible

These climatic key factors cause a general over-warming of subway tunnels compared to the outer atmosphere from late summer to winter. Similar to natural caves, inside branched structure of subway tunnels a separate climate develops with alternating air flow direction [3].

Natural Air flow in tunnels
Subway systems are characterized by branched underground tunnels with few openings from the outside atmosphere. Since it is proved that natural air flow occurs in tunnels and alternate from time to time, research was started to answer the question: Is the characteristic and direction of natural air flow in subway tunnels related to outside weather condition? Field work was done by the workgroup “Cave & Subway Climatology” of the Ruhr-University Bochum in some subways of the US (for instance New York City) and Europe like England and Germany. One of the most recent examinations has been done inside the NEXUS subway system in Newcastle upon Tyne [7] and Berlin in Germany. To date some possible influencing factors have been examined and proved in empirical studies:

- At tunnel portals, air masses are pressed into or out of tunnels depending on outer wind speed and direction [8]. This effect is limited only to the first stations after a tunnel portal.
- Penetration of cold outside air, especially in the winter months, which is warmed inside the tunnel system, creates a separate air pressure regime [9].
- The natural air flow is related to buoyancy effects (except close to tunnel portals) but the tunnel geometry can also have a controlling effect (see Figure 2).

The most recent long-term and most comprehensive measurements in Berlin (Germany) is embedded in the OrGaMIR project (Cross-organisational danger defence for the protection of men and critical infrastructures by means of prevention and reaction) and founded by the German Ministry of Education and Research (BMBF)[10]. The data of this research project showed that the difference in density of air is one of the key factors of natural air movement in subway tunnels. The density of air is controlled by air pressure, air temperature and relative humidity. If the outside air is significantly denser than the apparent in tunnels, then outside air will fall through pressure relief shafts, emergency exits (if they are open to the tunnel) and stations into underground sections. Relative differences in altitude can trap packets of air independent of their specific gravity. The well-
known lakes of cold air from mesoscale climatology (temperature inversions) could occur inside tunnels as well and can block an air mass exchange between stations through the tunnels (see Figure 1).

**Figure 1** Dynamics of air flow inside a subway system driven by the topographical situation

The annual sequence of air temperature inside tunnels flattens comparing to outside temperatures. The over-warming of tunnels is about 5 K in summer and 10 K in winter time. Tunnels show nearly the same relatively humidity of 30% to 50% over the year (see Figure 2). In relation to the cooler winter temperature, this means less moist air in the tunnels. As air pressure increases, temperature and humidity decreases, density increases.

\[ \rho = \frac{p}{R_f \cdot T} \]  
\[ R_f = \frac{R_i}{1 - \varphi \cdot \frac{p_d}{p} \cdot (1 - \frac{R_i}{R_d})} \]

\( \rho \): density of air \([\text{kg m}^{-3}]\)  
\( p \): air pressure \([\text{Pa}]\)  
\( T \): temperature \([\text{K}]\)  
\( R_f \): gas constant of humid air \([\text{J (kg K)}^{-1}]\)  
\( R_i \): specific gas constant of dry air \(, 287.058 \text{ J (kg K)}^{-1} \)  
\( p_d \): saturation vapour pressure \([\text{Pa}]\)  
\( \varphi \): relative humidity

During the cold months from November 2009 to February 2010 a significant higher outer air density was observed. The result was a steady penetration of denser air into the tunnel. On the other hand this air was warmed in the tunnel and becomes less dense. These differences in density of air forced an adjustment of air masses in order to reach equilibrium. So gravity plays a major role. Relatively differences in elevation of a subway tunnel control where cold dense air from the outside penetrates the tunnel and where the heated, less dense tunnel air rises up by convective through stations and shafts to the outside.
Figure 2 14 day moving average of air temperature (a), relative humidity (b) and density from outside, upper and lower level of a two lines crossing subway station. The data was recorded between March 2009 and February 2010 from a subway station in Germany. The air pressure inside the tunnels and stations is assumed equal to the outside air pressure.

CASE STUDY: AIR FLOW REGIME INSIDE A CROSSING STATION

Since 2008 field work has been done by the workgroup of Cave & Subway Climate as part of the OrGaMIR project. Climatic factors are recorded in several subway stations in Berlin, additional data comes from weather stations.

Set up of measurements
The best studied station is a classical crossing station. Two Lines (A and B) intersect nearly perpendicularly. B-Line runs above the A-Line with central staircases connecting them. B-Line runs from North to South. The northwards directed tunnel is described in the following as B1 wing, the southwards one as B2 wing. In the lower level the westward tunnel is signed as wing A1, the eastwards as wing A2 (see Figure 3).

Each tunnel mouth was equipped with ultra sonic anemometers and temperature sensors. In addition an automatic weather station was installed on the surface. More climatic data came from a nearby weather station (two kilometres from the station).
Observed air flow

The ultra sonic anemometers measured with a sample rate of 1s, the temperature sensors at 10s intervals, and the automatic weather station every 1 minute. The data of the nearby weather station was available every 15 min, all data were averaged to a sample rate of 15 minutes. The presented analysis focused only on the natural air flow, therefore only data during the nightly operational break was taken into account. 1063 data records averaged to 15 minutes from March 2009 till February 2010 were chosen.

The observed air flow of the upper level was relatively stable. The wing B2 showed 100% outgoing air flow, air moved from the station inside the tunnel (positive wind direction). The opposite wing B1 was also observed to have a very stable wind direction. On the lower level the situation was vague, especially in wing A1 which showed a high level of variability. A bit more than 60% of all cases indicated a clear incoming air flow (negative wind direction), 15% indicated an outgoing air flow and the remaining 25% were observed with a wind speed lower than 0.05 m/s, so no statement could be given here, because this is within the accuracy of the measuring devices (see Figure 2).

The stable wind direction on the upper level can be explained by the tunnel geometry. Southwards at wing B2 the tunnel rises up to the next station at approximately 20m (see Figure 3a). The relatively light warm air within the tunnel system is moved up to the next station by a strong chimney effect through the rising tunnel. Cold incoming air flow through the emergency exits in wing B2 should be gravitationally moved in direction of the crossing station, but the effect of warm outgoing air flow is dominant. The air volume in the upper level is up to 10K warmer than outside. Air masses are forced to flow out through the station exits.
The tunnel of the lower level lies deeper in the range of the crossing station (see Figure 3b). Existing cold air enters the station through adjacent emergency exits. The observed wind direction during annual measuring period showed the following pattern most frequently: wing A1 60%, A2 74% incoming air flow (see Figure 3). But the variability is too high to consider this as a simple rule.

So in the described case relatively dense air penetrates the station and the neighbouring tunnel section of the lower level, flows and heats up towards the station from both sides. The out-flowing air masses of the upper level must be replaced. A steady air flow from the upper to the lower level will be the result. If the tunnel section near the station of the lower line or the lower level of the station itself is affected by poisons or flue gases, the central escalator and the upper level will be affected very rapidly.

**Modelling natural air flow**

One aim of the research project is to model the natural air flow inside the tunnels. It will be too cost-intensive to equip all tunnel sections with anemometers. Cheap and low-maintenance temperature and humidity sensors can be installed fairly easy. In contrast to the ultrasonic anemometers these sensors have very low energy consumption, so a wireless solution seems possible.

Different parameters were selected to create a multiple regression-model. The flow velocities in the single wings were the dependent variables, with the knowledge that cold and heavy air masses as well as the regional wind field should have an influence on the air current and velocity inside the tunnels. Air pressure, moisture and temperature are directly related to the specific weight of air, so these parameters have to be taken into account. But the wind direction could not be neglected. In addition the dynamic, for example the change of temperature over the last hour or the difference between present temperature and the previous day maximum, could have an influence.

Due to the fact, that the upper level occurs a significant slope in one direction (see Figure 4), parameters which were highly connected with the density of air show here the strongest effect. Whereas the wind direction of the nearby automatic weather station showed very poor single correlation.

With a multiple regression analysis wing B2 could achieve $r^2$ of 0.74, which shows a fairly strong correlation. Wing B1 achieves a respectable value of 0.69. Figure 5a and b demonstrates that modelled and observed natural air flow match fairly well. For the lower level, the same method does not reach acceptable correlation factors.

**Improvement of the results by adding wind measurements**

The multiple regression models are improved by considering the empirical wind data from the ultrasonic anemometer device in the tunnel in wing A2. This results in a significant improvement of the forecast of air flow in wing A1. For the upper level the result is only slightly improved. The new multi-regression model reached a reasonable correlation of $r^2=0.67$ for wing A2. With this optimized model, the predicted and observed air flow match was quite good (see Figure 5c).
Figure 5 Comparison between predicted (modeled) air flow and measured airflow at January 4th 2010. Negative air flow: Air pushes from tunnel into station, positive: air is soaked from station to tunnel. a) and b): no anemometer measurements inside the tunnel were used. c) At wing A2 the measured air flow was taken into account also.

PREDICTING THE FLOW DIRECTION

The goal of the research work is, to provide an online forecast of air flow direction inside tunnels. This should be used by fire fighters and rescue forces to optimize operational plans. It can also be used to guide passengers to a safe exit by automatically light and sound signs.

If the velocity of air flow is neglected three classes can be built. Class -1 represents ingoing wind (negative) direction, class 1 outgoing (positive) air flow (see Figure 3). Class 0 stretched +/- 0.05m/s around 0. This is the measuring tolerance of the ultrasonic anemometers.

For all wings were a total of 83% of the wind directions correctly predicted. In 11% of cases there is a misleading of one class, in 6% one of two classes.

Due to the good regression model, as expected the air flow direction in the upper level is predicted quite well. Nearly 100% (wing B1) and 94% (wing B2) is predicted right. Only 2% of the predictions for the upper level are wrong by two classes. Although there was no acceptable regression model set up for the lower level, the prediction of direction is still high. 64% (wing A1) and 76% (wing A2) of the air flow direction is predicted correctly. But about 10% of the prediction is misleading by two classes (see Figure 6a). A further conclusion can be determined: If the air flow direction for wing A2 is predicted negative it will be likely right, if it is positive it will be likely wrong.

If the improvement method mentioned above is applied, better predictions are the result. The measurement in wing A2 is part of the regression model, therefore the prediction of the model is absolutely right. The tunnel section of the other side (wing A1) can be predicted now by 71% right.
CONCLUSION

The results so far proved the opportunity to predict the air flow in subway tunnels with an empirical model from local weather data and some less cost intensive temperature and moisture measurements in tunnels. This information is valuable for fire fighters and rescue forces. If the information is connected to an automatic guiding system, they can sign out safe evacuation ways by sound and lighting systems. This increases the chances during the self rescue phase after a catastrophic event in a subway system and leads to less casualties and dead.

OUTLOOK

Only data recorded during operational breaks was taken into account so far. Regarding data of traffic times and usage of further statistic methods should produce better prediction models. But the analysis during operational times needs a complicated filter algorithm to neglect the interfering effect of train movement. On the other hand the signal of natural air flow must be maintained. Due to the fact, that during operational brakes usually no evacuation is necessary, the next goal is to receive a prediction model which is valid for operational time also.

Figure 6  Prediction of air flow direction inside tunnels for each wing. Class -1: air flowing from station outward ($V > 0.05\text{ m s}^{-1}$), Class +1: air flowing to station inward, Class 0: air flow velocity is lower than 0.05m s$^{-1}$

(a) Prediction from outer conditions and tunnel temperature and humidities, analogue to Figure 4

(b) Data from one tunnel measurement was taken into account, analogue to Figure 5
REFERENCES


Multiscale Modelling of Fire Emergencies in a Transverse Ventilated Tunnel

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ABSTRACT

This paper applies a transient multiscale approach to model ventilation flows and fires in a transverse ventilated tunnel. The multiscale model couples dynamically a Computational Fluid Dynamics (CFD) solver with a simple 1D model, allowing for a more rational use of the computational resources. The 1D network models tunnel regions where the flow is fully developed (far field), and detailed CFD is used where flow conditions require 3D resolution (near field). Compared to full CFD, multiscale provides a reduction of the required computing time by almost 100 times without significant loss of accuracy. In comparison to longitudinal ventilated tunnels, the implementation of multiscale techniques in transverse ventilation systems is more complex due to the higher number of 1D-3D interfaces including gallery sections and extraction dampers.

The methodology has been applied to study the transient flow interaction between a growing fire and a ramping-up ventilation system in the Grand-Saint-Bernard Tunnel a two-way link between Italy and Switzerland with the total length of around 5850 m. A preliminary re-design of the present ventilation system has been performed in accordance with the most recent Swiss Standard.

The model allows for assessing the ventilation system response, for calculating the time required to realize smoke confinement as well as for assessing the effectiveness of the extraction dampers also in relation to their size and number. The paper shows that the multiscale methodology represents the most feasible tool to conduct accurate simulations in long tunnels domains, when the limitation of the computational cost becomes too restrictive.

INTRODUCTION

Tunnels are an important part of world transport infrastructure with a key role both in people and freight transfer. Past events show that fire poses a severe threat to safety in tunnels. Indeed, in the past decades hundreds of people worldwide have died as a result of fires in road, rail and metro tunnels [1]. In Europe alone, tunnel fires have brought vital parts of the road network to a standstill and have cost the European economy billions of Euros [1]. The analysis of the most catastrophic tunnel fires has shown that that fire emergencies must be managed by a global safety system capable of avoiding or minimizing the damage to occupants, rescue teams, and structures, while keeping the tunnel operational for as long as possible. This system and its emergency strategies must integrate detection, ventilation, evacuation and fire fighting activities. Within this, the ventilation system plays a crucial role because it takes charge of maintaining tenable conditions to allow safe evacuation and rescue, as well as fire service intervention.

The transient interaction between tunnel ventilation flows and fire dynamics is an important issue in tunnel fire protection. Indeed, such interaction determines the movement of smoke within the tunnel, and therefore determines its temperature, stratification, visibility and distribution of toxic gases. The resulting transient flow depends on the combination of the fire source, the forced ventilation and the atmospheric conditions at the portals, as well as the tunnel geometry and layout. The ability to predict these flows accurately allows for assessing the extension of the hazardous zones in the tunnel, and for designing and optimizing evacuation procedures or adoption of fixed fire-fighting systems (e.g. water mist or sprinkler systems).
The analysis of the time dependent evolution of a fire emergency in mainly performed using computational-fluid-dynamics (CFD) and one-dimensional (1D) tools.

CFD analysis of fire phenomena in tunnels suffers from the limitations set by the large size of the numerical grid and the number of fire/ventilation scenarios to be explored and requires significant computational resources. The computational cost escalates with the tunnel length and often becomes impractical for engineering purposes even for medium tunnels less than 500 m long. The task is near impossible for longer tunnels which are common in modern infrastructure. This drawback affects the validity of a fire safety assessment since only a limited number of scenarios can be explored in practical terms, leaving a wide range of possible conditions unexplored. A limited solution is to study only a small region around the fire, assuming that the flow velocities at the boundaries of the domain are known. But this approach is deficient because it wrongly assumes that the flow in the fire region does not interact with the ventilation system and rest of the tunnel. A wide review on the characteristics of CFD model for tunnel fire applications is available in [2].

A computationally less expensive alternative for CFD models are 1D models which were developed in the 70s. These provide the overall behaviour of the ventilation system under the assumption that all the fluid-dynamic quantities are effectively uniform in each tunnel cross section, and gradients are only considered in the longitudinal direction. Because 1D models have low computational requirements, they are specially attractive, and are widely used by industry, specially for parametric studies involving a large number of simulations. Most important examples of 1D tunnel fire models are SES [3] and Whitesmoke [4]. A detailed review of the literature on 1D fire models is given in [2]. However useful, this modelling approach cannot predict the characteristics of complex three-dimensional (3D) flow regions typically encountered close to operating ventilation devices (e.g. jet fans), intersection of galleries (e.g., ventilation shafts) or the seat of the fire. Thus, in order to account for these important elements, 1D models must rely on overall fitting coefficients either extracted from approximated calculations or extrapolated from the limited experimental data.

THE NEED FOR MULTISCALE MODELLING

The high computational cost of CFD is most problematic when flow conditions in locations far away from the region of interest must be considered to solve the problem at hand. This is the case of tunnel portals, ventilation stations or jet fan series located long distances away from the fire. In these cases, even if only a short length of the tunnel is of interest (e.g. the region close to the seat of the fire), a correct solution of the flow requires including all active ventilation devices and the entire tunnel layout. For typical modern tunnel lengths, this means that the computational domain maybe several kilometres long. Nowadays, the analysis of such complex phenomena is performed by using numerical computational fluid-dynamics (CFD) tools which, in the case of the tunnel fire scenarios, have a significant drawback due to the required computational time.

In general, two flow field regions can be found in a tunnel. Regions characterized by high temperature and velocity gradients (hereafter named Near Field) are found in the vicinity of operating jet fans or close to the fire seat and need to be calculated using CFD since a simpler approach would lead to incorrect results. However, at some distance from the near field, regions characterized by low velocity and temperature gradients can be indentified. These regions will be hereafter named Far Field and will be modelled using a 1D tool.

This type of hybrid 1D-3D models are called multiscale models. Multiscale models allow a significant reduction in the computational time as the more time consuming tool is applied only to a limited portion of the domain. Multiscale techniques have been applied for the first time to steady-state flow problems in long tunnels [5,6,7] and to solve the transient flow interaction in longitudinally ventilated tunnels [8]. These papers demonstrate that multiscale modelling is a compelling and efficient technique for the simulation of fires in long tunnels, and the most feasible tool to conduct complete fire safety assessments. The current paper builds on previous work and applies multiscale modelling the first time to solve the time-dependent flow evolution in a real transverse ventilated tunnel.
MULTISCALE MODELLING

In a multiscale simulation, the physical domain in decomposed in two or more sub-domains (see Figure 1) generating 1D-CFD interfaces where the 1D and the CFD models exchange flow information. In Figure 1 $\Omega_{3D}$ represents the sub-domain modelled by means of CFD while a 1D model is used in $\Omega_{1D}$. If one single solver is able to operate over the two models, the problem can be solved at once. In most of the cases, there is a different solver for each model, and therefore iterative calculations are necessary with the two solvers periodically exchanging information at the boundary interfaces.

![Figure 1](link)

*Figure 1* Example of a domain decomposition in 1D and 3D sub-domains.

It is important to highlight that the underlying assumption in multiscale modelling is that the interface is located in a region where the flow structure is 1D. If this is not the case, significant errors would be introduced into the simulation. A more general discussion of the effect of the interface position can be found in [6,8].

The CFD sub-model

The fluid behaviour in the 3D sub-domain has been modelled using the classical Reynolds-averaged Navier-Stokes equations (RANS) complemented with the k-\(\varepsilon\) model for turbulence [9]. Fire induced flows are essentially driven by buoyancy forces which have a significant impact on flow turbulence. Therefore, the modified k-\(\varepsilon\) model, developed for flow with large density gradients has been used to account for the production and the destruction of turbulent kinetic energy [10].

The standard k–\(\varepsilon\) model is not valid for fluid regions characterized by a low Reynolds number, like locations close to the walls [9]. Thus in these regions the standard wall functions have been used providing adequate results for high Reynolds flows, and avoiding the need to use very fine meshes to solve the viscous sub-layer. The wall functions approach is valid as long as the first mesh point is located within the logarithmic region of the boundary layer. This constraint has to be considered here and a posteriori post-processing has been performed to confirm that the dimensionless distance to the first mesh point ranges between 30 and 100.

The fire simulating a burning vehicle has been modelled as a volumetric source of heat without a dedicated combustion model [6]. The fire source is introduced into the computational domain as a rectangular slab releasing hot gases from the top surface. The size of the slab is determined using Froude scaling. Mass conservation is applied by the extraction of air from the four lateral surfaces of the slab. More details on the fire model are provided in [6].

The CFD model has been implemented in the commercial finite-volume CFD code FLUENT. A segregated solver has been used to address the Navier–Stokes problem. The fluid has been considered incompressible and the SIMPLE algorithm has been adopted to solve the pressure-velocity coupling.
The convective fluxes have been approximated by using a second-order upwind scheme. Temporal discretization uses a second order implicit time integration scheme. The time-step size has been fixed to 0.05 s. More details on the effects of the time step size on the accuracy of the numerical solution in similar problems can be found in [8].

Given the range of complex cross-section geometries typically encountered along real tunnels (e.g., horseshoe cross sections, intersections with shafts, hanging jet fans), a quasi-structured mesh has been used. Once a base mesh is produced, the grid has been systematically refined until a grid-independent solution was reached.

An iterative time-advancement scheme has been used. At any given time-step, all the equations are solved iteratively in a segregated fashion, until the convergence criteria are met. These criteria are that all scaled residuals are lower than $10^{-6}$ with the exception of the energy equation where the limit is $10^{-8}$.

The 1D sub-model

The 1D sub-model has been built using the 1D tool Whitesmoke [4] which has been especially developed to run also in multiscale fashion. The general characteristics of the 1D sub-model are available in [2,5,11] and only a brief overview is given here. The developed 1D model is based on a generalized Bernoulli formulation. It is designed to account for transient fluid-dynamic, buoyancy effects, thermal phenomena, piston effects and transport of pollutant species. It is developed to handle complex layouts typical of modern tunnel ventilation systems (especially true for transverse ventilated tunnels) on the basis of a topological representation of the tunnel network. The model solves for mass, momentum and energy conservation in the whole domain. The solution is obtained after discretizing the computational domain in control volumes which allows the integration of the conservation equations. Typically, the tunnel domain is discretized in oriented elements called branches, interconnected by nodes. More details on 1D modelling, including numerical features, are available in [2,5,11].

Formulation of the multiscale problem

For sake of simplicity, let suppose that the tunnel domain ($\Omega$) to be decomposed in two sub-domains $\Omega_{1D}$ (the far field) and $\Omega_{3D}$ (the near field) where the 1D sub-model and the CFD sub-model are respectively applied. $\Omega_{1D}$ and $\Omega_{3D}$ are built in order to be continuous in the streamwise direction. The 1D-3D interface $\Gamma_a$ is located in $x=a$ in such way that there is no overlapping between the 1D and the 3D sub-domains (see Figure 1).

The multiscale problem is formulated in order to guarantee the continuity of the following quantities at the interface $a$:

\[
\begin{align*}
\text{Area } A(a^-) &= A(a^+) \\
\text{Mean pressure } \bar{p}(a^-) &= \bar{p}(a^+) \\
\text{Mean velocity } \bar{v}(a^-) &= \bar{v}(a^+) \\
\text{Mean temperature } \bar{T}(a^-) &= \bar{T}(a^+) \quad (1)
\end{align*}
\]

The multiscale problem can be solved if the 1D and CFD models exchange information at the interface during the solution algorithm. On the right hand side of $\Gamma_a$ the 1D domain provides average values for pressure, temperature, velocity and mass flow rate; they are indicated as $p(a^+), \bar{T}(a^+), \bar{u}(a^+)$ and $m(a^+)$, respectively. These average values are then used to fill the boundary faces of the CFD domain. The use of a uniform boundary condition is possible being the 1D-CFD interfaces always placed sufficiently far away from the fire so that the flow-field is dominated by the streamwise component or in other words is quasi-one-dimensional. Analogously, the same quantities can be defined for the left side of $\Gamma_a$ which belongs to the 3D domain. The filling on the 1D boundary face requires first the values of the fluid-dynamic quantities to be reduced to one single value. This is done
by performing integral averaging at the CFD boundary face (see equations 2).

\[ \overline{u}(a^-) = \frac{1}{\Gamma_a} \int_{\Gamma_a} \mathbf{u} \cdot \mathbf{n} \, d\sigma \quad \overline{p}(a^-) = \frac{1}{\Gamma_a} \int_{\Gamma_a} p \, d\sigma \]

\[ \overline{u}(a^-) = \frac{1}{\Gamma_a} \int_{\Gamma_a} \mathbf{u} \cdot \mathbf{n} \, d\sigma \quad \overline{T}(a^-) = \frac{1}{\Gamma_a} \int_{\Gamma_a} T \mathbf{u} \cdot \mathbf{n} \, d\sigma \quad \dot{m}(a^-) = \frac{1}{\Gamma_a} \int_{\Gamma_a} \rho \mathbf{u} \cdot \mathbf{n} \, d\sigma \]

(2)

where \( \mathbf{u} \) represents the velocity vector, \( p \) the pressure, \( \rho \) the density, \( T \) the temperature, \( \mathbf{n} \) the unitary vector normal to the interface \( \Gamma_a \).

**Interaction between 1D and 3D sub-models**

The solution of the coupled multiscale problem is based on iterative computing procedures developed in the framework of domain decomposition methods, mainly in the framework of parallel computing. Two iterative methods are typically used for solving multiscale problems involving Navier-Stokes equations: Dirichlet-Dirichlet (known also as Schwartz method) and Dirichlet-Neumann [12]. Dirichlet-Dirichlet coupling requires the definition of overlapping regions between \( \Omega_{1D} \) and \( \Omega_{3D} \), and its application in FLUENT is cumbersome.

![Figure 2](image)

**Figure 2** Visualization of the coupling procedure.

The iterative Dirichlet-Neumann algorithm does not require the presence of overlapping regions and is easier to implement in FLUENT since the information exchange does not involve volumetric regions but only boundary faces. This is the approach used here. The iterative Dirichlet-Neumann algorithm is presented below for a simplified case in which a CFD model of the near field (\( \Omega_{ID} \)) is coupled with two 1D models (one at each end of the near field) of the far field (\( \Omega_{1,1D} \) and \( \Omega_{2,1D} \)) (see figure 2). Two interfaces \( \Gamma_i \) and \( \Gamma_j \) are therefore generated (see Figure 2). This approach is general and can handle scenarios with several interfaces like in the present paper.

The interaction model used in Dirichlet-Neumann coupling can be split into two sub-problems which are run iteratively \( k \)-times until a global multiscale convergence is achieved. These outer iterations hereafter indicated as multiscale iterations, are required to warrant the continuity of the average velocity, pressure and temperature values (Eq. 1) at the interfaces. The two sub-problems are:

1. 1D problem of the far fields \( \Omega_{1,1D} \) and \( \Omega_{2,1D} \) with Dirichlet boundary conditions (velocity boundary conditions) at the interfaces
2. 3D problem of the near field \( \Omega_{3D} \) with Neumann boundary conditions (pressure boundary conditions) at the interfaces

During each of the previous steps each model (1D or 3D) is run until reaching its internal convergence criteria. The complete sequence of operations is:

1. Run the 1D model of the far fields \( \Omega_{1,1D} \) and \( \Omega_{2,1D} \)
2. Pressure and temperature values at $\Gamma_i$ and $\Gamma_j$ from 1D models are used as boundary conditions to the CFD model.
3. Run the CFD model of the near field $\Omega_{3D}$
4. Calculate average velocity and temperature values at the interfaces $\Gamma_i$ and $\Gamma_j$ from the CFD model (to be used as boundary conditions to the 1D models in step a)
5. Check global convergence:
   a. If global convergence is not reached go back to point a (eventually a relaxation step can be added)
   b. If global convergence is reached quit the calculation or proceed to the next time step for time dependent calculation

The global convergence is monitored via the evolution of any average fluid-dynamic variable at the interfaces during the multiscale iterations. In particular, the multiscale iterations continue until the difference in value of a series of fluid-dynamic variables between two sequential iterations is lower than a fixed tolerance.

CASE STUDY: GRAND-SAINT-THEMART TUNNEL

The Grand-Saint-Bernard tunnel is a two-way link between Italy and Switzerland. The tunnel is around 5850 m long with a cross-section of around 40 m$^2$. The tunnel layout has two slopes: +0.2% for the first 3000m from the Swiss portal and -1.7% for the remaining tunnel portion. The current ventilation system is transversal with extraction dampers located on the tunnel ceiling every around 80 m. Fresh air is also supplied through grills located on the tunnel walls in the vicinity of the road deck. Supply and extraction ducts are located above the tunnel false ceiling and have variable cross-sections. The actual ventilation system includes 4 ventilation stations for air extraction located in the vicinity of the Swiss side and close to the 2 intermediated shafts. A supply station is located in the vicinity of the Italian portal.

![Figure 3  Schematic of the tunnel layout](image)

Among all the proposed updating solutions of the tunnel layout, some of them include the construction of a parallel service tunnel with 10 m$^2$ cross-section which will be connected to the main tunnel through about 20 cross-passages. Several retro-fitting alternatives for the current ventilation system have been also proposed. Among all the possible solutions, this paper will take into account a semi-transversal ventilation system complemented with jet-fans for enhancing the longitudinal air control. The location of the five ventilation (ES1-ES5) stations dedicated to smoke extraction is presented in figure 5.

According to the most recent Swiss standard the ventilation system has to be operated in order to generate airflow velocity converging towards the fire not below 1.5 m/s in order to minimize smoke spread. Smoke extraction has to take place over a length of 200 m with dampers located every 100 m and sized in order to keep the airflow velocity around 15 m/s. In order to minimize the interventions
on the tunnel structures, the spacing between extraction dampers has been kept constant and 4 dampers are supposed to be open in case of a fire emergency. This layout corresponds to a total extraction length of 240 m. According to the standard prescriptions, the total extracted flow rate has to be above 160 m$^3$/s. The dampers cross-section has been considered equal to 2.7 m$^2$ in order to comply with the maximum velocity requirements. A schematic of the ventilation system and tunnel layout has been presented in Figure 3.

**Description of the scenarios**

The standard prescriptions suggest a maximum fire HRR equal to 30MW while no information regarding the fire growth curve are given. Therefore, the fire growth curve has been built on the basis of the work by Carvel [14] applicable to typical fires of European HGVs cargos which considers two different growth regimes: during the first regime, the fire grows slowly up to 1 or 2 MW at 4 to 14 kW/s, and after a delay typically lasting from 120 to 360 s, the fire transitions to a much faster growth regime at 30 to 400 kW/s. For the case study at hand, average values have been chosen: the slow regime grows at 8 kW/s, the delay is 240 s (4 min) long, and the fast regime grows at 250 kW/s. Hence, the peak power of 30 MW is reached 350 s after ignition and remains at the peak value indefinitely during the simulation (see figure 4).

The simulations have been conducted considering the fire to be located at 2200 m from the Swiss portal. Consequently, after detection (which is supposed to take place after 2 min), the ventilations stations ES2 and ES3 become operational and reach the full extraction mode after 30s. The extraction dampers, which in normal operating conditions are closed, start the opening procedure after 2 min and reach the full open status after 15 s. The fire scenarios taken into account in this work consider only negligible pressure difference across the portals. However for the full design of the ventilation system, the design pressure difference has to be equal to the 95% of the maximum measured value.

Three difference ventilation scenarios have been simulated corresponding to progressively increasing smoke extraction rates: 170 m$^3$/s, 200 m$^3$/s and 240 m$^3$/s. They are indicated hereafter as case 1, case 2 and case 2, respectively.

**Figure 4** Evolution of the fire HRR after ignition and time to detection considered in the transient simulations.

**Mesh characteristics and multiscale setup**

The computational domain has been discretized using 700,000 quasi-structured cells with refinements introduced close to the walls and in the vicinity of the fire source and extraction dampers. An example of the meshing patterns is presented in figure 5.a. The longitudinal extension of the computational domain is around 360 m and it has been computed in order to avoid the spread of smoke outside the CFD domain during the early stages of the fire emergency when the ventilation system is not active. The CFD sub-domain of the fire near-field has been coupled to the 1D model of the remaining tunnel sections and extraction ducts (see figure 5.b) comprising around 220 branches and 150 nodes. Six different 1D-CFD interfaces are therefore generated: 4 are located at the extraction dampers, 2 at the tunnels 1D-CFD intersections (see figure 5.b).
Figure 5  
\textit{a) Meshing pattern in the vicinity of the fire source. b) Multiscale model setup. }

**Time-dependent results**

The simulations are run from $t=0$ until steady-state flow conditions in the tunnel are reached, being this around 10 min in all simulations presented here. Figure 6 shows the temporal evolution of the airflow velocity at the 1D-CFD interfaces for the three scenarios characterized by extraction rates of 170 m$^3$/s (case 1), 200 m$^3$/s (case 2) and 240 m$^3$/s (case 3), respectively. As already explained in the previous section, such velocities have to be larger that 1.5 m/s in order to confine smoke in a limited portion of the tunnel (see [13]). It can be seen that for case 2 and case 3 the ventilation system is able of generating a ventilation velocity above 1.5 m/s. However, since the fire seat is located closer to the Swiss portal, the amount of fresh air entering the tunnel from the Swiss side of the fire is larger in comparison to the air flow at the Italian side. This behaviour becomes critical for case 1 where, due to the lower air extraction rate, the minimum air velocity threshold is not reached at the downstream domain boundary.

![Figure 6](image)

\textit{Figure 6  Temporal evolution of the airflow velocity at the fire seat. The upstream boundary corresponds to the Swiss side of the fire region. The downstream boundary corresponds to the Italian side of the fire region. Positive values correspond to air velocity converging toward the seat of the fire.}

The calculation allows also for an assessment of the ventilation system response time. Indeed, the average time required to reach the minimum air velocity threshold at the fire seat ranges between 30s for case 3 and 45s for case 2. For case 1, the minimum velocity requirements are only reached at the upstream boundary after around 45 s. The maximum velocity reached at the downstream boundary is 1.3 m/s.
Figure 7 shows the thermal and flow conditions within the tunnel 120 s after ignition, just before the ventilation system is activated. There is no preferential direction and thus the velocity and temperature fields are almost symmetric across the fire seat. The smoke front has travelled for around 100 m away from the seat of the fire. This shows that when the ventilation system is activated the back-layering nose is contained within the CFD domain.

Figure 8 shows the temperature contours within the tunnel 600 s after ignition. It can be observed that the temperature stratification is not symmetric across the fire seat. Indeed, due to the lower ventilation velocity at the RHS of the fire seat, the smoke tends to propagate for a longer distance (see figure 8.a). This behavior tends to be less evident for higher extraction rates where the longitudinal extension of the smoke occupied zones is mainly related to the number and spacing of the operating dampers. The analysis also confirm that the increase in the extraction rate from 170 m$^3$/s to 240 m$^3$/s produces a reduction of the tunnel regions occupied by smoke by almost 70 m (see figures 8.a and 8.c). It can be also observed that the variation in the extraction rate has a minimum impact on the vertical temperature stratification even thought slightly higher temperatures are observed for lower extraction velocity.

**CONCLUSIONS**

A multiscale modelling technique has been applied to simulate the transient response of a transverse
ventilation system during a fire emergency in a Gran-Saint-Bernard tunnel. A series of ventilation scenarios involving different extraction rates have been simulated. The transient simulations allow for a complete analysis of the ventilation system response and its interaction with the fire. Information on the time required to reach the minimum velocity threshold in the vicinity of the fire seat (as required by the Swiss standard) is obtained in a computationally efficient approach. The effect of the smoke extraction rates on the extension of the smoke occupied zones and temperature stratification has been analysed. This information is indeed fundamental to develop fire safety strategies in tunnels, to design evacuation procedures and to determine the optimum timing for the activation of fire fighting systems (e.g. water mist or deluge systems). Compared to full CFD, multiscale provides a reduction of the required computing time by almost 100 times without the loss of accuracy. These results confirm that the multiscale methodology represents the most feasible tool to conduct accurate simulations in long tunnels domains, when the limitation of the computational cost becomes too restrictive.

REFERENCES

Abstract
Fire sizes used for the design of ventilation systems have increased in recent years as a result of the significant fires that occurred in European road tunnels in the late 90’s. These fire sizes challenge the ability of ventilation systems to control smoke movement and complicates both the egress of tunnel users and the ability of emergency responders to fight the fire.

The prescriptive design fire sizes adopted in codes and standards in different countries varies widely, from 30 to 300 MW, and can depend on the nature of the vehicles allowed in the tunnel and the ventilation system employed. Longitudinal systems, for example, appear to accommodate larger fires, since the technical requirements for providing a critical velocity in a tunnel are somewhat less than those required for extraction systems. The design of longitudinal systems is also much simpler with regard to quantifying the ventilation capability.

Extraction systems which are primarily used in bi-directional tunnels do represent a more complex safety condition for the tunnel user. Smoke will spread on either side of the fire, and longitudinal flows generated by traffic movement or environmental effects may influence the smoke spread. The sizing of extract systems has been previously undertaken by prescribing a volume extraction [1,2]. With larger fires the question is raised as to how large a system is required and what ancillary control, such as the control of longitudinal velocity, is required.

This paper examine the performance of extraction systems at off-design conditions. A 3D CFD model is used to establish typical road tunnel geometries and extraction system components. Verification of the model has first been established by modeling small-scale experimental studies [3]. These have then been extended to full scale, and the influence of fire size, longitudinal flow and extraction capacity studied.

KEYWORDS: CFD, Smoke Control, Confinement, single- and two-point extraction

INTRODUCTION
The objective of smoke control in tunnels is to promote tenable conditions so that users can safely evacuate in the event of a fire emergency. The ventilation systems provide either longitudinal or transverse flow of air and smoke in the tunnel, and each system has its pros and cons. For example longitudinal ventilation in a unidirectional tunnel is a robust method when the air flow is in the direction of traffic flow and traffic is free-flowing. The traffic behind the incident may be stalled, but in clean air, whilst the traffic downstream of the incident can exit the tunnel. In congested traffic, this would not be the case and users would be at risk. The issues associated with different ventilation methods are discussed more fully in PIARC [4].

This paper addresses issues associated with transverse ventilation systems since these are somewhat problematic in terms of smoke control, and such systems have been involved in the serious fires that occurred in Europe. These fires, in Mt Blanc, Tauern and Gotthard tunnels, focused attention on many issues associated with emergency response, including the issue of ventilation and smoke control.
In older systems where the extraction is distributed along the tunnel with relatively small but numerous vents closer together there is little possibility of containing smoke in a short length of tunnel. A smaller number of large vents with controllable dampers have the advantage of concentrating the ventilation extraction capacity to the region of the fire and, in the absence of other effects, promoting a longitudinal velocity toward the fire on each side, thus containing the smoke and improving the efficiency of extraction. To optimize this arrangement in practice there is a need to monitor and control the longitudinal velocity in the tunnel.

A number of studies have been undertaken to study smoke extraction. 1/15th scale models were used by Lacroix et al [5] to study the geometry of different vents using a helium/air mixture to simulate buoyant smoke. The most influential parameters determined from these tests was the total extraction flow, maximum effectiveness being reached as the extraction flow equals 4/3 of the smoke flow, and the location of the vent, ceiling vents being more effective side-wall vents. The vent shape was not found to be influential. This view was confirmed in numerical studies reported by Oucherfi et al [6] which showed little change in efficiency with vent shape unless the vent extended across the width of the tunnel, in which case the efficiency almost doubled due to the reduction in entrainment of normal air.

Oucherfi also examine the effect of longitudinal velocity on extraction efficiency, showing the reduction of performance as the velocity increased. The need to control longitudinal velocity to improve the efficiency of extraction has led to tunnel systems employing jet fans specifically for this purpose. The process of confining the extraction zone has also been studied experimentally by Vauquelin and Telle [7], employing helium/air mixtures in a reduced scale. This study showed that relatively large extraction was required, but this was affected by the nature of the experiment – as pointed out by Ingason & Li [3], the use of helium to simulate smoke distorts the apparent efficiency of the extraction system.

Ingason & Li [3] have performed 1/23 rd scale fire tests to examine the required extract capacity for larger fires than those considered in previous tests. Single- and two-point extraction systems were tested using natural and forced ventilation. Wood cribs were used to provide the fire source.

In this paper we report on a CFD model developed and applied to reproduce Ingason & Li’s experiments; extended to full scale to confirm the scaling behavior and then applied to examine capacities required to remove and contain smoke. Capacity, however, is not the whole question, since smoke can spread considerable distances before the ventilation systems are fully operational. So we also discuss the response times to give a more comprehensive view of the response issues.

**CFD Modeling**

**Physical Situation**

A CFD model has been developed to represent the experiments performed by Ingason and Li. The experimental tunnel is 10 m long, 0.4 m wide and 0.2 m high. A number of fire experiments were conducted to study one- and two-vent configurations, longitudinal ventilation effects and fire spread between simulated vehicles. In this paper we report three of the experimental cases that were studied, Test 2, a single vent configuration, and Tests 9 and 10, corresponding to a two-vent configuration. These are shown schematically in Figures 1 and 2. The area of each vent was 0.026 m² and they are positioned 1.7m and 3.87m from the left portal. The vent led to a channel 0.1 m high and equal to the tunnel width which was connected downstream to an extraction fan providing exhaust flow rates of 0.14 m³/s in Tests 2 and 10 and 0.09 m³/s in Test 9. Note that the ventilation system was in operation throughout the test and so a steady ventilation regime was in operation prior to the fire.

Wood cribs were used for the fire source, these were 540 mm long, weighed 0.91 to 1.24 kg and were positioned on a weighing platform, the center of which was 2.87 m from the left portal. The fire grew
to about 60 kW, which was equivalent to about 150 MW at full scale, in three minutes. See reference [3] for full details.

A fan located at the left portal provided longitudinal velocity for some of the tests. However, this was not modeled in the CFD study, the tests examined for validation were selected from the zero longitudinal velocity cases.

Many measurements were taken during the experiments. For the purpose of this paper we have chosen to compare temperatures T1 and T4, shown on Figures 1 and 2. These are located 35 mm below the ceiling of the tunnel, and 1.235m and 3.92 m from the left portal respectively. Overall mass flow rates are also compared.

**Modeling Approach**

The ANSYS CFX 13.0 computer software has been used to develop the CFD models. The geometry included the tunnel, the exhaust duct and the pipework connecting the exhaust duct to the exhaust fan. A fire Heat Release Rate (HRR) varying with time is taken from the experimental case. Figure 3 shows the results from reference [3] for Test 2. It can be seen that there is some variation depending on the type of measurement used to estimate the HRR.

A combustion model based on gaseous methane was used to simulate the fire growth. A source of methane, varying with time and proportional to the HRR was provided as a source within the crib zone. The gas flow field is modeled by the Reynolds Averaged Navier - Stokes (RANS) equation set closed by the SST turbulence model with additional buoyancy production and dissipation terms. An eddy dissipation model is used for combustion. Thermal radiation is modeled using the discrete transfer method.
The portals were modelled as pressure boundaries with relative pressure set to be zero (0) Pascal. In the reduced scale model, convective heat transfer coefficients for the Promatect boards and the window glaze are specified as the wall boundary conditions. In the full scale model, a constant wall temperature (equal to ambient temperature) is used as the wall boundary condition. The volumetric flow rate of the fan is specified at the duct outlet boundary.

**COMPARISON OF SIMULATION AND EXPERIMENT**

In order to verify the CFD model, the single point extraction experiment (Test 2) and the two point extraction experiments (Tests 9 and 10) of Ingason & Li were simulated.

**Single Point Extraction System**

The single point extraction test (Test 2) was simulated transiently up to the point where the fire reaches peak HRR (i.e. up to T=3 minutes from the start of the fire). In the CFD model, the HRR curve determined from the experiment is used to specify the mass flow rate of gaseous methane. Since the combustion model is based on the assumption that the fuel that mixes with oxygen is burned, the HRR curve estimated by the oxygen consumption calorimetry method is used. The HRR obtained by the oxygen consumption method rather than the HRR obtained by the fuel mass loss method is an appropriate indicator of the combustion efficiency.

The transient temperatures downstream (T4) and upstream (T1) of the fire estimated by the CFD model are compared to the experimental values in Figures 4 and 5. The maximum temperature downstream of the fire (T4) agrees well with the experimental values. The maximum temperature upstream of the fire (T1) is over predicted by the CFD model. The temperatures predicted by the CFD model seem to lag behind the experimental values for the first minute.

The average upstream velocity for Test 2 in the experiment was 0.25 m/s (averaged over the entire experiment). The CFD model predicted velocities greater than 0.4 m/s for the duration of the simulation (i.e. from T=0 to T=3min). This may explain the delay in the temperature rise at location T4, and the cause of this discrepancy might be the balance of the overall resistances in the model – wall friction, the resistance of the crib etc. The corresponding lower velocity from the left portal (1.5 m/s in the experiment versus 1.35 m/s in the simulation) should perhaps result in a quicker arrival of the backlayer at location T1. However, this is not the case and despite the lower velocity from the left portal the temperature rise at T1 is delayed. This slower smoke spread in the simulation may imply that the radiation losses are too high or that HRR is either slightly lower than it should be or displaced in time in comparison with the experiment.
Although, there seems to be some differences in the results predicted by the CFD model and the experimental values, the level of verification was considered adequate enough to simulate the two point extraction ventilation experiments.

![Figure 5 – Comparison of Temperature T1 estimated by CFD model to the measured values in Test 2](image)

**Two Point Extraction Ventilation System**

The two point extraction ventilation tests were simulated for two volumetric air flow rates, 0.09 m³/s (Test 9) and 0.14 m³/s (Test 10). The results of the simulations are presented as plots of temperature and visibility in Figures 6 and 7. For the 0.09 m³/s case, the flow induced through the portals is not sufficient to confine the smoke to the zone between the vents whereas for 0.14 m³/s case, confinement is achieved.

![Figure 6- Temperature plots for the longitudinal centerline section of the model - Two point extraction ventilation](image)
Figure 7: Two point extraction ventilation – reduced scale model results for $Q=0.09 \text{ m}^3/\text{s}$ and $Q=0.14 \text{ m}^3/\text{s}$

Figure 8, reproduced from [3], shows a schematic of the two point extraction ventilation system and defines the back-layering lengths $L_{\text{left}}$ and $L_{\text{right}}$, the distances that the smoke layer moves beyond the left and right extraction vents. The upstream and downstream velocities as well as the back layering lengths observed in the experimental tests are compared to the CFD results for the volumetric flow rates $0.09 \text{ m}^3/\text{s}$ and $0.14 \text{ m}^3/\text{s}$ in Table 1. For a volumetric flow rate of $0.09 \text{ m}^3/\text{s}$, back-layering extending 1 m (i.e. $L_{\text{left}}$ and $L_{\text{right}} > 1\text{m}$ – Table 1) beyond the vents was observed both in the experimental test (Test 9) and the CFD simulation. The longitudinal velocities ($V_{\text{left}}$ and $V_{\text{right}}$) achieved were lower than 0.6 m/s in both the $Q=0.09 \text{ m}^3/\text{s}$ cases (i.e. in Experiment and CFD).

In the experiment-Test 10, when the exhaust volumetric flow rate was increased to $0.14 \text{ m}^3/\text{s}$, the back layering lengths ($L_{\text{left}}$ and $L_{\text{right}}$) observed were not zero. The smoke layer extended beyond the vents but the smoke was confined to a zone within 0.5m of the vents. Similarly in the CFD simulation, with an exhaust volumetric flow rate of $0.14 \text{ m}^3/\text{s}$, the back layering lengths were not zero but the smoke was confined to a zone within 0.25 m distance of the vents. Further analysis of the smoke layer beyond the vents in the CFD results was carried out. The analysis has shown that the smoke seen beyond the vents in the $Q=0.14 \text{ m}^3/\text{s}$ case is due to the smoke that gets around the vents and back in to the vents (as can be seen in the vector plot of Figure 9). This indicates that although the back layering length is not equal to zero, smoke confinement and control is achieved for the $0.14 \text{ m}^3/\text{s}$ case. The longitudinal velocity induced in the tunnel with the volumetric flow rate $0.14 \text{ m}^3/\text{s}$ is greater than 0.6 m/s in both directions. Thus, the experimental and modeling results suggest that if a longitudinal velocity equal to 0.6 m/s is achieved in both directions, then it is possible to achieve smoke confinement.

The CFD model has then been used to study the two point extraction ventilation system for the full scale tunnel and verify if a longitudinal velocity of 2.9 m/s (equivalent to 0.6 m/s at the 1:23 scale) can achieve confinement of smoke.

Figure 8 – Schematic diagram of a two point extraction system [Ingason et.al]
Table 1: Comparison of the experimental and CFD results for two point extraction ventilation systems

<table>
<thead>
<tr>
<th>Test</th>
<th>HRR</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume Flow Rate ( V_{ex,right} + V_{ex,left} )</td>
<td>( Q_{max} )</td>
<td>( V_{left} )</td>
</tr>
<tr>
<td>Experiment (Test 9)</td>
<td>0.09</td>
<td>51.4</td>
<td>0.40</td>
</tr>
<tr>
<td>CFD</td>
<td>0.09</td>
<td>48*</td>
<td>0.39</td>
</tr>
<tr>
<td>Experiment (Test 10)</td>
<td>0.14</td>
<td>52.6</td>
<td>0.52</td>
</tr>
<tr>
<td>CFD</td>
<td>0.14</td>
<td>48*</td>
<td>0.60</td>
</tr>
</tbody>
</table>

* In experiments, the peak HRR varied based on the test. For the CFD simulations, a single HRR curve is used for all simulations. The HRR curve used for the two point extraction CFD simulations is consistent with the HRR curve used for the single point extraction case (as shown on Figure 3).

Figure 9: Two point extraction ventilation – Vector plot for \( Q = 0.14 \text{ m}^3/\text{s} \) showing the smoke flow pattern at the vents.

Full Scale Model – 160 MW fire in a tunnel

A 160 MW fire in a tunnel measuring 230 m x 9.2 m x 4.6 m (using the 1:23 scale) was simulated. The simulations were carried out for total exhaust volume flow rates of 225 m$^3$/s to 385 m$^3$/s corresponding to reduced scale flow rates of 0.09 m$^3$/s to 0.15 m$^3$/s. The results of the simulation are presented as the plots of visibility in Figure 10. For the volumetric flow rate of \( Q = 225 \text{ m}^3/\text{s} \), the velocities induced on either side of the fire are less than 2.9 m/s and the confinement of the smoke is not achieved. The smoke extends all the way to the upstream portal (left). The result is consistent with the result for the corresponding reduced scale flow rate of \( Q = 0.09 \text{ m}^3/\text{s} \) (Figure 7).

When the volume flow rate was increased to \( Q = 355 \text{ m}^3/\text{s} \) (\( Q = 0.14 \text{ m}^3/\text{s} \) in reduced scale) the velocity (3.17 m/s) induced at the downstream portal of the fire is greater than 2.9 m/s. The velocity upstream of the fire (2.4 m/s) is still below 2.9 m/s and hence some back-layering of smoke at the upstream vent is observed. The volume flow rate was increased to \( Q = 385 \text{ m}^3/\text{s} \) and the velocities induced upstream (2.89 m/s) and downstream (3.4 m/s) direction of the fire are greater than 2.9 m/s. Hence, the confinement of smoke is achieved with a flow rate of \( Q = 385 \text{ m}^3/\text{s} \) for a 160 MW fire in the full scale tunnel simulation. The results validate the concept that a velocity of 2.9 m/s (0.6 m/s in reduced scale) needs to be achieved to contain the smoke to the area between the vents.

The full scale model required slightly higher volumetric flow rate (\( Q = 385 \text{ m}^3/\text{s} \)) than the scaled value of \( Q = 355 \text{ m}^3/\text{s} \) (0.14 m$^3$/s) to achieve confinement of the smoke. There are also some differences in the back layering lengths observed between the reduced scale model and the full scale mode. These
differences could be due to the wall boundary conditions used in the two cases. Rather than use the scaled wall heat transfer coefficients used in the model scale for the full scale simulations, the more realistic boundary conditions (constant wall temperatures) were specified.

![Figure 10 - Two point extraction ventilation system – 160 MW Fire Full scale tunnel simulation results](image)

**CONCLUSIONS**

The CFD simulations have shown that in order to confine the smoke from a 160 MW fire to a zone 55 m long (or 12 tunnel heights) a volume flow rate of 385 m$^3$/s is required. This shows the advantage of a ventilation system with controllable dampers so that the full effect of ventilation can be focused in a zone near the fire. However, activation of a ventilation system that needs to extract such a large volume flow rate requires considerable amount of time. In a real fire event the smoke may spread beyond the fire zone before the ventilation is activated. Further, establishing a longitudinal flow in longer tunnels could take some time, and these factors need to be considered in a life safety context.

**References**

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Theoretical Analysis on Longitudinal Tunnel Ventilation in Fire Emergency

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ABSTRACT
This paper presents the analytical solution of a 2D longitudinal tunnel fire ventilation model. The solution has led to the introduction of a ventilation dependent definition of flame height that is different from the flame length in traditional fire engineering. In the proposed model, the height of flame relative to that of the tunnel is denoted as \( Q' \) which is identified as the most important parameter controlling the behavior of critical velocity and ceiling temperature. Therefore it is a natural measure of fire size in terms of life and structure safety. The critical ventilation velocity, as part of the solution, is a logarithmic function of \( Q' \) reflecting the behavior observed but not well understood in previous experiments of large tunnel fire. The solution of the proposed model has also clarified the formation of Froude number \( Fr \) used as a normalized ventilation velocity. Contrary to common belief, it is the dimension of fire site, not the height of the tunnel, which should be included in \( Fr \). Without any adjustment, the current theoretical solution has been tested using 3 independent sets of experimental data with or without tunnel blockages and fire site elevation. The good agreement achieved lends strong support to the mechanisms revealed by the model. The discrepancies due to the energy and momentum losses of fire flame indicate that the \( Fr-Q' \) curve from the current analysis represents the theoretical maximum ventilation requirement of any tunnel fire.

KEYWORDS: tunnel fire, ventilation, fire plume, critical velocity

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>( A )</td>
<td>Tunnel cross section area (m(^2))</td>
</tr>
<tr>
<td>( c_p )</td>
<td>Specific heat at constant pressure (J/kg.K)</td>
</tr>
<tr>
<td>( Fr )</td>
<td>Froude number</td>
</tr>
<tr>
<td>( g )</td>
<td>Gravity (m/s(^2))</td>
</tr>
<tr>
<td>( h )</td>
<td>Specific enthalpy (J/kg)</td>
</tr>
<tr>
<td>( H )</td>
<td>Tunnel height (m)</td>
</tr>
<tr>
<td>( k )</td>
<td>Thomas' constant</td>
</tr>
<tr>
<td>( K )</td>
<td>Constant for tunnel grade correction</td>
</tr>
<tr>
<td>( L )</td>
<td>Flame height (m)</td>
</tr>
<tr>
<td>( m )</td>
<td>Mass flow rate (kg/s)</td>
</tr>
<tr>
<td>( p )</td>
<td>Pressure (N/m(^2))</td>
</tr>
<tr>
<td>( Q )</td>
<td>Total thermal power (W)</td>
</tr>
<tr>
<td>( q )</td>
<td>Heat release rate of fire per tunnel width (W/m)</td>
</tr>
<tr>
<td>( T )</td>
<td>Local temperature in fire plume (K)</td>
</tr>
<tr>
<td>( u )</td>
<td>Local velocity (m/s)</td>
</tr>
<tr>
<td>( w )</td>
<td>Tunnel width (m)</td>
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<td>Longitudinal coordinate (m)</td>
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<td>( z )</td>
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<tr>
<td>( \Delta z )</td>
<td>Thickness of backlayer (m)</td>
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<tr>
<td>( \delta )</td>
<td>Longitudinal width of fire plume (m)</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Density (kg/m(^3))</td>
</tr>
</tbody>
</table>

Superscript/Subscript

- \( f \) Fire plume property
- \( t \) Gas state at the interface between smoke and the main body of fire plume.
- \( v \) Property of ventilation air.
INTRODUCTION
The interest of finding the critical ventilation velocity in tunnel-like structures started from Thomas in 1968[1]. He suggested that critical velocity should be determined by the balance between the buoyancy force in the combustion plume and the inertial force of ventilation. The following correlation was given based on his scale analysis.

\[ u_v^3 = k \frac{g q_f}{\rho c_p T_v} \]  \tag{1}

where \( q_f \) is the heat release rate (HRR) of fire per unit tunnel width, \( u_v \) is the critical ventilation velocity and \( k \) is an experimentally-determined constant. The above expression is often referred as Thomas’ cubic root correlation. Subsequent experiments have shown that the correlation (1) is quite adequate for small to medium size fires but not for the large ones[2-5]. In small tunnel fire, critical velocity increases as the HRR of fire increases as in (1). Once the HRR is larger than a certain value, the rate of change of the critical velocity drops toward zero. This phenomenon was called “leveling-off of critical velocity” by Oka who was one of the few people first studied it experimentally [3].

In the attempt of improving the prediction from (1), Danziger and Kennedy substituted the air temperature in (1) with that of the smoke and proposed the following correlation[6]:

\[ u_v = K \left( \frac{g H Q_f}{F_{rc} A \rho c_p T_f} \right)^{1/3} \]  \tag{2}

where \( K \) is a correction factor for tunnel grade and \( F_{rc} \) is an experimentally determined Froude number. Correlation (2) has been built into the SES program where \( F_{rc} \) has been given a value of 4.5[7].

Figure 1 shows the measured critical velocity in Oka’s experiment[3] together with 3 curves representing the predictions from Thomas, Danziger & Kennedy and Oka’s own correlation. Unlike in Oka’s original paper, the axes in Figure 1 are linearly scaled in order to show the true discrepancies relative to the critical velocity itself. Numerically, the Danziger & Kennedy correlation offers the best fit to the average value of experimental data. However the large discrepancies between the prediction and the measurements as well as that among the measurements themselves still need to be understood. Such need motivated the current authors to carry out this investigation.
THE 2D MATHEMATIC MODEL OF FIRE PLUME

Figure 2 shows the 2D fire plume in the current model. The tunnel is horizontal along the $x$-coordinate and the fire pool is a trench in the $y$ direction. Combustion is not modelled and heat is released into the plume on the surface of the fire pool. The heat release rate is represented by $Q_f$ and the height of the tunnel is $H$. A smoke layer with thickness $\Delta z$ is assumed under the tunnel ceiling. The fire plume is tilted toward the downstream of ventilation flow that has a mean velocity of $u_v$. At steady state, the equations governing mass, momentum and energy conservation of the mean flow in the fire plume can be written as\(^1\):

\begin{align}
\frac{d(m)}{dz} &= \rho_v u_v w \quad \text{(3)} \\
\frac{d(mu_v)}{dz} &= \rho_v u_v^2 w \quad \text{(4)} \\
\frac{d(mu_z)}{dz} &= g(\rho_v - \rho) A_z \quad \text{(5)} \\
\frac{d(hm)}{dz} &= \rho_v u_v h_v w \quad \text{(6)}
\end{align}

where $A_z = \omega \delta$ is the cross section area of the fire plume in the $x$-$y$ plane.

Figure 2 The modelled 2D fire plume

Applying equations (3) to (6) to a free fire plume (without the tunnel ceiling), the mean vertical velocity of smoke can be written as

\[ u'_z = F_{Fr}^{-2} \frac{(1 - h'_f)}{h'_v + z'} \ln(1 + z') + \frac{h'_v}{h'_v + z'} u'_f \quad \text{(7)} \]

where $u'_z = u_z/u_v$, $u'_f = u_f/u_v$, $h'_v = h_v/h_f$, $u_f$ and $h_f$ are the initial fuel velocity and enthalpy on the surface of the fire pool. $z'$ is the normalized $z$-coordinate. The normalization factor will be defined later. The Froude number in (7) has been defined as:

\[ F_{Fr} = \frac{u_v}{\sqrt{g \delta}} \quad \text{(8)} \]

\(^1\) The details of the model and the comparison with experimental data have been written in 2 papers to be published in Tunneling and Underground Space Technology.
It should be noticed that in (8) the length scale is the width of fire trench $\delta$ instead of tunnel height $H$ as in most of the previous correlations.

Moving the fire plume back into a tunnel as in Figure 2, the following assumptions have been made:

1. The behavior of the fire plume is the same as the free plume up to the ceiling layer (point $t$).
2. The pressure at point $s$ is the result of vertical momentum stagnation. Its value can be approximated by the vertical momentum at point $t$.
3. The critical condition (when backlayer is disappearing) is the condition that the momentum of the smoke is balanced by the momentum of the ventilation flow within $\Delta z$.

Based on the above assumptions, the solution of equations (3) to (6) gives the following condition for the prevention of backlayering:

$$ Fr \geq \frac{(1-h')\ln(1+H')}{h'(1-u'_f) + H'} $$

(9)

Equalizing the two sides in (9) yields the formula for critical velocity.

In condition (9), $z$-coordinate has been substituted by the tunnel height $H$ as $\Delta z$ in Figure 2 becomes zero at critical point. $H'$ is the normalised tunnel height defined as

$$ H' = \frac{H}{L} $$

(10)

and

$$ L = \frac{Q_f}{\rho_u h_w} $$

(11)

Here $L$ has the dimension of length representing the height of flame. Therefore $H'$ is the height of tunnel relative to the height of flame. In this sense, the reciprocal $Q'=L/H$ is the fire size measured not only by the heat release rate of fire but also by the ventilation flow and the height of tunnel.

![Figure 3 Comparison with first set of experimental data](image-url)
COMPARISON WITH EXPERIMENTAL DATA

Trench fires on tunnel floor
Figure 3 shows the comparison of Froude number predicted by condition (9) and that from 3 sets of experimental data. In the experiments, the fire sources are nearly rectangular trenches on the tunnel floor. The correlations from Thomas and Danziger & Kennedy are also presented in Figure 3. What needs to be mentioned is that in both cases, the Froude number is defined by tunnel height as in the original correlation. The experimentally defined constants $k$ and $Fr_c$ in (1) and (2) are not included since the purpose here is not data fitting and the effect of the constants are not difficult to image.

Tunnel with blockage and elevated fire site
Unlike pool fire that often lies on the tunnel floor, real tunnel fires may have a location some where between the tunnel floor and the ceiling. They may also involve blockages such as a stopped vehicle. In the current model, it means that $H$ should be the vertical distance between the fire surface and tunnel ceiling. $u_v$, as a local ventilation velocity within the vertical range of smoke layer, should be scaled according to local blockage ratio. Based on such considerations, the prediction from (9) is also compared with the experimental data by Oka[3] and Li[5] in Figure 4. In Oka’s experiment, the fire site was also elevated to the top of the blockages as shown in Figure 5. In Li’s case, a model vehicle was place in the tunnel but the fire site was the same as in Figure 3 for tunnel B. The area blocked by the vehicle is about 20% of the tunnel cross section.

![Figure 3: Comparison of the current model prediction with experimental data](image)

Figure 4 Comparison of the current model prediction with experimental data under conditions of tunnel blockage and elevated fire

![Figure 5: Scenarios of tunnel blockages in Oka’s experiment](image)

Figure 5 Scenarios of tunnel blockages in Oka’s experiment
Counting the loss
In the model proposed by the authors, no unrecoverable energy loss has been taken into account. Therefore discrepancies between the theoretical prediction and experimental data due to heat transfer (both radiative and convective) to the tunnel walls and the viscous loss due to turbulence should be expected. It is indeed the case as shown in Figure 6.

The aspect ratio in the legend of Figure 6 is defined for the geometry of the fire pool as the ratio of its length (in tunnel longitudinal direction) to its width (in tunnel transversal direction). Both large aspect ratio of the fire pool and/or small tunnel width to height ratio \( w/H \), in other words, large exposure of fire flame to tunnel walls, leads to higher energy loss from tunnel fire. From (11), such reduction of energy results in a smaller flame height and smaller \( Fr \) as shown in Figure 6. What is also interesting to see is that although the energy loss has reduced the maximum Froude number that the system can reach but the turning point of the \( Fr-Q' \) curve is more or less the same (around \( Q'=0.7 \)).

![Figure 6 The effects of the aspect ratio of fire site and of the w/H of tunnel](image)

DISCUSSION AND CONCLUSION

Fire sizing
The size of a fire is undoubtedly related to its heat release rate. However the potential of damage that a fire can cause may not be so simply defined. Obviously the damage that a 10MW fire may cause would be quite different in tunnels with different cross section and ventilation flow. The current theory has logically linked the three most important factors, namely the heat release rate of fire, the height of tunnel and the ventilation flow, using the definition of flame height \( L \) given by expression (11).

The flame height \( L \) defined here should be distinguished from the flame length\(^1\) in the traditional fire engineering theory such as that described by Heskestad in the SFPE handbook\(^[8]\) where it is determined by the dimension of fire site and its heat release rate. It is understandable since the concern there is compartment fire without cross flow. Air entrainment in such case is driven by the fire generated buoyancy. In other words, every thing is dependent on the fire itself.

In tunnel fire with longitudinal ventilation, air supply is an “independent” input parameter. Therefore the flame height of fire should be a function of both the heat release rate of fire and the ventilation flow.

\(^1\) In SFPE handbook, Heskestad used “flame height” most of the time but “flame length” was also used in the same chapter. In order to distinguish it from the flame height \( L \) defined in this paper, “flame length” is used referring to the definition in SFPE handbook.
flow.

Figure 7 illustrates the relation between the flame length given in SFPE handbook and the flame height in the current model. In a small fire such as that depicted in Figure 7, the flame leans towards the downstream of ventilation. Increasing the heat release rate of fire, its flame not only becomes longer but straighter upwards due to increased buoyancy. Both lead to the increase of flame height $L$. According to (9), $u_v$ needs to be increased to stop backlayering. Eventually, the fire flame impinges the tunnel ceiling. From this point on, the original small fire becomes a large fire and, also according to (9), there is no need to increase the critical velocity $u_v$ further. In reference [3], Oka has described their experience in experiments at the Health and Safety Laboratory, Buxton, UK as “the fire size increases to the point where the flame length exceeds the tunnel height, the critical velocity becomes much more weakly dependent on the heat release rate than predicted by the one-third power law”.

![Figure 7 The relation between flame length and flame height](image)

**Tunnel ceiling temperature**

The importance of $H’$ (or $Q’$) can be further demonstrated through the variation of tunnel ceiling temperature as part of the current solution:

$$\frac{T - T_v}{T_v} = \frac{1 - h_v'}{1 + H'}$$

(12)

Figure 8 shows that for $H’<1.0$ when the ceiling of the tunnel is within the range of fire flame, the ceiling temperature changes rapidly with tunnel height. Once $H’$ becomes larger than 1.0, further increase of tunnel height does not yield significant benefit in terms of reducing the thermal load of tunnel ceiling structure.

![Figure 8 Tunnel ceiling temperature vs tunnel height $H’$](image)
Critical ventilation velocity

Once the issue of fire sizing has been clarified, the question of critical velocity becomes simple. For small fire, the critical velocity increases with the heat release rate of fire according to (9). The cubic root correlation such as that given by Thomas and Danziger & Kennedy can be also used for the prediction as shown in Figure 3. However, for large fire, the cubic root correlation may lead to significant error depending on the experimentally determined constants.

The nearly constant $Fr$ in the case of large fire is the result of changing buoyancy in the fire plume. As shown in Figure 9, the relative temperature of fire plume near the tunnel ceiling increases monotonically with $Q'$. The corresponding density variation also increases with $Q'$ but is limited by 1.0. According to equation (5), it limits the buoyancy in the plume. Such limit can be easily understood from Archimedes' principle: for a submerged volume, the (maximum) buoyancy is the weight of displaced fluid (fresh air).

Froude number and the dimension of fire site

Previous research work in tunnel fire has not paid much attention to the dimension of fire site although Lee and Chaiken have suggested to include it into scaling analysis based on their coal mine fire experiment[9]. In fact, the definition of Froude number in equation (8) is no stranger to the fire community. In compartment fire [8], the Froude number is defined as

$$Fr = \frac{u^*}{\sqrt{g\delta}}$$  \hspace{1cm} (13)\footnote{In the 4th Edition of SFPE handbook, Froude number in section 2-3 is denoted as $\dot{Q}'$.}

where $\delta$ is the diameter of fire source and $u^*$ is a characteristic velocity of the fire plume defined as

$$u^* = \frac{Q_f}{\rho_C T C_p \delta^2}$$  \hspace{1cm} (14)

The subscript $\nu$ in (14) refers to ambient condition instead of ventilation flow.

The implication of equation (8) is that the larger the longitudinal dimension of the fire site, the higher
The ventilation velocity should be. The limitation of course is the oxygen requirement for combustion.

**The effect of tunnel wall and turbulence**
Tunnel walls generate two kinds of loss, momentum loss due to wall friction and thermal energy loss due to heat transfer (both radiative and convective). Apart from radiation, all the losses are assisted by turbulence inside and outside the fire plume. Inside the plume, turbulence transfers kinetic energy of the mean flow into thermal energy. Between the main body of fire plume and the surrounding air, turbulence acts as a momentum diffuser. All these momentum losses directly reduce the Froude number $Fr$ in (9). The thermal energy loss results in lower temperature in the plume which in turn reduces its buoyancy. Such losses lead to the discrepancies between the measured and the predicted $Fr$ seen in Figure 6. As any real system will be associated with momentum loss in one way or another, the $Fr-Q'$ curve given by (9) represents the theoretical maximum longitudinal ventilation requirement of a tunnel fire.

**The conclusion**
In terms of life and structure safety, a tunnel fire can be measured by the ratio between the flame height of fire and the height of tunnel. This ratio, denoted as $Q'$, is also equal to the ratio between the heat release rate of fire and the enthalpy flux of the ventilation flow. Therefore it has been defined as fire size in the current model. Its reciprocal is the normalised tunnel height in the context of fire safety.

In terms of backlayering prevention, condition (9) defines the theoretical maximum longitudinal ventilation requirement of a tunnel fire. Graphically, the relation (9) is depicted by the $Fr-Q'$ curve. The curve can be divided in two sections by the point $Q'=1.0$. Each section represents a distinctive fire category. In a small fire ($Q'<1.0$), the flame of fire can not reach the ceiling of tunnel and $Fr$ increases with $Q'$. In a large fire ($Q'>1.0$), the flame of fire impinges the ceiling of tunnel and $Fr$ is nearly independent of $Q'$.

For a given large design fire ($Q'>1.0$), raising tunnel ceiling reduces the fire size, reducing therefore the thermal load of tunnel ceiling. However such benefit diminishes after $H'$ becomes larger than 1.0.

Further research work is required to understand the effect of tunnel wall on the energy and momentum losses of fire flame in order to quantify and model the discrepancies seen in Figure 6.
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The influence of blockages on backlayering in tunnel fires: A numerical study

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ABSTRACT

Critical ventilation velocity (CVV) is the most well investigated phenomenon in tunnel fire research. The majority of studies of CVV/backlayering have involved either theoretical analysis or experiments of an open fire in a tunnel, generally with no obstructions in the locality of the fire which could disturb the flow pattern and influence the backlayering behaviour. However, in reality, fires in tunnels do not happen in such idealised situations. Generally there are obstructions due to the vehicle’s construction or adjacent vehicles. Such blockages can modify the flow behaviour and may influence the CVV / backlayering.

This paper presents the findings of a preliminary computational fluid dynamics (CFD) study looking at the influence of overhead blockages and upstream blockages on smoke behaviour at critical ventilation conditions and in the sub-critical regime. Simulations are presented for a reasonably typical two lane road tunnel using the Fire Dynamics Simulator (FDS) model. It is found that certain overhead blockages interrupt the flow sufficiently to significantly reduce the CVV or reduce the backlayering length and temperature in the sub-critical regime. However, upstream blockages and overhead blockages closer to the ceiling have a negative effect, sometimes resulting in backlayering at above the CVV for an unobstructed fire.

KEYWORDS: critical ventilation velocity (CVV), computational fluid dynamic (CFD), blockages

INTRODUCTION

Critical Ventilation Velocity (CVV) is the “single most well investigated fire phenomenon found in the tunnel fire research literature” [1]. It has generally been found that, for a given size of fire, there exists a longitudinal ventilation velocity able to blow all the smoke produced by the fire to the downstream side of the fire, this is the CVV. At ventilation velocities just below the CVV, there exists a flow of smoke against the ventilation flow direction, upstream of the fire location. This phenomenon is known as ‘backlayering’.

For many years, the tunnel safety community has been fixated on the task of ensuring that, in the event of a fire in a tunnel, the longitudinal flow in the tunnel meets or exceeds the CVV for whatever the ‘design fire’ scenario is for their tunnel. However, the majority of studies of CVV and the majority of ‘design fires’ used in ventilation system specification are highly idealised. Real vehicle fires in real tunnels are not as simple. Vehicles by their very nature introduce a number of kinds of blockages into the tunnel in the locality of the fire, including blockages immediately upstream or downstream of the fire (e.g. a heavy goods vehicle (HGV) cab if we are considering a trailer fire) or an intermediate ceiling in between the fire and the tunnel ceiling (e.g. the roofs on the carrier wagons in the Channel Tunnel HGV shuttles).

This paper presents the results of a preliminary study using computational fluid dynamics (CFD) to investigate the influence of blockages above and immediately upstream of a generic fire in a rectangular two lane tunnel. Given the simple scenario presented, it is acknowledged that the absolute numbers of CVV, etc., presented are not able to be generalised to real tunnels, however the kind of
variations in flow behaviour due to blockages, observed in this study, may be replicated in real tunnel scenarios.

CRITICAL VENTILATION VELOCITY

The CVV for smoke control in tunnels, corridors and ducts has been the subject of many studies. Some of these will be summarised here. The emphasis in this overview is not on the equations produced, or the values predicted, but on the scenarios used to derive the equations and numbers.

The earliest well known equation for smoke control in a corridor with longitudinal ventilation was derived by Thomas in the 1960s [2]. Thomas’s equation was derived from a theoretical analysis of flow and concerns a generic fire with only one defining variable, the heat release rate (HRR), commonly denoted Q. The analysis was non-dimensional and relative to a characteristic length-scale of the corridor (assumed to be the height) but, otherwise, no geometrical features are accounted for in the model.

The CVV model derived by Kennedy and various co-workers, first described in the 1980s [3] and described in more detail in the 1990s [4], again used a theoretical generic fire defined only by its HRR. The novelty in this study, however, was that the various constants used in the analysis were calibrated against small scale fire experiments in ducts carried out by Lee et al. [5]. The fire source in the experiments by Lee was a wooden lining attached to the perimeter of the duct, so there are no significant geometrical effects in their results, and hence no significant geometrical effects are translated into Kennedy’s equations. The way the equations are used in the Subway Environmental Simulator model (SES) [6] does take account of blockages in that they restrict the cross-sectional area of the tunnel, however, the fire is still considered to have no upstream or downstream blockages [4].

Oka and Atkinson [7] carried out an experimental analysis of CVV in a model scale tunnel (0.24m high) using propane burners as the fire source. The majority of tests were carried out with the burner flush with the tunnel floor, although some experiments were carried out with the burner elevated on top of a blockage. None of the tests featured a blockage upstream of the fire or above the fire. The same apparatus was used by Wu et al. [8] to investigate the effect of slope on CVV. Again, the fire source was a propane burner, in this instance flush with the floor for all experiments.

Other aspects of CVV, including the influence of tunnel geometry, have been studied experimentally at laboratory scale by Wu and Bakar [9]. Once again, the primary fire source in these experiments was an unobstructed burner.

While other CVV studies have been presented, the above are the primary references in the literature. It is clear from these that, when it comes to defining the CVV for a tunnel, only unobstructed fires have been studied in any detail. This study was carried out to test the hypothesis that the presence of blockages upstream or above a fire in a tunnel would significantly influence the CVV required for smoke control. That is to say, that current design velocities may be too high, or possibly too low, for real fires in tunnels.

A BRIEF NOTE ON FIRE DEVELOPMENT

An important question to address at this point is why does it matter? If there are indeed small variations in CVV by introducing blockages into a tunnel, why shouldn’t we simply design as if the tunnel were unobstructed, even if smoke control could be achieved at lower velocities for some real scenarios?

The lead author of this paper has published extensively on the subject of the effects of ventilation on fire development and fire size. A summary of these works was recently published [10] and need not be detailed again here. In essence, however, it has been shown that, in general, increasing longitudinal ventilation velocity has an enflaming effect on the fire, so higher velocities of airflow tend to result in
more severe fires (i.e. higher HRR) [11]. Furthermore, it has been shown that there appears to be a trend (up to about 3 or 4 ms\(^{-1}\) at least) whereby increasing the longitudinal flow increases the growth rate of a fire [12]. In addition to that, increasing longitudinal flow also tends to increase the likelihood of fire spread to adjacent downstream vehicles [13]. Thus it appears that, all other factors being equal, using a lower airflow velocity would result in a smaller, slower growing, and less likely to spread fire than if using a higher airflow velocity.

Our current design assumptions are based on unobstructed fires. If CVV can be shown to be lower for certain real fires than for idealised fires, then we may be able to reduce our design assumptions, hence our flow rates, and hopefully keep the fire growth, size and chance of spread of any fires as low as we can.

**METHODOLOGY**

This study is a simple application of CFD to the scenario discussed. The model used was the Fire Dynamics Simulator (FDS) version 5.5.3. This model is described in detail elsewhere [14] and the assumptions and limitations of the model will not be discussed here.

The tunnel modelled in all simulations was rectangular in cross-section, 12 m wide, 6 m high and 100 m long. The tunnel was modelled as perfectly horizontal, so there are no longitudinal buoyancy effects. The tunnel walls, ceiling and roadway were all modelled as concrete with density 2100 kgm\(^{-3}\), thermal conductivity 1.2 Wm\(^{-1}\)K\(^{-1}\) and specific heat capacity 0.88 Wm\(^{-1}\)K\(^{-1}\). The default emissivity suggested in the FDS user guide is 0.9 and this was adopted here. The thickness of the concrete surface was assumed to be 0.1 m and the roughness was assumed to be 3 mm. When an intermediate ceiling is included in the simulations, it is assumed to be of identical concrete as that specified for the walls, floor and ceilings of the tunnel. The intermediate ceiling is assumed to be a flat rectangular plane of 0.01 m thickness and is of identical plan area to that of the fire source being modelled.

The object on fire was modelled in all simulations as a rectangular blockage, 6 m long, 3 m wide and 3 m high. It was placed centrally in the modelled tunnel for most simulations. In all simulations, the fire was modelled as a propane burner at the upper surface of the object on fire, burning at a constant HRR of 50 MW.

Longitudinal flow (shown as left to right in all figures presented here) was generated in the tunnel domain by imposing a pressure difference between the portals, which are otherwise assumed to be fixed pressure boundaries on the domain. In each simulation, the longitudinal flow was allowed to reach a steady state condition before the fire was ‘switched on’. In the majority of simulations, the simulation time required to reach steady state flow was between 50 and 120 s. The fire was then modelled as burning at a constant HRR for 300 s and the smoke behaviour was observed.

A grid refinement and sensitivity study was carried out in accordance with good CFD practice [15]. It was found that the results of the model became largely independent of the numerical grid when the cells were 0.5 \(\times\) 0.5 \(\times\) 0.5 m. All results presented used this grid resolution or higher.

In experimental and numerical studies of backlayering in tunnels, one of the recurring issues is how the presence or absence of backlayering in a given scenario is determined. ‘Smoke’ is not a phenomenon with well defined edges, instead there is generally a transition from somewhere with totally smoke free air and another location with dense smoke. Comparison between the ‘Smokeview’ (part of the FDS software suite) visualisations of smoke and the temperature data showed a repeatable correlation between the edge of the visible smoke and a predicted temperature of 80°C, thus the presence of temperatures above 80°C upstream of the fire location is taken to imply the presence of backlayering. The correlation between smoke and a temperature iso-surface of 80°C is shown in Figure 1.
The longitudinal ventilation velocity in the modelled tunnel is never perfectly uniform in time or across the entire cross-section. To determine the characteristic ventilation velocity, the flow was examined on a plane through the tunnel, halfway between the upstream portal and the upstream edge of the fire object. Once the flow had reached ‘steady state’ conditions, the flow through this plane was averaged across the entire area and through 20 s of simulation time.

A number of simulations were carried out with no obstructions to determine the CVV for the base case scenario. It was found that a longitudinal flow of 4.30 ms\(^{-1}\) was sufficient to reduce backlayering to less than 25 m and a longitudinal flow of 4.49 ms\(^{-1}\) was required to reduce backlayering to less than 5 m upstream. Thus, for the purposes of this study, 4.49 ms\(^{-1}\) is taken to be the CVV for the unobstructed case.

**RESULTS**

Various simulations were carried out with different imposed ventilation velocities, and different configurations of blockages above and upstream of the fire object.

The blockages considered were:

- An intermediate ceiling 1 m above the fire (i.e. 2 m below the ceiling)
- An intermediate ceiling 2 m above the fire (i.e. 1 m below the ceiling)
- A 4 m high planar blockage 1 m upstream of the fire
- A 5 m high planar blockage 1 m upstream of the fire

These are shown in Figure 2.
Some simulations were also run with intermediate ceilings offset from the fire location, and the fire object to one side of the tunnel, but these will not be discussed here.

Examples of some of the simulations are given in Figure 3.

**Figure 3** Four examples of FDS velocity data for simulations with a longitudinal flow of 4.49 ms$^{-1}$ with (a) no obstructions, (b) a 5 m high blockage 1 m upstream of the fire object, (c) an intermediate ceiling 1 m above the fire object, and (d) an intermediate ceiling 2 m above the fire object. (Note, it is not clear in black & white, but the dark areas in all four images correspond to low flow velocities (in the longitudinal direction), whereas the lighter areas near the ceiling correspond to higher ventilation velocities)
The presence of the obstructions was observed to influence the flow pattern in the following ways:

1. An intermediate ceiling 1 m above the fire object generally had a beneficial influence on the smoke behaviour. That is, the critical ventilation velocity required to prevent backlayering was reduced from 4.49 ms\(^{-1}\) to about 4.3 ms\(^{-1}\). In sub-critical ventilation conditions, the intermediate ceiling also tended to reduce the backlayering length and reduce the temperature of the backlayer.

2. An intermediate ceiling 2 m above the fire object did not have a beneficial influence on the smoke behaviour. The presence of a 2 m high ceiling resulted in backlayering upstream of the fire location with a flow of 4.49 ms\(^{-1}\). However, in the sub-critical ventilation regime, one effect of the 2 m high ceiling was, once again, to reduce the temperature of the backlayer.

3. A planar blockage 1 m upstream of the fire object did not have a beneficial influence on the smoke behaviour. The presence of the blockage resulted in backlayering even with a flow of 4.49 ms\(^{-1}\). The 4 m high blockage seemed to generate more backlayering than the 5 m high blockage.

**DISCUSSION & FUTURE RESEARCH**

The preliminary study carried out so far shows that some blockages and obstructions near a large fire in a tunnel can significantly influence backlayering behaviour and influence the temperature of the backlayer. However, from the simulations carried out so far it is hard to draw any trends in behaviour which may be used to influence future tunnel design or fire strategy.

The most beneficial obstruction, in terms of reducing CVV and reducing backlayering temperature in the sub-critical regime is an intermediate ceiling which is quite close to the fire. Further research will need to be carried out to investigate if this phenomenon is an artefact of the model or if this effect would be beneficial in reality.

Other obstructions, be they closer to the tunnel ceiling or upstream blockages, appear to promote the formation of a backlayer. This is most clearly evident by considering the temperatures 5 m upstream of the fire object, see Figure 4.

![Figure 4 Temperatures 5 m upstream of the fire object, for a ventilation flow of 4.49 ms\(^{-1}\).](image)

Future research is intended to investigate the phenomena in more detail, by varying the position of the blockages and the height of the fire object itself in a more detailed manner.
TENTATIVE CONCLUSION

In three out of the four cases studied, the CVV required for smoke control was higher than that for an unobstructed fire. As all significant studies of CVV to date have used or assumed unobstructed fires, this may mean that the equations currently in use are under-predicting the CVV required to control smoke from real fires in real tunnels. However, further research is needed.

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Design, simulations and implementation of ventilation system for Metro Line 9, at Barcelona city in Spain

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KEYWORDS: metro system, two-level tunnel, critical control velocity, evacuation strategy, ventilation shafts, “shaft” type stations, SES, CFD.

INTRODUCTION
Line 9 of Metro of Barcelona is one of the most innovative design oriented metro lines in the world. This tunnel system is a two-level tunnel. Ventilation shafts are connected with each tunnel. Decision about ventilation and evacuation strategies has been achieved through SES and CFD simulations for metro line: tunnels and stations. The traffic in the tunnel would be just metro passengers trains. “Shaft” type stations have a special design, in this innovative project. This present project has been constructed and is currently in operation in Barcelona City.

Figure 1 – Two-level tunnel

INFRAESTRUCTURE
- Section Can Zam – Telescopi and Tramo Gorg – Telescopi converge at Bon Pastor.

Figure 2 – Line 9 Section 4 Metro of Barcelona TMB.
• Bi-level tunnel. These two tunnels are interconnected with ventilation shafts and ramps.

Figure 3 – Two-level tunnel and detail of ramp.

• Ramps for platform exchange are enclosed between Egglesia and Fondo, Fondo and Bon Pastor, and Bon Pastor and Onze de Septembre.
• Cavern type Stations, closed with Platform Screen Doors (PSDs) (only open when train stops in stations). Then, the tunnel is isolated from the stations.

Figure 4 – Can Peixauet Station.
Figure 5 – Tunnel Ventilation Shaft scheme.

- Interstation shafts include calculated fans:
  - Flowrate at confort (at 500 rpm): 40m³/s = 144,000 m³/h
  - Emergency flowrate at (1000 rpm), around 70m³/s = 252,000 m³/h.

**SES METHODOLOGY (TUNNEL)**

**Methodology**

The following steps have been achieved

- SES simulation of a unique model of tunnel and stations, including trains passing, in normal operation, and emergency conditions with a train in fire, in different scenarios.
- Calculation of necessary ventilation system. Then, SES simulations will be performed. Corresponding to normal operation and emergency operation.
- Validation of ventilation system with the above results, and TVS operational schema.

**Geometrical Model**

In order to develop the tunnel geometrical model necessary for simulations, the following parameters were used:

- Geometrical data. Those were introduced, according to the needs of SES programme (nodes, sections, segments, subsegments, etc.). For segment of the tunnel, cross section perimeter, roughness, temperature, relative humidity, accumulated height (gradient) as well as head losses related to geometry changes of the tunnel.
- Fans Data. According to initial airflows proposed, fans curves, adjusting these flows in SES.
- Thermal data. Humidity, temperature, and soil and structure thermal properties.
- Train performance Data. These will include physical parameters, friction aerodynamic coefficients, and traction curves.
- Routes Data in normal operation, and train frequencies, velocities, etc.
- Fires corresponding to trains.
- The first step to use SES simulator is to convert all parameters in a one-dimensional model.

The location of ventilation shafts is as follows:

<table>
<thead>
<tr>
<th>TVS</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV1</td>
<td>Can Zam</td>
</tr>
<tr>
<td>PV2</td>
<td>Between Singuerlin-Egglesia</td>
</tr>
<tr>
<td>PV3</td>
<td>Fondo</td>
</tr>
<tr>
<td>PV4</td>
<td>Can Peixauet</td>
</tr>
<tr>
<td>PV5</td>
<td>Telescopi (I. Can Zam)</td>
</tr>
<tr>
<td>PV6</td>
<td>Gorg</td>
</tr>
<tr>
<td>PV7</td>
<td>Entre La Salut-Gorg</td>
</tr>
<tr>
<td>PV8</td>
<td>Telescopi (L. Gorg)</td>
</tr>
<tr>
<td>PV9</td>
<td>Bon Pastor</td>
</tr>
<tr>
<td>PV10</td>
<td>Entre Ozone Septembre-Bon Pastor</td>
</tr>
</tbody>
</table>

*Table 1- Ventilation shafts*
SES MODEL

TD&T’s specialised design tools

Tools developed by TD&T are:
- SES input pre-processor
- SES segment generator
- SES route generator
- SES output Post-Processor
- Fire editor
- Fans editor

Segmentation of tunnel

The first part of the discretisation of tunnels/stations system, will consist in defining the segments which the tunnel system will be divided into. Tunnels and stations will correspond to sections and line segments.

Plant and profile

For execution of simulations of the model, the plant and profile of the tunnel are reproduced exactly as provided in the project.

Location of Nodes / Sections

Next task, after reproducing plant ant profile of tunnel and stations tarea, is situating nodes. Criteria to set up nodes are:
- Changes of grade
- Connection between tunnels
- Connection of ventilation shafts
- Connection with atmosphere (portals)

Division of sections / Segments

Line sections have been divided into segments with an objective length of 22m (car length), with a tolerance of ±5%. Where this has not been possible, the most uniform division of segments has been intended.

Characterization of segments

Line segments generated, as describe in last paragraph, are described by
- Free area (cross section minus rails section, and any other element).
- Perimeter.
- Absolute rugosity of section.
- Accumulated height.
- Length.
- Head losses coefficients affecting circulating flows.
- Initial dry and wet bulb temperatures.

Line Sections/ Ventilation Segments

Other tan regular segment characterization, ventilation shafts should show other parameters as
Shafts and ducts
All ventilation shafts have been modeled, for tunnels and stations, using our AutoCAD plug-in tool. See Appendix 1.

Tunnel ventilation shafts
The fan used for each tunnel ventilation shaft is the one shown in figure X with airflow of around 60 m/s.

Station ventilation shafts
The fan used for each station ventilation shaft is the one shown in figure X with airflow of around 60 m/s.

Subplatform & plenum ventilation segments
Sub-platform ducts and plenum (grates) have been designed and included in SES model. Grates/plenum have been described into SES model, for every platform, in all stations, as well as sub-platform ducts. Data are described in AutoCAD plug-in.
SES SIMULATIONS

Normal Mode

Comfort situation (passenger trains):
The comfort situation has been simulated, and ventilation strategies have been provided. Trains pass at headways of 3 seconds.
Two different ventilation schemas have been considered:

- Type A: Inmisión en Can Zam + Inmisión en Gorg
- Type B: Extracción en Can Zam + Extracción en Gorg

<table>
<thead>
<tr>
<th>TVS</th>
<th>Location</th>
<th>Operational mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV1</td>
<td>Can Zam</td>
<td>Intake, Exhaust</td>
</tr>
<tr>
<td>PV2</td>
<td>Entre Singuerlin-Eglesia</td>
<td>Exhaust</td>
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<td>Can Peixauet</td>
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<td>Telescopi (L. Can Zam)</td>
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<td>Gorg</td>
<td>Intake, Exhaust</td>
</tr>
<tr>
<td>PV7</td>
<td>Entre La Salut-Gorg</td>
<td>Exhaust, Intake</td>
</tr>
<tr>
<td>PV8</td>
<td>Telescopi (L. Gorg)</td>
<td>Intake, Exhaust</td>
</tr>
<tr>
<td>PV9</td>
<td>Bon Pastor</td>
<td>Extracción, Inmisión</td>
</tr>
<tr>
<td>PV10</td>
<td>Entre Onze Septembre-Bon Pastor</td>
<td>Intake, Exhaust</td>
</tr>
</tbody>
</table>

After all simulations, it has been considered the ventilation Schema B. Exhaust will be done in extremes and intake will be achieved in several low points, i.e. at shaft between La Salut and Gorg.

When running these simulations, in normal operation, air velocity is around 1m/s.

Emergency situation (passenger trains)

SES Fire simulations have been done, when passenger trains are stopped, between every two shafts. Each emergency situation has required a different set of solutions, for smoke control, and people evacuation. After several studies, fire considered was 22MW for aluminium car.

Different fire cases have been simulated at the different tracks, upper and lower. Different fire cases have been simulated in upper and lower tunnels and different sections (Can Zam – Telescopio, Gorg – Telescopio, Telescopio, Onze de Septiembre). After reviewing all results we can conclude that the system works properly, which means that air velocity goes over critical control velocity and there is no back layering. Then, tunnel ventilation system (TVS) works correctly

MODELING OF STATION WITH CFD

The behaviour of a train in fire with open doors, stopped in a platform with PSD open, has been modelled through CFX simulations.

It has been reviewed the adequacy of the solution designed by TMB, in this fire situation.

Three CFD simulations have been done:

1) Ventilation solution proposed by TMB
2) Ventilation design proposed by TD&T,
3) Improvement to TD&T Design, including holes in PSDs. 5 m. x 0.75 m., in each extreme of platforms, to be open at 155s. of simulation.
OBJECTIVE
Validation or redesign of ventilation scheme for Can Peixauet Station, Section 4 of Barcelona Metro Line, for a fire emergency for an aluminium train car, with a maximum Heat Release Rate of 15MW.

METHODOLOGY
- Drawings review.
- Regulations review.
- 3D Modelling of station geometry, ventilation design and fire.
- Mesh creation.
- Selection of physical sub-models.
- Contour conditions at every region.
- Initial conditions.
- Monitoring of iterative solution, controlling parameters for adequate numerical resolution.
- Analysis of solution.
- Conclusions.
- Recommendations and improvements.

MODELS
Fire
Fire evolution according to Eq. (1):

\[ HRR = \alpha t^2 \] (1)

\[ HRR = HRR_{\text{max}} e^{-\beta(t-t_0)} \] (2)

(“An Overview of Vehicle Fires In Tunnels”, de Haukur Ingasson, presentado en el congreso “Safety in Rail and Road Tunnels” celebrado en Madrid, ITC 2001)

Figure 8- Fire.

Multi-Component Flux
Multi-component flux of air, smoke and CO have been modelled, where:

- SOOT COEF = 2.5 g.s\(^{-1}\).MW\(^{-1}\).
- CO COEF = 0.915 g.s\(^{-1}\).MW\(^{-1}\).
**Mesh**
The dominium of calculus has been generated as 3D solids. From a volume of 9593 m³, a mesh has been obtained of 6.037.489 tetrahedra, 1.117.256 for simulations 1 y 2. Th simulación 3 includes openings in platforms.

![3D Model](image)

*Figure 9- 3D Model.*

**CFD SIMULATIONS**

**Simulation 1**

![Temperatures](image)

*Figure 10 Temperatures.*
Simulation 2 and Simulation 3

Figure 11 Tunnel openings.

Figure 12 Plane of temperatures.
Figure 13 Soot mass concentrations.

Figure 14 Plane of temperatures.
The Dynamics of Tunnel Ventilation and Fire Development

Yajue Wu
Department of Chemical & Biological Engineering, Faculty of Engineering, Sheffield University, Mappin Street, Sheffield S1 3JD, UK

ABSTRACT

Critical velocity is determined by the tunnel fire heat release rate and the tunnel geometry. It is widely accepted that although the critical velocity increases with the fire heat release rate, there is a "ceiling" to the critical velocity value, the critical velocity tends to flatten out and became insensitive to the heat release rate. This study is aimed at examining the underlying mechanisms responsible for this change in the relationship between the heat release rate and the critical velocity. The combustion phenomena inside the tunnel was analyzed using a combustion efficiency factor which was determined from the heat release rate measurement and the fuel release rate from the fire during the tunnel fire development. The fire development in a medium scale test tunnel was analyzed through detailed measurement of oxygen consumption rate and the fuel mass loss rate. The ventilation velocity was varied to examine the effect of ventilation on the fire development.

KEYWORDS: critical ventilation velocity, fire development and combustion efficiency

INTRODUCTION

The relationship between the “critical velocity” and the fire heat release rate has been studied intensively in recent years [1-7]. The formulas of critical velocity are usually correlated with the heat release rate and the parameter representing tunnel geometry. The critical velocity generally increases with increasing fire heat output for small to medium sized fires, however there is a ceiling for the critical velocity – called “super” critical velocity when the critical velocity becomes insensitive to the fire power and remains constant once the fire reaches certain level. The current techniques for prediction of the values of the critical velocity for various tunnels were predominately based on semi-empirical equations obtained from the Froude Number preservation combining with some experimental data. The methods provided simple and effective semi-empirical solution to determine the value of the critical velocity. However the underlying mechanisms responsible for the change in the relationship between the heat release rate and the critical velocity was not very well understood. One of the ambiguities in the critical velocity prediction based on the Froude Number modeling is the value of the temperature for the formulas. The Froude Number modeling is based on the concept of buoyancy force of the backlayering. The momentum of the buoyancy force in the backlayering is sustained by the combustion flow produced by the burning. The fundamentals of the critical velocity theory cannot be fully understood and justified without proper analysis of the combustion phenomena occurred in the fire. This study used a tunnel fire zoning model based on the fire plume theory to simplify the flow inside the tunnel and highlight the features of the tunnel fire. A case study was carried out using the experimental information obtained in a medium scale test tunnel (2.44 m height). The tunnel was large enough to simulate a realistic pool fire development in a tunnel and also allowed for the detailed monitoring and simultaneously measurement of the velocity, the fuel mass and the oxygen & carbon dioxide concentration. The fire development was analyzed using the fuel/air ratio, the combustion efficiency factor which was determined by the heat release rate, the fuel release rate.
ZONING A TUNNEL FIRE

Based on the fire plume theory for a tunnel proposed in previous studies [8], a ventilated tunnel fire can be divided into the upstream backlayering zone, the fire zone and the downstream zone for combustion fumes as illustrated in Figure 1. The fire zone can be divided further into the combustion zone above the fuel bed where most of combustible volatiles release from the fuel source is burned and the buoyant plume/intermittent flames which interacts with the tunnel ceiling.

The zoning model is idealized to capture and highlight the features in a tunnel fire. The objective is not to size the zones and locate the boundaries of the zones, but to simplify and characterize the flow in each zone. The zoning also emphasizes the differences of the zones and highlights the interactions between the zones which would influence the fire development.

The four zones have distinctive features. The backlayering is the buoyant flow which travels upstream of the fire against the tunnel ventilation flow. In the backlayering, the momentum of the buoyancy force is sustained by the high temperature flow produced by the burning in the combustion zone and the intermittent flame zone. The burning of the combustible volatile materials in the combustion zone is controlled by the fuel and oxygen supply process in the combustion zone. The downstream flow contains the combustion products and could be stratified in nature. The combustion zone obviously plays a key role in the tunnel fire development.

The most commonly used parameters to describe a tunnel fire are the heat release rate from the fire (HRR) and the maximum gas temperature. Those parameters are used to quantitatively describe the severity of a fire. The type of flames in tunnel fire can usually be classified as diffusion flames. The combustion in the fire is controlled by the fuel and oxygen supply processes. The ratio of fuel to oxygen could be used to describe the burning status which controls the fire development. To measure the effectiveness of the reactions, a combustion efficiency factor is defined as the ratio of rate of fuel supply to the rate of combustion. Those parameters are used in the discussions of the conditions controlling the tunnel fire development in the case study.

THE COMBUSTION MODE IN A TUNNEL FIRE

FUEL/AIR RATIO

The combustion mode of a fire is normally depended on the level of oxygen to fuel ratio and could be described as fuel rich, oxygen rich or Stoichiometric. Oxygen rich fire is produced when the oxygen level is high and there is excessive oxygen in the combustion fumes. Fuel rich fire is generated when oxygen level is low and usually no oxygen is remained in the fumes. Stoichiometric is used to describe a fire with the exact amount of oxygen is supplied for the complete combustion of fuel.

For a tunnel fire, an overall combustion status of the fire could be determined by measuring the ventilation rate and the oxygen volumetric concentration in the downstream smoke flow. The
downstream flow is stratified in natural and usually the oxygen concentration is measured at a few points and an average oxygen concentration is determined.

**COMBUSTION EFFICIENCY**

However an oxygen rich fire doesn’t indicate all the combustible volatile materials released in the fire are consumed. The combustion efficiency factor, $\eta_c$, defined as the ratio of the rate of fuel combusted to the volatile release rate into the fire, could be related to the heat release rate (HRR) from the fire, $\dot{Q}_c$ and the combustible mass release rate, $\dot{m}$ as the following:

$$\dot{Q}_c = \dot{m} \eta_c \Delta H_c$$  \hspace{1cm} (1)

where $\Delta H_c$ (MW/kg) is the calorific value or the heat of combustion of the combustible materials in the fire.

The $\dot{Q}_c$ released in the fire can be determined based on the oxygen consumption rate applying the principle that the heat released from combustion of any common combustible is uniquely related to the mass of oxygen removed from the combustion stream [9] and:

$$\dot{Q}_c = (0.21 - \chi_{O_2}) \dot{V} \rho \Delta H_{O_2}$$  \hspace{1cm} (2)

Where $\chi_{O_2}$ is the mole fraction of oxygen in the downstream fumes, $\dot{V}$ is the volumetric flowrate of air, $\rho$ is the air density and $\Delta H_{O_2}$ is the heat generated per unit mass of oxygen consumed, taken as 43.2 MJ/kg for kerosene, and 19.5 MJ/kg for wood. Therefore the combustion efficiency factor can be determined from the heat release rate estimated from the oxygen consumption by the fire and the potential fire size if all the released combustible mass is consumed in the fire as:

$$\eta_c = \frac{(0.21 - \chi_{O_2}) \dot{V} \rho \Delta H_{O_2}}{\dot{m} \Delta H_c}$$  \hspace{1cm} (3)

Here the combustible mass release rate, $\dot{m}$, should be measured directly and is usually determined by monitoring the weight of the fuel during the fire and assuming all the mass loss is converted to combustible materials into the fire.

**Case Study**

The experimental tests discussed here were carried out in a medium scale tunnel [10] with internal cross section area of 5.6 m$^2$ and 366 m long. The tunnel height is 2.44 m and the maximum width is 2.75 m. The ventilation is provided by one main fan with maximum flow rate of 50 m$^3$/s and two secondary fans and the ventilation velocity could be varied by adjusting the settings for the fans. The ventilation velocity was measured by 8 velocity sensors and the gas concentration of oxygen, carbon dioxide and carbon monoxide was measured at the downstream near the exit of the tunnel. Each test lasted about 35 minutes.

Two tests were selected in the discussion here. The first test produced by burning kerosene in two trays with total pool area of 1.76 m$^2$. Two velocity setting were used in the test. The initial velocity was set at 1.1 m/s and the fire reached a steady burning at 5 MW. Then the ventilation velocity was increased and maintained at 1.6 m/s. In this test, the mass loss in the fuel load was measured by a weighting system and oxygen concentration in downstream was measured. Therefore the oxygen consumed was used to determine the HRR using equation 2. The combustion efficiency factor was calculated using equation 3. Figure 2 shows the ventilation velocity measured during the test and the HRR and the combustion efficiency factor were shown in Figure 3. The oxygen concentration in the downstream fumes was shown in Figure 4.
The second test used four kerosene trays with total pool area of 7.0 m². The initial ventilation velocity was set as 1.7 m/s and a fire output of 18.9 MW was achieved, then the velocity was reduced to 1.1 m/s, further down to 0.7 m/s, then it was increased to 1.2 m/s briefly and then further increased to and maintained at 1.9 m/s until the fuel was consumed completely. The oxygen and carbon dioxide concentration was measured downstream and was used to determine the HRR using equation 2. Because of large size of fuel tray, the weighting system was not used and the mass loss rate was not measured. Figure 5 shows the calculated HRR and measured ventilation velocity during the fire. The oxygen and carbon dioxide concentration is show in figure 6.
DISSCUSIONS

THE INFLUENCE OF THE VENTILATION ON THE HRR

It is clear shown from the HRR shown in Figure 3 & 5 that the HRR was strongly influenced by the ventilation velocity. In the test1, under the steady ventilation of 1.1 m/s, the fire reached steady state about 10 minutes after ignition and the HRR maintained steadily at 5 MW for about 8 minutes. When the ventilation velocity increased to 1.6 m/s, the HRR increased sharply to 7.5 MW, however the fuel started to exhaust and the HRR declined. The HRR responded to the change in the ventilation velocity promptly before the fire declining. It can be concluded that higher velocity produced higher HRR.

The relationship between the HRR and the velocity was also clearly demonstrated in the test 2 in Figure 5. The initial ventilation velocity was set 1.7 m/s. Under this high ventilation velocity, the fire established much more rapidly and maintained steadily at a high HRR value of 22 MW. When the ventilation velocity was dropped, the HRR decreased as well and for the following 10 minutes, the HRR responded to the velocity changes sensitively and kept the trend with the ventilation velocity as shown in Figure 5. The HRR stopped to respond to the ventilation changes when the fire started to die out about 25 minutes into the test and HRR gradually reduced to zero despite the velocity was increased back to the highest value of 1.9 m/s.

Although the HRR increases with the ventilation, the HRR value is also depended on the fuel surface area. The fuel tray surface area in the test 2 was four time of the one in test 1. Under the same ventilation velocity of 1.1 m/s, the HRR obtained was 5 MW in test 1, 16 MW in test 2, the HRR in the test 2 was much higher than in the test 1.

THE BURNING STATUS

The oxygen concentration measurement in Figure 4 showed that oxygen was detected throughout test 1, and the fire can be considered as oxygen rich. Although the test 1 produced an oxygen rich fire through the test duration, the combustion efficiency curve in Figure 3 showed that it varied with the HRR. During the initial fire growth stage, the combustion efficiency was less than 100%, which indicated that the fuel release rate was greater than the rate of combustion in the fire zone. When the fire reached steady state, the combustion efficiency is also reached relatively steady around 100%. It indicated that it was equilibrium between the fuel supplying and the burning in the fire zone. The equilibrium could be interpreted as the burning in the combustion zone was most efficient and fuel volatiles released were combusted completely.

Test 2 started with a high ventilation velocity and fire grew and established under oxygen rich conditions. Fuel rich fire occurred briefly in the test 2, when the ventilation velocity was dropped below 1 m/s suddenly, the oxygen concentration in downstream was reduced to zero, however the oxygen level increased as soon as the ventilation was increased above 1 m/s. Although the fuel mass was not measured in this test and the combustion efficiency factor cannot be calculated, the period of steady HRR and the constant oxygen and carbon dioxide in the downstream under the ventilation 1.7 m/s indicated the equilibrium between the fuel supplying and the burning was reached.

EFFECT ON THE BACKLAYERING

Smoke density measurement and video camera was set up to monitor the backlyering during the tests. It was shown in the test 1 that at 1.1 m/s ventilation velocity, the backlayer was well under control and
the smoke backing up distance was held about 20 m steadily. When the velocity was increased to 1.6 m/s, the backlayering was completely eliminated.

In test 2, there was no backlayering under the initial ventilation velocity of 1.7 m/s. But the smoke flow backed up quickly when the velocity was dropped to 1 m/s and the was able to retreat when the velocity increased to 1.1 m/s and hold steady with the backing up distance about 20 m.

The tests demonstrated that regardless the fire size, the smoke flow was very well controlled by the ventilation velocity of 1.1 m/s with the backing up distance at 20 m. The evidence indicated that 1.1 m/s was very close to the critical velocity. Therefore it is reasonable safe to assume that the combustion conditions under the critical velocity remained the same as the one under 1.1 m/s in the test 1 and can be used to discuss the burning status under the critical velocity.

EFFECT ON THE CRITICAL VELOCITY AND GAS TEMPERATURE

Both tests showed that at the critical condition, the fire was definitely oxygen rich. Oxygen rich could be considered as one of the essential conditions for the critical velocity.

Although the tunnel fire is oxygen rich at the critical ventilation condition, the combustion efficiency factor suggested that the burning at the combustion zone is near 100% efficiency with equilibrium between the fuel supplying and the burning in the fire zone. From the combustion point of view, equilibrium burning in diffusion flames means the combustion is at the optimum conditions to result the highest possible local flame temperature in the combustion zone. The high local flame temperature could enhance the buoyancy force in the backlayering and favor promoting fire spread due increasing the heat transfer into the fuel bed. The gas temperature measurement in test 1 shown in Figure 7 demonstrated that the gas temperature upstream of the fire was sensitive to the heat release rate. However the overall gas temperature in the downstream of the combustion zone was not strongly influenced by the ventilation, Figure 8 showed that the downstream gas temperature didn’t vary with the fire heat release rate and remained at a steady level of 1100 °C.

![Figure 7: The gas temperature in test 1 at 2.5 m upstream.](image1)

![Figure 8: The gas temperature in test 1 9 m downstream of fuel bed.](image2)

The gas temperature upstream of the fire increases with the flame temperature and the heat release rate, however the flame temperature has a “ceiling” which occurs near the stoichiometric fuel/air ratio. The analysis of the combustion mode and the effects on heat release rate and gas temperature provided evidence to support the existence of a super critical velocity and maximum gas temperature.

CONCLUSIONS

The fuel/air ratio, combustion efficiency factor, the HRR and gas temperature are used in the discussions of the conditions controlling the tunnel fire development in the case study. It was shown that under the critical ventilation, the combustion was basically oxygen rich with excessive oxygen.
was detected downstream of the fumes, but the combustion efficiency was near 100% with equilibrium between the fuel supplying and the burning in the fire zone. The combustion mode produced high local flame temperature, which influence the buoyance force in the backlayering and the heat transfer from the fire to the fuel bed. The underline physical conditions for the super critical velocity were discussed.

REFERENCES

The Importance of Exit Spacing to the Choice of Tunnel Ventilation System

Paul Williams
Norman Disney & Young
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ABSTRACT
Smoke control in tunnels is often considered from a performance based approach with each tunnel assessed against a number of parameters. Current guidance [1] indicates that the main factors in determining an appropriate emergency smoke ventilation system are the expected traffic volume, the length of the tunnel and whether there is uni-directional or bi-directional traffic flow.

Typically for high traffic volume, significant tunnel length and bi-directional traffic, smoke extraction near the fire location will be incorporated. However for low traffic volume and short tunnels it is generally considered that a longitudinal ventilation system without local extract would be sufficient.

The use of local smoke extraction instead of a purely longitudinal system tends to increase the cross-sectional area of the tunnel. In most tunnel projects the cross-sectional area is proportional to the construction cost and therefore minimising the cross-sectional area is paramount.

This paper presents a quantitative risk analysis suggesting that, in addition to the factors listed above, another important parameter for consideration when designing the ventilation system is the exit spacing. Through varying the distance between emergency exits this paper demonstrates that the differences in the risk to life safety between different ventilation systems can be outweighed by the appropriate choice of exit spacing.

In a real world application the correct choice of exit spacing could minimise the reliance on a ducted ventilation system thus saving cross-sectional area and ultimately cost without increasing the risk to life safety.

KEYWORDS: tunnel ventilation, quantitative risk assessment, exit spacing, ventilation reliability

INTRODUCTION
Different standards and guidance documents recommend varying parameters for the design of tunnel emergency ventilation systems. Mechanical ventilation for a short, low traffic tunnel may not be deemed necessary however in most instances some form of mechanical system is generally provided comprising longitudinal impulse fans and/or transverse ventilation ducts.

Tunnel ventilation systems are rarely designed in a consistent manner due to dissimilar guidance and experience across different jurisdictions. The purpose of this paper therefore is not to address specific nuances of ventilation design but instead to look at the use of a local smoke extraction system versus providing a purely longitudinal system particular in the context of the overall fire strategy and life safety risk.

Separate to this the two systems also both have advantages and disadvantages in respect to asset protection. The choice of tunnel systems for asset protection is the subject of an entirely separate paper as a significant incident may have various societal, political and financial impacts. This is an important note since tunnel designers will typically also consider asset protection for significant
infrastructure however the risk assessment presented in this paper focuses solely on life safety.

Life safety in a tunnel can be affected by a number of factors. This paper focuses on the inter-relationship between four specific areas:

- The ventilation design i.e. local smoke extraction or longitudinal ventilation
- The ventilation system reliability
- The frequency of congestion
- The travel distances between emergency exits

In an ideal world a simple flow chart addressing these bullet points would result in the correct decisions. There is however significant overlap making the decision much less clear cut. The remainder of this paper presents a model risk analysis combining these four factors.

The model risk analysis can be used to determine the impact of the ventilation system design, congestion in the tunnel and the emergency exit spacing and subsequently demonstrate how the same level of risk can be achieved using different combinations of these parameters. Alternatively if the acceptable level of risk is pre-defined this model risk analysis can be used to find the balance between all these factors in order to achieve that stated level of risk.

**MODEL RISK ANALYSIS**

The risk analysis undertaken in this paper follows a fairly typical approach whereby event trees are constructed to determine the frequency of specific events. The consequence of each event is separately determined and the risk of a single event or combined events can then be calculated through the product of the frequency and the consequence.

A simplified event tree is shown in Figure 1. The numbers within the event tree are all fictional to demonstrate the approach. For any given tunnel the frequencies and consequences will depend on the specific design and ultimately influence the overall risk. In other words since the risk is a product of the frequency of an event and its consequences it is clear that the risk can be affected by controlling either or both of these parameters.

**Figure 1  Typical event tree**

The following sections of this paper firstly outline a longitudinal ventilation system design and a ventilation design incorporating local smoke extraction. Subsequent sections address sequentially
each “branch” of the event tree to provide a step by step approach to implementing this model risk analysis in a real world application.

**VENTILATION DESIGN**

In order to provide a benchmark system the author proposes to use the German approach adopted in the RABT [2] as the basis for the ventilation system with local extraction. In this concept the smoke clearance is achieved by utilising a high level duct and opening a number of remotely actuated mechanical dampers that are evenly distributed along the length of the tunnel. Extract points are located approximately every 50m to 100m and the smoke contained within a zone of approximately 200m to 300m. This system is indicatively shown in Figure 2 and it is noted that additional systems (such as longitudinal jet fans) may also be required in order to provide sufficient make-up air and adequate airflow along the tunnel to maintain the smoke within the extract zone.

*Figure 2  Indicative RABT mechanical ventilation system with local extract*

The alternative to local extraction is to provide an air flow along the tunnel in order to clear the smoke through the tunnel portal. This can be achieved using a simple longitudinal ventilation system comprising longitudinal jet fans along the tunnel length. The system is designed to provide a minimum air flow through the tunnel driven by the requirement to minimise back-layering of smoke. The calculation is based on many different factors but typically air flow of the order of 3m/s is generally considered sufficient.

*Figure 3  Indicative longitudinal ventilation system*

**INITIAL EVENT (COLUMN 1)**

To provide a complete risk analysis for the life safety of tunnel users a wide range of incidents need to be considered including:

- Breakdowns
- Collisions (without fire)
- Fires (without dangerous goods)
- Dangerous goods incidents
- External influences (e.g. environmental disaster, terrorism etc.)

This paper focuses specifically on the third bullet; a fire incident but excluding at this time any involvement of dangerous goods. The frequency of these initial events will depend on the specific tunnel in question and ultimately the method presented in this paper can be adopted on any given tunnel project.
In order to provide a relevant example, the frequency of initial events presented below are based on the Waterview Connection in New Zealand which is currently under design and soon to be under construction. By way of a disclaimer, at the time of writing the author of this paper has no involvement with the design or construction of the Waterview Connection and all facts and figures presented in this paper are based on information available in the public domain.

The Waterview Connection tunnel is 2.5km long and is expected to carry 90,000 vehicles per day. The tunnel is uni-directional and there are no entry or exit junctions within the tunnel.

Vehicle fires within the tunnel are expected to occur as a result of two initial events; firstly a collision leading to a fire and secondly a technical fault leading to auto-ignition.

Based on a 2007 German report on the safety of road tunnels [3] the estimated number of fires is 0.06 fires per year due to collisions and 0.25 fires per year due to technical faults. This gives a total of 0.3 fires per year (accounting for rounding errors in the individual figures) or roughly one fire every three and half years.

In a road tunnel no two fires will be identical and as such some assumptions must be made particularly regarding the maximum heat release rate. For the purpose of this analysis the simplified distribution Table 1 is assumed.

Table 1 Distribution of heat release rates as a percentage of the expected number of fires [3]

<table>
<thead>
<tr>
<th>Maximum Heat Release Rate (MW)</th>
<th>Percentage of Fires</th>
<th>Number of Fires per Year</th>
<th>Approximate Fire Return Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5MW</td>
<td>90.00%</td>
<td>0.27</td>
<td>4 years</td>
</tr>
<tr>
<td>30MW</td>
<td>9.90%</td>
<td>0.03</td>
<td>33 years</td>
</tr>
<tr>
<td>50MW</td>
<td>0.09%</td>
<td>~0.00</td>
<td>3700 years</td>
</tr>
<tr>
<td>100MW</td>
<td>0.01%</td>
<td>~0.00</td>
<td>33,000 years</td>
</tr>
</tbody>
</table>

DOES THE VENTILATION SYSTEM OPERATE? (COLUMN 2)

This branch of the event tree incorporates two separate factors; firstly the choice of ventilation system and secondly the reliability of the chosen ventilation system. The two options in regard to ventilation design are the longitudinal approach and local extraction approach presented earlier.

Both of these are designed and maintained to provide a certain level of reliability between 0% and 100%. A reasonable expectation would be for the reliability to be close to 100% however this need not or may not always be the case.

Assuming that all other variables in the event tree are equal, and that the inclusion of the ventilation system reduces the overall risk, then the reliability of the ventilation system directly impacts on the risk to life safety.

IS THE TRAFFIC IN THE TUNNEL CONGESTED? (COLUMN 3)

Traffic congestion in a tunnel can be influenced by a number of elements but will typically depend on the number of vehicles and whether there are any disruptions to the flow such as junctions within the tunnel or close to the tunnel portals. For example a rural tunnel carrying 10,000 vehicles per day is unlikely to experience congestion while an urban tunnel carrying 100,000 vehicles per day may expect to experience congestion particularly during peak hours.

Estimating how likely congestion is to occur can be a difficult for a tunnel under construction. Traffic planners may be able to provide some useful insight however if it is likely that congestion will occur then a range of frequencies, again between 0% and 100% of the time, should be used. In reality congested traffic for more than 5% of the time (equates to approximately two hours per week day) is
unlikely to be acceptable and if this is occurring highlights potentially bigger problems with the traffic network or the proposed design.

Congested traffic has a number of influences on life safety in a fire specifically in the context of the choice of ventilation system. The tunnel used in this example is uni-directional and therefore it is assumed that in the event of a fire all vehicles upstream of the incident are prevented from travelling any further while in uncongested flow vehicles downstream are able to drive out of the tunnel. As such the ventilation system should be designed to protect occupants upstream until they are able to reach an exit on foot. Of the two systems presented in this paper both, when operational, should achieve this performance objective.

Now consider the congested traffic case whereby vehicles downstream of the fire are unable to drive out of the tunnel. Occupants of these vehicles must also evacuate on foot and as such the ventilation system should also afford these occupants some protection. Using a ventilation system with local extract means that in general occupants within a zone of 200m – 300m downstream of the incident may be affected by smoke. Using a longitudinal system, occupants much further downstream may be affected. While the impact is expected to drop the further occupants are from the fire source it is clear that there is the potential for more occupants to be at risk.

Note that bi-directional tunnels will require different assumptions however this does not preclude the use of this model but will strongly favour a ventilation system with local smoke extraction.

**FREQUENCY OF EVENT (COLUMN 4)**

Once the ventilation system reliability and the expectation of congested traffic are determined the frequency of a given event can be estimated as per the example in Figure 4.

**CONSEQUENCE OF EVENT (COLUMN 5)**

For each scenario there will be a consequence. In this context the consequence is considered to be the number of fatalities. In general relatively fewer fatalities are expected with smaller fire sizes than with larger fire sizes. Similarly to the frequency of each event the number of fatalities is considered to be

![Example event tree for a 5MW fire with 90% operational ventilation and congested traffic over 5% of the time](image)
based on the following factors:

- Local smoke extraction v. Longitudinal ventilation
- The ventilation system reliability
- The frequency of congestion

The point of difference between frequency and consequence is that in addition the consequence of an event is considered to be based on the travel distances between emergency exits. The underlying assumption here is that the longer occupants are within the tunnel the longer they are potentially exposed to fire and smoke and hence the higher level of risk to life safety.

Ignoring for the moment the influence of the travel distance between emergency exits, Table 2 presents a matrix of scenarios for which consequences are to be determined.

**Table 2: Scenario definition for variable ventilation and traffic congestion**

<table>
<thead>
<tr>
<th>Scenario*</th>
<th>Ventilation Operating?</th>
<th>Tunnel Congestion?</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1/T1</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>L2/T2</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>L3/T3</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>L4/T4</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* L1 – L4 represent scenarios with a longitudinal ventilation system and T1 – T4 represent scenarios with local smoke extraction.

**Consequences with Longitudinal Ventilation**

For scenario L1 (operational ventilation and no tunnel congestion) the expected number of fatalities is given in Table 3 for each fire scenario. The number of fatalities is based on weighting factors presented in [3] which should be multiplied by a model value appropriate to the particular tunnel. For the purposes of this paper the model value is not important since the risk analysis is comparative. In essence for the remainder of this paper the model value is assumed to be 1.

**Table 3: Expected number of fatalities for scenarios L1 – L4**

<table>
<thead>
<tr>
<th>Heat Release Rate</th>
<th>5MW</th>
<th>30MW</th>
<th>50MW</th>
<th>100MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>0.02</td>
<td>0.14</td>
<td>0.69</td>
<td>0.79</td>
</tr>
<tr>
<td>L2</td>
<td>0.05</td>
<td>0.25</td>
<td>0.69</td>
<td>0.79</td>
</tr>
<tr>
<td>L3</td>
<td>0.05</td>
<td>0.25</td>
<td>0.69</td>
<td>0.79</td>
</tr>
<tr>
<td>L4</td>
<td>0.07</td>
<td>0.36</td>
<td>0.69</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Table 3 also gives the expected number of fatalities for scenarios L2, L3 and L4.

Comparing scenario L1 to L2 the ventilation failure results in occupants upstream of the incident being at greater risk. Note that occupants downstream are able to drive clear of the tunnel and are considered to be at no greater risk.

Comparing scenario L1 to L3, the traffic has changed from uncongested to congested and therefore occupants downstream of the incident are now at risk since they must evacuate by foot. Note that occupants upstream of the incident are no more at risk in scenario L3 than scenario L1.

Finally in scenario L4 the ventilation system has failed to operate and the tunnel is congested leading to occupants both upstream and downstream of the incident being affected.

**Consequences with Local Smoke Extract Ventilation**

Similar expected number of fatalities can be calculated for the local smoke extraction scenarios as presented in Table 4. In general the fatalities follow the same trend between scenarios with one notable exception. In scenario T3 the traffic is congested however the ventilation system is
operational. In this scenario occupants downstream are only considered to be affected within a period of 200-300m from the fire. Outside of this distance occupants should not be exposed to smoke unlike in the equivalent longitudinal scenario (L3) where smoke is spread downstream for a much greater distance.

**Table 4** Expected number of fatalities for scenarios T1 – T4

<table>
<thead>
<tr>
<th>Heat Release Rate</th>
<th>5MW</th>
<th>30MW</th>
<th>50MW</th>
<th>100MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Number of Fatalities</td>
<td>T1</td>
<td>0.02</td>
<td>0.14</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>0.05</td>
<td>0.25</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>0.02</td>
<td>0.11</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>0.07</td>
<td>0.36</td>
<td>0.69</td>
</tr>
</tbody>
</table>

**Impact of distance between emergency exits**

The final factor which is considered to influence the expected number of fatalities is the distance between emergency exits.Crudely the further emergency exits are apart the greater the expected number of fatalities.

Under the German RABT guidance the exit spacing is set at 350m. Therefore for scenarios L1 – L4 and T1 – T4 the expected number fatalities in Table 3 and Table 4 are given based on an exit spacing of 350m.

For scenarios L1 – L4 the number of fatalities is assumed to scale based on exit spacing. For example if the exit spacing is reduced to 250m the expected number of fatalities scales by a factor of 250/350. Conversely if the exit spacing increases to 450m the number of fatalities scales by a factor of 450/350.

In reality it is unlikely that the exit spacing will linearly affect the number of fatalities. A rigorous approach would involve a fractional equivalent dose (FED) analysis. While this is outside the bounds of this paper and will be considered as an extension to this work, the general trend is expected to be such that the number of fatalities reduces proportionally with the exit spacing.

For scenario T1 – T4 a similar logic is followed with one exception. For scenario T3 the ventilation system is assumed to control the spread of smoke to within 200m downstream of the fire. As such the maximum distance occupants may have to travel through smoke is considered to be 200m. Therefore an exit spacing less than 200m is considered to reduce the number of fatalities while an exit spacing greater than 200m is considered to be no worse than an exit spacing of 200m.

The trend in expected number of fatalities for each scenario is shown graphically in Figure 5.

**Figure 5** Trend in expected number of fatalities against exit spacing
RISK (COLUMN 6)
The risk to life safety is calculated by multiplying the frequency of an event by the consequence of the same event and the outcomes of the model are best demonstrated with a number of examples. Consider in the first instance the proposed tunnel is designed with a longitudinal ventilation system (scenario A) which is 98% reliable and secondly that the tunnel is designed with a local smoke extraction system (scenario B) which is also 98% reliable. In both instances congested traffic is expected 2% of the time and the exit spacing is set at 350m.

As shown in Table 5, Scenario B with the local smoke extraction results in fewer fatalities. This is because in the event of congested traffic the local smoke extraction system minimises the number of occupants exposed to smoke. Logically this is the correct outcome.

Note that with this combination of ventilation reliability and frequency of traffic congestion it is not possible to change the exit spacing such that a different conclusion is reached. In all instances the local smoke extract system is considered to present a lower risk than the longitudinal ventilation system.

<table>
<thead>
<tr>
<th>Scenario A v. Scenario B</th>
<th>Scenario A</th>
<th>Scenario B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation System</td>
<td>Longitudinal</td>
<td>Local Extract</td>
</tr>
<tr>
<td>Ventilation Reliability</td>
<td>98%</td>
<td>98%</td>
</tr>
<tr>
<td>Frequency of Traffic Congestion</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Exit Spacing</td>
<td>350m</td>
<td>350m</td>
</tr>
<tr>
<td>Expected number of fatalities per year</td>
<td>0.01133*</td>
<td>0.01110*</td>
</tr>
</tbody>
</table>

* the accuracy of the results to five decimal places can be debated as to their statistical significance however for the purposes of a useful result it is necessary to be able to identify which scenario results in the greater number of fatalities.

Assume now that the local smoke extract system is less reliable than the longitudinal system. This is not an inconceivable assumption and based on a fault tree analysis of the design of the two systems is a fairly likely outcome. The expected number of fatalities with the longitudinal ventilation system remains as before. However the expected number of fatalities with a local smoke extraction system increases by a small percentage as shown in Table 6.

<table>
<thead>
<tr>
<th>Scenario C v. Scenario D</th>
<th>Scenario C</th>
<th>Scenario D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation System</td>
<td>Longitudinal</td>
<td>Local Extract</td>
</tr>
<tr>
<td>Ventilation Reliability</td>
<td>98%</td>
<td>96%</td>
</tr>
<tr>
<td>Frequency of Traffic Congestion</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Exit Spacing</td>
<td>350m</td>
<td>350m</td>
</tr>
<tr>
<td>Expected number of fatalities per year</td>
<td>0.01133</td>
<td>0.01129</td>
</tr>
</tbody>
</table>

Now assume that the exit spacing is in fact 100m. If everything else is kept consistent it is calculated by the model that the number of fatalities is expected to be lower with the longitudinal system than with the local smoke extraction system as shown in Table 7.

<table>
<thead>
<tr>
<th>Scenario E v. Scenario F</th>
<th>Scenario E</th>
<th>Scenario F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation System</td>
<td>Longitudinal</td>
<td>Local Extract</td>
</tr>
<tr>
<td>Ventilation Reliability</td>
<td>98%</td>
<td>96%</td>
</tr>
<tr>
<td>Frequency of Traffic Congestion</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Exit Spacing</td>
<td>100m</td>
<td>100m</td>
</tr>
<tr>
<td>Expected number of fatalities per year</td>
<td>0.00324</td>
<td>0.00326</td>
</tr>
</tbody>
</table>
Scenario C to Scenario F indicate that, all other variables being equal, by reducing the exit spacing from 350m to 100m the ratio of fatalities between the longitudinal ventilation system and the local smoke extract system changes from 1.004 to 0.994. In other words by reducing the exit spacing the longitudinal system changes the risk from being greater than with the local smoke extract system to less than with the local smoke extract system.

Continuing this further there is logically an exit spacing at which the risk to life safety is identical for both the longitudinal ventilation systems and local smoke extraction system for every tunnel. In this case the answer is approximately 288m for which the model predicts 0.00931 fatalities regardless of the choice of ventilation system as shown in Table 8.

<table>
<thead>
<tr>
<th>Scenario G v. Scenario H</th>
<th>Scenario G</th>
<th>Scenario H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation System</td>
<td>Longitudinal</td>
<td>Local Extract</td>
</tr>
<tr>
<td>Ventilation Reliability</td>
<td>98%</td>
<td>96%</td>
</tr>
<tr>
<td>Frequency of Traffic Congestion</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Exit Spacing</td>
<td>278m</td>
<td>278m</td>
</tr>
<tr>
<td>Expected number of fatalities per year</td>
<td>0.00931</td>
<td>0.00931</td>
</tr>
</tbody>
</table>

There are in fact an infinite number of scenarios which can be calculated by varying the reliability of the two systems, the frequency of traffic congestion and the exit spacing. The results of all these calculations can be used to develop a plot as shown in Figure 6 which, for different ventilation reliabilities and congestion frequencies, can be used to determine which ventilation system would present the lowest risk to life safety.

Figure 6  Plot highlighting choice of ventilation system as a function of the frequency of congestion and the system reliability

Within the central shaded area (Area B) both ventilation systems can be shown to present a similar risk subject to the appropriate choice of exit spacing. The example calculated above (scenario G and...
scenario H) sits within this range.

In Area A and Area C changing the exit spacing within reasonable bounds will not change which ventilation systems presents the lowest risk to life safety.

An example of a scenario in the range marked Area A would be as given in Table 9. For the expected number of fatalities to be the same in both scenarios the exit spacing is tending towards infinity or more practically the extent of the tunnel. The reason for this is that the unreliability of the local smoke extraction system relative to the longitudinal system far outweighs the additional risk posed to occupants downstream of a fire during the 1% of time in which the traffic is congested.

Table 9  
| Scenario in which longitudinal ventilation minimises the risk to life safety |
|---------------------------------|------------------|
| Scenario J                      | Scenario K       |
| Ventilation System              | Ventilation Reliability | Frequency of Traffic Congestion |
| Longitudinal                    | 99%              | 1%                             |
| Local Extract                   | 96%              | 1%                             |

Alternatively an example of a scenario in the range marked Area C would be as given in Table 10. In this instance the frequency of congestion and the small relative reliability of the two ventilation systems means that the exit spacing must tend towards zero for there to be an equal risk to life safety. This is of course impractical.

Table 10  
| Scenario in which local extract smoke ventilation minimises the risk to life safety |
|---------------------------------|------------------|
| Scenario L                      | Scenario M       |
| Ventilation System              | Ventilation Reliability | Frequency of Traffic Congestion |
| Longitudinal                    | 99%              | 5%                             |
| Local Extract                   | 98%              | 5%                             |

SUMMARY

The risk analysis model presented in the paper outlines an approach for determining the balance between choice of ventilation system, traffic congestion and exit spacing in order to minimise the risk to life safety. The key conclusion from the risk analysis model is that with the appropriate choice of exit spacing a longitudinal ventilation system can be shown to present an equal or lower risk to life safety than if a local smoke extraction system is provided even assuming a reasonable level of congestion.

Often the cost and time associated with tunnelling can be significantly reduced if a local smoke extraction system is not required. This is both as a result of the reduced cross-sectional area, through minimising the ventilation ductwork, and the reduced complexity due to the simplified ventilation system design. In a number of cases this risk analysis model can show that a ducted system is not necessary to achieve the required level of life safety and as such this approach has the potential to improve the financial viability of tunnel projects, reduce the construction risk and lower the maintenance requirements.

REFERENCE LIST

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Proceedings from the Fifth International Symposium on Tunnel Safety and Security, New York, USA, March 14-16, 2012

Edited by Anders Lönnermark and Haukur Ingason

Volume 2
ABSTRACT

This report includes the Proceedings of the 5th International Symposium on Tunnel Safety and Security (ISTSS) held in New York, 14-16th of March, 2012. The Proceedings include 68 papers given by session speakers and 19 papers presenting posters exhibited at the Symposium. The papers were presented in 12 different sessions. Among them are Security, Explosions, Risk and Cost Benefit, Human Behaviour and Evacuation, Passive Fire Protection, Active Fire Protection, Ventilation, and Fire Dynamics.

Each day was opened by two invited Keynote Speakers addressing broad topics of pressing interest. The Keynote Speakers, selected as leaders in their field, consisted of Martin Brown, Transport of London, UK, Ricky Carvel, Edinburgh University, UK, William Connell, Parson Brinkerhoff, USA, William H. Arrington, U.S. Department of Homeland Security, USA, Peter Johnson, Arup, Australia and Marieke Martens, TNO, The Netherlands.
PREFACE

These proceedings include papers presented at the 5th International Symposium on Tunnel Safety and Security (ISTSS) held in New York 14-16th in March 2012. The success of the International Symposium on Tunnel Safety and Security is a tribute to the pressing need for continued international research and dialogue on these issues, in particular connected to complex infrastructure such as tunnels and tunnel networks. These proceedings provide an overview of emerging research and regulatory actions coupled to state-of-the-art knowledge in the field of safety and security in undergrounds structures.

We are very proud to have been able to establish this symposium which regularly attracts over 250 delegates from all parts of the world. This symposium represents an arena for researchers to discuss safety and security issues associated with complex underground transportation systems. The Symposium is unique in the sense that it is the only conference that combines safety and security issues and introduces separate security sessions focused on underground facilities and their specific needs. The need for expertise in this field, is increasing and we feel confident that ISTSS will provide a leading forum for information exchange between researchers and engineers, regulators and the fire services and other stakeholders in the future.

In particular, we see that active fire protection has become a major field of interest. Further, risk and engineering analysis continues to be an area that attracts many papers. Numerous renowned researchers and engineers have contributed to these and other topics at this symposium for which we are very thankful. Fire related issues still attract many presentations but the focus has shifted towards technical solutions that can mitigate the fire development should a fire occur. The enormous costs for underground structures forces engineers to design alternative solutions. The sessions that have greatest focus on mitigation of fire development include those dealing with the effects of ventilation systems, active and passive fire protection, fire fighting and human behaviour.

We received over 100 papers in response to our Call for Papers (not including our six invited Keynote Speakers) and believe that the quality of the papers is a testament to the calibre of research that is ongoing around the world. Unfortunately, we were only able to accept 74 papers for presentations but have a strong poster session with 19 papers to canvas other interesting emerging research and an exhibit to allow producers to present their particular solutions. The selection process was carried out by a Scientific Committee, established for this symposium, consisting of many of the most well known researchers in this field (a list can be found on the Symposium website). We are grateful for their contribution to make this symposium as the leading one on fire and safety science in tunnels.

Finally, we would like to thank our Event Partners the National Infrastructure Institute Centre for Infrastructure Expertise (NI2CIE) and L-surf Services for their co-operation and help.

Haukur Ingason
Anders Löönermark
TABLE OF CONTENTS

VOLUME 1

KEYNOTE SPEAKERS

Martin Brown, Transport for London (TfL), UK

Mitigation of Tunnel Fires
Ricky Carvel, University of Edinburgh, UK

Regulating Road Tunnel Fire Safety
William G. Connell, Parsons Brinkerhoff, USA

Risk Reduction for Today’s Critical Infrastructure

Fire Safety Engineering – a Tool in Tunnel Design
Peter Johnson, Arup, Australia

Human Behaviour in Tunnels
Marieke H. Martens, TNO, The Netherlands
Gunnar D. Jensen, SINTEF, Norway

ACTIVE FIRE PROTECTION; SUPRESSION SYSTEMS

Advantages of Electronically Controlled Sprinklers (ECS) for fire protection of tunnels
Sergey Kopylov, Russian Research Institute for Fire Protection, Russia
Leonid Tanklevsky, Mikhail Vasilev and Varvara Zima, Gefest Enterprise Group, Russia,
Alexander Snegirev, St.-Petersburg State Polytechnic University, Russia

Benefit of Sprinkler Systems in Protection of Tunnel Structure from Fire
Bobby J. Melvin and Kenneth J. Harris, Parsons Brinckerhoff, USA

Water Mist Concept – Effective Choice for Improving Safety in Road Tunnels
Pasi Vuolle, Marioff Corporation Oy, Finland

Automatic sprinkler system in tunnel fires
Ying Zhen Li and Haukur Ingason, SP Technical Research Institute of Sweden

A study of the interactions between a water suppression system and a longitudinal ventilation system in a tunnel
Yoon Ko and George Hadjisophocleous, Carleton University, Canada

ACTIVE FIRE PROTECTION; DETECTION & SUPRESSION

Automated Fire Detection and Mitigation in Railway Tunnels Designed for Freight Trains
Frank de Vries, Covalent Infra Technology Solutions BV, The Netherlands
Gas Analytics for the Early Detection of Fires in Road Tunnels
Maximilian Wietek, VSH Hagerbach Test Gallery Ltd., Switzerland
Christian Berweger, Xirrus GmbH, Switzerland
Christian Lämmle, Combustion and flow solutions GmbH, Switzerland

CFD-based Assessment of Fixed Fire-Fighting Systems in Tunnels
Xavier Ponticq, CETU (Tunnels Study Centre), France

Fire in Road Tunnel in Slovenia January 2010
Milan Dubravac, National Fire School, Slovenia

DESIGN & FUNCTIONAL SAFETY

An Integrated Functional Design Approach for Safety Related Tunnel Processes

The Stockholm Bypass – Enhanced Design and Interaction Between Safety Systems
Leif Eklöf and Ulf Lundström, Swedish Transport Administration, Sweden
Henric Modig and Bo Wahlström, Faveo Projektledning AB, Sweden

Decision Support to Determine Safe Tunnel Availability
Diderick Oerlemans, Covalent Infra Technology Solutions, The Netherlands

Problems with Tunnel Safety Systems
Gary English, City of Seattle Fire Department, USA

EXPLOSIONS

Protective Design Guideline of Tunnels
Sunghoon Choi, Parsons Brinckerhoff, New York, USA

Design Loads and Methods for Prestressed Open Cut Tunnels under Severe Accidental and Malicious Threats – Explosions
Assad Nawabi, Andreas Bach and Ingo Müllers, Schüßler-Plan Ingenieurgesellschaft mbH, Germany and BRS-Design, Germany
Alexander Stolz, Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, Germany and BRS-Design, Germany
Markus Nöldgen, Cologne University of Applied Science, CUAS, Germany

Rescue Operations in Underground Mass Transport Systems at Fires and Deliberate Attacks
Mia Kumm, Mälardalen University, Sweden
Anders Palm, Mälardalen University, Sweden and Greater Stockholm Fire Brigade, Sweden

Studies of Explosions Occurring in a Metro Carriage in a Tunnel
Gero Meyer, Mälardalen University, Sweden
Anders Bryntse, Swedish Defence Research Agency, Sweden
Bo Janzon, Mälardalen University, Sweden
SECURITY

Safety and Security of Underground Infrastructure – New Concepts for Evaluating and Mitigating Risks of Tunnels
Goetz Vollmann and Markus Thewes, Ruhr University Bochum, Institute for Tunnelling and Construction management, Germany
Frank Heimbecher, Federal Highway Research Institute, Germany

Influence of Different Tunnel Ventilation Systems on the Dispersion of Light and Heavy Gases due to Car Accidents
Marion Meinert, Muenster University of Applied Science, Germany
Wolfram Klingsch, University of Wuppertal, Germany

Identification of Critical Tunnels in a Road Network
Ingo Kaundinya and Frank Heimbecher, Federal Highway Research Institute, Germany

SAFETY AND REGULATORY FRAMEWORK

Some of the NFPA 130 Improvements Proposed for the 2014 Edition
Harold L. Levitt, the Port Authority of New York & New Jersey (PANYNJ), USA
William D. Kennedy, Parsons Brinckerhoff, USA

Safety of Dutch Tunnels Guaranteed by Standard Approach
Hans A. Ruijter and Fred Bouwmeester, Directorate General of Public Works and Water Management (Rijkswaterstaat), The Netherlands.

Current Practice of Fire Design for Road & Rail Tunnels in Austria
Johannes Wageneder, GEOCONSULT Wien ZT GmbH, Austria

A North-American Approach to the Refurbishing of Existing Tunnels Based on European Specific Hazard Investigations
Hubert Dubois, CIMA+ Consulting Engineers, CANADA

VENTILATION

Some Effects on Natural Ventilation System for Subway Tunnel Fires
Ahmed Kashef, Institute for Research in Construction, National Research Council, Canada
Zhongyuan Yuan and Bo Lei, School of Mechanical Engineering, Southwest Jiaotong University, China

External conditions have a significant impact on the air flow in tunnels using transverse ventilation for smoke extraction.
Jonas Andersson, City of Stockholm Traffic Administration, Sweden
Anders Lönnemark, SP Technical Research Institute of Sweden

Dynamics of Natural Air Flow Inside Subway Tunnels
Markus Brüne, Andreas Pflitsch, Ruhr-University of Bochum, Germany
Brian Agnew, University of Northumbria, Newcastle upon Tyne, United Kingdom
Jonathan Spiegel, Ruhr-University of Bochum, Germany
Multiscale Modelling of Fire Emergencies in a Transverse Ventilated Tunnel
Francesco Colella, Adriano Sciacovelli, Vittorio Verda, Romano Borchiellini,
DENERG, Politecnico di Torino, Italy
Guillermo Rein, Ricky Carvel, BRE Centre for Fire Safety Engineering, University of
Edinburgh, UK

Design Fires in Road Tunnels & the Impact on Ventilation Systems
Norman Rhodes, Kirit Kottam and David Hartman, Hatch Mott MacDonald, USA

Theoretical Analysis on Longitudinal Tunnel Ventilation in Fire Emergency
Qihui Zhang, Attilio Canfora, Eugenio Trussoni, Giuseppe Astore, Shulin Xu and
Piergiorgio Grasso, GEODATA Engineering SpA, Italy

The Influence of Blockages on Backlayering in Tunnel Fires: A Numerical Study
Ricky Carvel, David Bishop & Stephen Welch, University of Edinburgh, UK

Design, Simulations and Implementation of Ventilation System for Metro Line 9, at Barcelona
City in Spain
Ana M. Ruiz-Jimenez & A. Matas, TD&T S.L., Spain

The Dynamics of Tunnel Ventilation and Fire Development
Yajue Wu, Sheffield University, UK

The Importance of Exit Spacing to the Choice of Tunnel Ventilation System
Paul Williams, Norman Disney & Young, New Zealand
VOLUME 2

FIRE DYNAMICS

Rickard Hansen, Mälardalen University, Sweden

Large Scale Fire Tests for the “Calle 30 Project”
Fernández, S., FFII - CEMIM. Madrid, Spain.
Del Rey, I., ETSII-Universidad Politécnica de Madrid, Spain
Grande, A., Espinosa, I., FFII - CEMIM. Madrid, Spain
Alarcón, E., ETSII-Universidad Politécnica de Madrid, Spain

Experimental Study on Burning Rate in a Full-Scale Train Model
Shaohua Mao, Yuanzhou Li, Haobo Wang, Shi Zhu, Ran Huo, University of Science and Technology of China, China,

Large-scale Commuter Train Fire Tests – Results from the METRO Project
Anders Lönnemark, Johan Lindström, Ying Zhen Li and Haukur Ingason, SP Technical Research Institute of Sweden, Sweden
Mia Kumm, Mälardalen University, Sweden

Full-scale Experiments for Heat Release Rate Measurements of Railcar Fires
George Hadjisophocleous, Carleton University, Canada
Duck Hee Lee and Won Hee Park, Korea Railroad Research Institute, Korea

RISK & COST BENEFIT ANALYSIS

On Bayesian Probabilistic Networks for Risk Analysis of Road Tunnels
Rune Brandt, HBI Haerter, Switzerland
Niels Peter Høj, HOJ Consulting, Switzerland
Matthias Schubert, Matrisk, Switzerland

Assessment model for the transport of dangerous goods through road tunnels
Mirjam Nelisse and Ton Vrouwenvelder, TNO, the Netherlands

Fire Ventilation Upgrades: Can a retrofit be detrimental to Fire Life Safety?
Sam Hoffman, Daniel McKinney and Bruce Dandie, AECOM Technical Services, Inc., USA

Risk Framework – Methodology for Tunnel
Jimmy Jönsson, Arup Fire, Spain
Peter Johnson, Arup Fire, Australia

Fixed Fire Fighting Systems for Tunnels – SOLIT2 Research Project
Max Lakkonen, FOGTEC Fire Protection, Germany

Effectiveness Analysis of a Fire Detection System Config-ured as a Multi-Function Portal Aimed at Protecting Railway Tunnels
Marco Cigolini, RFI spa, Italy
<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk-based Evaluation of Longitudinal Ventilation with Enhanced Safety Concept</td>
<td>527</td>
</tr>
<tr>
<td>Göran Nygren, Johan Lundin and Per-Olof Jönsson, WSP, Sweden</td>
<td></td>
</tr>
<tr>
<td>Assessing Fire Development Risk in Rail Vehicles and the Impacts on Tunnel Infrastructure</td>
<td>437</td>
</tr>
<tr>
<td>Jarrod Alston &amp; Kurt Schebel, Arup, USA</td>
<td></td>
</tr>
<tr>
<td>Brian Meacham, Worcester Polytechnic Institute, USA</td>
<td></td>
</tr>
<tr>
<td>Andrew Coles, Sereca, Canada</td>
<td></td>
</tr>
<tr>
<td>Optimization of Measures Directed on the People Safety at Tunnel Fire by Means of Computational Methods</td>
<td>547</td>
</tr>
<tr>
<td>Karpov A.V., Khasanov I.R., Kopylov N.P., Ushakov D.V., All-Russian Research Institute For Fire Protection (VNIIPo), Russia</td>
<td></td>
</tr>
<tr>
<td>DECISION SUPPORT &amp; OPERATION</td>
<td></td>
</tr>
<tr>
<td>Decision Support System for Emergencies in Road Tunnels</td>
<td>557</td>
</tr>
<tr>
<td>Jorge A. Capote, Daniel Alvear, Orlando Abreu, Arturo Cuesta, Virginia Alonso, University of Cantabria, Spain</td>
<td></td>
</tr>
<tr>
<td>Brisbane’s Busway Network – Twelve Years of Designing and Operating Safe Tunnels</td>
<td>567</td>
</tr>
<tr>
<td>Nick Agnew, Stacey Agnew Pty Ltd, Australia</td>
<td></td>
</tr>
<tr>
<td>Matthew Bilson, Parsons Brinckerhoff, Australia</td>
<td></td>
</tr>
<tr>
<td>Ray Donato, Donato Consultancy, Australia</td>
<td></td>
</tr>
<tr>
<td>The Use of Traffic Flow Predictions to Enhance Tunnel Safety</td>
<td>577</td>
</tr>
<tr>
<td>Tomas Julner, Swedish Transport Administration, Sweden</td>
<td></td>
</tr>
<tr>
<td>Safety in Swedish Railway Tunnels</td>
<td>585</td>
</tr>
<tr>
<td>Per Vedin and Peter Lundman, Swedish Transport Administration, Sweden</td>
<td></td>
</tr>
<tr>
<td>On the Power of Simulation and the Need for Experimental Validation</td>
<td>593</td>
</tr>
<tr>
<td>Marco Bettelini, Amberg Engineering Ltd., Switzerland</td>
<td></td>
</tr>
<tr>
<td>Max Wietek, VSH Hagerbach Test Gallery Ltd., Switzerland</td>
<td></td>
</tr>
<tr>
<td>DESIGN FIRES</td>
<td></td>
</tr>
<tr>
<td>New Concept for Design Fires in Tunnels</td>
<td>603</td>
</tr>
<tr>
<td>Haukur Ingason, Ying Zhen Li, SP Technical Research Institute of Sweden, Sweden</td>
<td></td>
</tr>
<tr>
<td>Fine Water Spray Tunnel Fire Protection from Fixed Installed Systems</td>
<td>613</td>
</tr>
<tr>
<td>Carsten Palle, VID Fire-Kill, Denmark</td>
<td></td>
</tr>
<tr>
<td>HUMAN BEHAVIOUR &amp; EVACUATION</td>
<td></td>
</tr>
<tr>
<td>Taking Advantage of Theories and Models on Human Behaviour in the Fire Safety Design of Underground Transportation Systems</td>
<td>619</td>
</tr>
<tr>
<td>Karl Fridolf, Daniel Nilsson and Håkan Frantzich, Lund University, Sweden</td>
<td></td>
</tr>
<tr>
<td>Ways of Improvements in Quantitative Risk Analyses by Application of a Linear Evacuation Module and Interpolation Strategies</td>
<td>627</td>
</tr>
<tr>
<td>Christoph Forster, Bernhard Kohl, ILF Consulting Engineers, Austria</td>
<td></td>
</tr>
</tbody>
</table>
Topic E - ERRA A5: Evacuation of a complex underground facility
Maximilian Wietek, VSH Hagerbach Test Gallery Ltd., Switzerland
Jonatan Hugosson, SP Technical Research Institute of Sweden, Sweden
Frank Leismann, STUVA, Germany
Fabien Fouillen, INERIS, France

Design of Voice Alarm Systems for Traffic Tunnels: Optimisation of Speech Intelligibility
Evert Start, Duran Audio BV, The Netherlands

Emergency Escape and Evacuation Simulation in Rail Tunnels
Marco Bettelini & Samuel Rigert, Amberg Engineering Ltd., Switzerland

Experiment for Behavior Estimation in the Egress Using Electronic Eevices in the SAVE ME Project
Stefano Marsella, Corpo Nazionale dei Vigili del Fuoco, Italy
Jan-Paul Leuteritz, University of Stuttgart, Germany
Francesco Tesauri, University of Modena and Reggio Emilia, Italy
Uberto Delprato, IES Solutions, Italy

French Initiative to Implement PIARC’s Recommendations Regarding HGV Driver Training in France
Marc Tesson, Véronique Aurand & Bertrand Perrin, CETU, France

PASSIVE FIRE PROTECTION

Quantification of Fire Damage of Concrete for Tunnel Applications
Joakim Albrektsson, Robert Jansson, Mathias Flansbjer, SP Technical Research Institute of Sweden, Sweden
Jan Erik Lindqvist, CBI Swedish Cement and Concrete Research Institute, Sweden

Submerged Floating Tunnels, a New Tunnel Concept, Creating New Challenges in Tunnel Safety and Security
Lidvard Skorpa, Norwegian Public Roads Administration, Norway

Mobile Furnace for Determining Spalling Sensitivity of Existing Concrete Tunnel Linings
Martin Vermeer, Arnoud Breunese & Leander Noordijk, Efectis Nederland BV, The Netherlands

Temperature Loads and Passive Protection in Structural Tunnels
Stefan Zmigrodzki, CIMA+ Consulting Engineers, Canada

Test Methods for Determining Fire Spalling of Concrete
Lars Bostrom, Robert Jansson, SP Technical Research Institute of Sweden, Sweden

Assessing the Fire Resistance in Existing Tunnels
Leander Noordijk, Tim van der Waart & George Scholten, Efectis Nederland BV, The Netherlands
Coen van der Vliet, ARCADIS Nederland BV, The Netherlands
POSTERS

Rockdrain – a Novel System for Water Drainage, Insulation and Fire Protection for Tunnels
Lars Boström, SP Technical Research Institute of Sweden, Sweden
Robert Melander, Cathrine Ewertson, CBI Swedish Cement and Research Institute, Sweden

Crossrail Fire Safety Designs
Iain Bowman, David Eckford & Holy Liang, Mott Macdonald Limited, United Kingdom

Automatic Fire Suppression in Tunnels with Stationary Compressed Air Foam Extinguishing Systems (CAFS)
Axel Jaeger, Thorsten Behnke & Franziska Freudenberger, One Seven of Germany GmbH, Germany

Concept of Cost Effective Modernization of Old Single-tube Road Tunnels
Case Study: Učka Tunnel
Miodrag Drakulić, Mladen Lozica, CTP PROJEKT Ltd. Croatia

Carmel Tunnels – Case Study and project profile
Fire alarm & voice evacuation system
Eliezer Ezra, G4S, Israel

Analysis of Tunnel Fires over Twenty Years
Peter Schenkenhofer, LISTEC GmbH, Germany

FFFS for Flammable Liquid Fires in Road Tunnels
Kenneth J. Harris & Bobby J. Melvin, Parsons Brinckerhoff, USA

Commissioning of Performance Based Fire Systems
Charles Kilfoil, USA

Prediction of the Temperature Evolution in a Tunnel Construction in Case of Fire, by Coupling the Temperature-Dependent Heat Transfer Mechanisms Inside the Structural Components and at their Surface
Christian Knaust, Andreas Rogge, BAM Federal Institute for Materials Research and Testing, Germany

Active Open-Area Smoke Imaging Detection
Ron Knox, Xtralis, Australia

Emergency Egress Corridor Evacuation Analysis –Virginia Elizabeth River Midtown Tunnel
Praveen Kumar & Norris Harvey, Parsons Brinckerhoff, USA

Continuous Emergency Egress Corridor Pressurization Along a Tunnel Ventilated by Jet Fans
Andrew Louie, Norris Harvey, Parsons Brinckerhoff, USA

Design Loads and Methods for Prestressed Open Cut Tunnels under Severe Accidental and Malicious Threats –Fire
Frank Lukaschek, Ingo Müllers, Assad Nawabi; Schüßler-Plan Ingenieurgesellschaft mbH, Germany, BRS-Design, Germany
Markus Nöldgen, Cologne University of Applied Science, CUAS, Germany
Numerical Predictions of Blast Waves Caused by Accidental or Intentional Detonations of Gaseous and Condensed Explosives in 3D Complex Geometries.
Christophe Matignon, Jean-Yves Vinçon, CEA, DAM, DIF, France
Sébastien Eveillard, CEA, DAM, DIF, France, PNRI, France

Model Scale Fire Tests in a Highly Inclined Tunnel
Hans Nyman, Brandskyddslaget, Sweden
Haukur Ingason, SP Technical Research Institute of Sweden, Sweden

Challenges and Consequences in Designing for Underground Station Fire Events in the Post 9/11 World
Marc Morgan, & Ian Ong, Hatch Mott MacDonald, USA
Thomas Eng, Los Angeles County Metro, USA

Design, Simulations and Implementation of Ventilation System for Metro Line 12 at Mexico D.F.
Ana M. Ruiz-Jimenez & E. Barrio, TD&T S.L., Spain

Fire Resistance of Smoke Control Air Outlets in Tunnel Constructions
Nikolay D. Solntsev, Boris B. Serkov, Academy of the Ministry of the Russian Federation for Civil Defence, Emergency Management and Natural Disasters Response, Russia

Towards 1D/3D Coupling for Fire and Ventilation Modelling in Large Underground Infrastructures?
Benjamin Truchot, Stéphane Duplantier, INERIS, France
Methodologies for calculating the overall heat release rate of a vehicle in an underground structure.

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KEYWORDS: Heat release rate, critical heat flux, vehicle fire, tunnel, underground structure

INTRODUCTION
Most common type of object involved in fires in underground structures such as underground mines is vehicles [1-3]. A major concern is the lack of documented fire experiments in vehicles/mobile equipment, which is especially the case for working vehicles such as loaders, drilling rigs etc. The resulting heat release rate (HRR) curves are essential knowledge when designing new tunnel or mine sections and overlooking existing sections, thus there is a great need for HRR curves. This paper encompasses the measurement of the HRR for two full-scale fire experiments with vehicles representative for underground structures and the reconstruction of the measured HRR by investigating what methodology that fits the measured values best. The main purpose of the methodologies is to provide HRR curves without having to perform full-scale fire tests of the vehicles, which would be of considerable value.

INVESTIGATED METHODOLOGIES
This paper describes the application of potential methodologies to calculate the overall HRR of a vehicle in a tunnel or in an underground structure. The methodologies basically sum up the individual HRR curves from each object of the vehicle by estimate when ignition between objects occurs. The HRR for each object is represented by an exponential function of time. The exponential curves used originate from the work by Numajiri and Furukawa [4]. Ingason [5] [6] has further developed the concept and introduced the design parameters: maximum HRR ($Q_{\text{max}}$), total energy content ($E_{\text{tot}}$) and the retard index ($n$), which is an arbitrarily chosen parameter with no physical meaning. Based on these parameters the time to maximum HRR ($t_{\text{max}}$) and the fire duration ($\tau$) can be calculated. Other parameters that are used in the model include the amplitude coefficient ($r$) and the time width coefficient ($k$), which are calculated based on the information given. The choice of methodology will vary depending upon what ignition criterion that is used - either a critical heat flux or an ignition temperature – and whether longitudinal ventilation is present or not. In this paper the critical heat flux ignition criterion is used for a case with longitudinal ventilation (where the heat transfer mechanism includes radiation as well as convection) and a case without longitudinal ventilation (where the primary heat transfer mechanism is radiation). The results are validated against experimental data obtained from two full-scale experiments. More detailed information on the methodologies can be found in Hansen and Ingason [7] [8].

DRILLING RIG FIRE
The site of the full-scale fire experiments was the underground mine of Björka Mineral AB on the outskirts of Sala, Sweden. The drilling rig in question was an Atlas Copco Rocket Boomer 322. The initial fire consisted of a diesel pool fire in a circular container with a diameter of 1 m, placed right beside the rear tyres. A longitudinal ventilation velocity was established in the mine drift throughout the entire experiment. During the fire experiment it was observed that after approximately two minutes both rear tyres are ignited and the fire is spread further to hydraulic hoses and electrical cables in the...
rear, upper part. Within the first ten minutes the cab is fully engulfed in flames and after approximately 12 minutes the right, forward tyre is ignited. It is assumed that the left, forward tyre is ignited at about the same time.

Figure 1. The Rocket Boomer 322 drilling rig. Photo: Andreas Fransson.

The burn off time of the diesel pool fire was calculated to ~17 minutes. Assuming a maximum HRR per unit area of 1.33 MW/m² the maximum HRR of the diesel pool fire was calculated to 1.04 MW. The peak HRR was assumed to occur after ~8 minutes and the heat release rate was constructed based upon the peak value data and energy content:

\[ \dot{Q} = 1040 \cdot 3.1 \cdot 2.26 \cdot (1 - e^{-0.0022t})^{2.1} \cdot e^{-0.0022t} \text{ [kW]} \] (1)

When calculating the maximum HRR of the fire in the tyre, a maximum HRR per exposed surface area – presented by Ingason [9] - of 0.20 MW/m² was used. The total outer surface of each drilling rig tyre was calculated to approximately 3 m². Assuming that the longitudinal ventilation velocity would increase the maximum HRR with a factor 2 [10] as the tyre thread was relatively deep, the maximum HRR of each drilling rig tyre was calculated to 1.5 MW. In an earlier tyre fire experiment the maximum HRR occurred after approximately 30 minutes [11], but due to the longitudinal ventilation – leading to faster fire behaviour - the maximum HRR was assumed to occur after 10 minutes instead when studying the HRR curves by Lönnermark and Ingason [10]. The energy content of each tyre was estimated at ~1050 MJ, which was obtained by multiplying the weight of the tyre with its heat of combustion value, resulting in the following HRR curve:

\[ \dot{Q} = 1500 \cdot 9 \cdot 2.56 \cdot (1 - e^{-0.00366t})^{8} \cdot e^{-0.00366t} \text{ [kW]} \] (2)

Based upon the visual observations the rear tyres are assumed to be ignited 2 minutes after the start of the diesel pool fire.

Underneath the drilling rig the fire gases and the flames from the pool fire and the fires in the tyres will be pushed along the bottom of the drilling rig towards the front tyres. Using a critical heat flux as ignition criterion for the front tyres and using the following expression for the incident heat flux, average gas temperature and average temperature at the fire [12]:

\[ \dot{q}_{flux}^* = h_c (T_{avg} - T_a) + F \cdot \varepsilon \cdot \sigma (T_{avg}^4 - T_a^4) \text{ [kW/m²]} \] (3)
Where:

\( h_c \) is the convective heat loss coefficient [kW/m\(^2\)-K]
\( T_{avg} \) is the average gas temperature [K]
\( T_a \) is the ambient temperature [K]
\( F \) is the view factor
\( \varepsilon \) is the emissivity factor
\( \sigma \) is the Stefan-Boltzmann constant, \( 5.67 \times 10^{-11} \) kW/m\(^2\)-K\(^4\)

\[
\frac{\Delta T_{avg}(x)}{\Delta T_f} = e^{\left(-\frac{h_c T_{avg} x}{\varepsilon \sigma} \right)} \tag{4}
\]

Where:

\( \Delta T_f = (T_f - T_a) \) is the average excess temperature at the fire location [K]
\( h \) is the lumped heat loss coefficient [kW/m\(^2\)-K]
\( P \) is the perimeter [m]
\( x \) is the location of interest [m]
\( \dot{m}_a \) is the massflow [kg/s]
\( c_p \) is the specific heat of air [kJ/kg-K]

\[ T_f = T_a + \frac{2}{3} \frac{\dot{Q}}{\dot{m}_a c_p} \] [K] \tag{5}

In the calculations only the massflow in the lower region of the drift was accounted for (i.e., up to the bottom of the vehicle, ~0.3 m), as the total massflow would lead to too low temperatures and heat fluxes but only using the segment underneath the vehicle would overestimate the heat flux as the bottom of the drilling rig is not entirely enclosed and thus fire gases will escape on the sides and delay the ignition of the front tyres. Assuming a critical heat flux of 17.1 kW/m\(^2\) [13] - which applies to natural rubber — the time of ignition of the front tyres was calculated to approximately 10 minutes, which is fairly closed to the visually observed 12 minutes.

The cab is assumed to be ignited mainly due to the flame radiation from the rear tyres, as the cab will protect the interior from the convective flow. The delay of ignition due to the influence of the windows was not accounted for in the calculations. Applying Heskestad flame height correlation [14] for the tyre fires:

\[ L_f = 0.235 \cdot \dot{Q}^{2/5} - 1.02 \cdot D \] [m] \tag{6}

Where:

\( D \) is the diameter of the fire [m]

When calculating the incident radiant heat flux to the cab interior from the flames it is assumed that the boundaries of the flames of a tyre fire have the shape of a rectangle.

\[ \dot{q}_{fire} = \frac{\dot{Q}_{rad}}{2 \cdot (A_{width} + A_{depth})} \cdot F \cdot \tau \] [kW/m\(^2\)] \tag{7}

Where:

\( A_{width} \) is the area of the flame along the full width of the tyre [m\(^2\)]
\( A_{\text{depth}} \) is the area of the flame along the side of the tyre [m²]
\( \tau \) is the atmospheric transmissivity, assumed to be 1

The distance between the tyres and the cab interior was estimated to \( \sim 1.8 \) m. Assuming a critical heat flux of 1.3 kW/m² for the cab interior – which was obtained through cone calorimeter tests – the ignition of the cab was calculated to occur after approximately 9 minutes. The average HRR per unit area of the cab interior was measured to 158 kW/m² and the duration of the cab fire was estimated to approximately 10 minutes based upon the results from cone calorimeter tests. The surface of the flammable surfaces in the cab interior was estimated to 7 m². The maximum HRR of the cab interior was calculated to 1106 kW and assumed to occur 5 minutes after ignition of the cab interior.

\[
\dot{Q} = 1106 \cdot 3.1 \cdot 2.26 \cdot (1 - e^{-0.00377t})^8 \cdot e^{-0.00377t} \quad \text{[kW]} \quad (8)
\]

Approximately 300 meters of electrical cable participated in the fire, with an average outer diameter of 25 mm. The electrical cables were assumed - for simplifying the calculations – to be uniformly distributed along the body of the vehicle. Using the results of a report by Axelsson et al. [15] the flame spread along the electrical cables was estimated to \( \sim 2 \) mm/s, applicable to a horizontal fire scenario with a longitudinal ventilation velocity of 0.6-0.7 m/s (assuming that the cable fires will be shielded by the vehicle construction) and a mixture of halogen and halogen free cables. Using the results of cone calorimeter experiments the average HRR per unit area was set to 190 kW/m² and the fire duration to \( \sim 10 \) minutes – i.e. the fire duration of a small segment of electrical cable; the addition of all cable segments would lead to the overall fire duration of the cable fires. The electrical cables are assumed to ignite as the rear tyres are ignited. The fire is assumed to start in one cable, after one minute doubling the amount of cables on fire, after two minutes doubling yet again the amount of cables on fire etc. The maximum value of 1100 kW is assumed to occur approximately 20 minutes after the ignition of the electrical cable (i.e. when the fire has reached the maximum amount of fuel surface being burned).

\[
\dot{Q} = 1100 \cdot 3.3 \cdot 2.29 \cdot (1 - e^{-0.000994t})^{2.3} \cdot e^{-0.000994t} \quad \text{[kW]} \quad (9)
\]

The hydraulic hoses and the hydraulic oil inside the hoses are assumed to ignite at the rear tyres at the time of ignition of the tyres. One hydraulic hose is assumed to be ignited first and after each minute doubling the amount of hoses that are on fire. The total length of the hydraulic hoses on the drilling rig is approximately 900 meters, the hydraulic hoses have an average outer diameter of 22 mm and the amount of hydraulic oil per meter hose is 0.17 litres. The fire in the hoses is regarded as a continuous line fire along uniformly distributed hoses. No applicable flame spread data for the hydraulic hose was found during a search, but when studying pictures from the experiment it was estimated that the fire in the hoses reached the waist after approximately 6 minutes and resulting in an approximate flame spread velocity of 7 mm/s. Using the flame spread velocity, the average HRR per unit area of 152 kW/m² and fire duration time of \( \sim 8.5 \) minutes based upon the results from the cone calorimeter experiments and assuming that the duration of the fire in the hydraulic oil is the same as for the hose, the maximum HRR was estimated to 10220 kW and to occur approximately 20 minutes after the ignition of the hydraulic hose (same as for the electrical cable fire). Using the data above, excluding the hydraulic hoses in the forward part of the boom that did not participate in the fire, the HRR of the fire in the hydraulic hoses and the hydraulic oil within the hose was reconstructed.

\[
\dot{Q} = 10220 \cdot 15.9 \cdot 2.63 \cdot (1 - e^{-0.0023t})^{14.9} \cdot e^{-0.0023t} \quad \text{[kW]} \quad (10)
\]

The hydraulic oil tank will be emptied when a suction hose burns off. The tank is situated right behind the waist and a hose is assumed to burn off 8.5 minutes after the fire reaches the waist (i.e. the fire duration time of the hydraulic hose) and a pool fire is started. The inner diameter of the hose is 12 mm. Calculating the flow rate through the hose (assuming an initial liquid height of 0.7 m in the tank) using an expression by Ingason [16]:

422
\[ q = 2000 \cdot A_T \cdot k \cdot \left( \sqrt{h_i} - k \cdot t \right) \quad \text{[l/s]} \quad (11) \]

\[ k = \frac{C_v \cdot \pi \cdot D^2 \cdot \sqrt{2g}}{8 \cdot A_T} \quad (12) \]

Where:
- \( A_T \) is the horizontal surface area (m²), is assumed to be 0.8 m²
- \( D \) is the hole diameter (m)
- \( h_i \) is the initial height of fluid (m)
- \( C_v \) is the flow contraction coefficient, is set to 0.7

Assuming a thick fuel bed – as the uneven structure of the road will form deep puddles - a HRR per unit area of 2.2 MW/m² is used [17]. The regression rate of the thick fuel bed is then calculated to 0.051 kg/s·m². Calculating the maximum spillage area using an expression by Ingason [16]:

\[ A_{\text{max}} = \frac{q \cdot \rho}{1000 \cdot \dot{m}^*} \quad \text{[m}^2\text{]} \quad (13) \]

Where:
- \( \rho \) is the density of fluid (kg/m³)
- \( \dot{m}^* \) is the spillage burning rate (kg/s·m²), setting it at 0.051 kg/s·m²

The calculations resulted in an average maximum spillage area of ~3.5 m² and a maximum average HRR of 7.7 MW. The peak value was assumed to occur after ~5 minutes from the ignition of the pool.

\[ \dot{Q} = 7700 \cdot 1.53 \cdot 1.75 \cdot (1 - e^{-0.00118t})^{0.53} \cdot e^{-0.00118t} \quad \text{[kW]} \quad (14) \]

The remaining diesel in the tank was not assumed to have participated in the fire as the electrical valve on the tank was closed.

The resulting calculated HRR curve for the drilling rig together with the measured curve is shown in figure 2. As can be seen the calculated HRR curve matches the measured HRR curve very well. In both cases the total amount of energy – which was obtained by calculating the area underneath each curve – was ~31 GJ.

**BUS FIRE**

Hammarström et al. [18] presented HRR measurements of a Volvo bus for 49 passengers. The scenario was a fire in the engine compartment in the rear end of the bus. The fire source was a propane burner with a steady state HRR of 100 kW. The fire was free to develop into the passenger compartment and continue to the rest of the bus. Due to overflow in the measuring system the measurement had to be cancelled at the time 19 minutes and 12 MW. It was predicted that a HRR of 15-20 MW would occur after 20 minutes.
The initial phase of the bus fire took place in the rear compartment; a propane burner was placed in the compartment. After 8 minutes and 50 seconds from ignition the left side panel of the compartment – with an area of approximately 1 m² - fell off. When studying photographs taken at the experiment it can be seen that when the panel fell off a flashover occurred in the compartment with flames coming out from the opening. It can also be seen that fire gases at an early stage started to leak into the adjacent compartments and that flashover occurred in the centre compartments 20-30 seconds after the flashover in the rear compartment. It is assumed that the rear compartment encompassed a total fuel surface of approximately 7 m² and that the centre compartments encompassed a total fuel surface area of approximately 27 m² (the area of the panels were not included as the PVC flooring did not cover the panels). Using an average HRR per unit area of 130 kW/m² for the PVC flooring based upon the results of Johansson et al. [19] and assuming that after 8 minutes and 50 seconds after ignition 7 m² of PVC flooring and after 9 minutes and 15 seconds an additionally 27 m² of PVC flooring will participate in the fire, resulting in a HRR of 910 kW and 3510 kW respectively. The duration of the fire in the compartments was estimated to last for 16 minutes before decaying based upon the results from ISO 5660 tests. Verifying the above calculated HRR of the compartments with respect to the stoichiometric HRR [20]:

\[ \dot{Q}_{\text{stoichiometric}} = 1500 \cdot A_0 \cdot \sqrt{H_0} \quad \text{[kW]} \quad (15) \]

Where:
- \( A_0 \) is the opening area [m²]
- \( H_0 \) is the opening height [m]

The height of the panel of the rear compartment was estimated to 1 m and the area to 1 m², resulting in a stoichiometric HRR of 1500 kW. The height of the panel to the centre compartment – which was open during the entire test – was estimated to 0.5 m and the area to 2.5 m², resulting in a stoichiometric HRR of approximately 2700 kW. Thus the fire in the rear compartment was fuel controlled and set to 910 kW and the fire in the centre compartment was ventilation controlled and set to 2700 kW.

Resulting in the following heat release rate expressions:

\[ \dot{Q}_{\text{rear}} = 910 \cdot 3.16 \cdot 2.27 \cdot (1 - e^{-0.00236 \cdot t})^{2.16} \cdot e^{-0.00236 \cdot t} \quad \text{[kW]} \quad (16) \]
\[
Q_{\text{centre}} = 2700 \cdot (1.5 \cdot 1.654 \cdot (1-e^{-0.0004 \cdot r})^{0.5} \cdot e^{-0.0004 \cdot r} + 4.76 \cdot 1.53 \cdot (1-e^{-0.00028 \cdot r})^{3.76} \cdot e^{-0.00028 \cdot r}) \quad \text{[kW]} \quad (17)
\]

During the experiment the rear, left tyre was observed to be ignited after approximately 12 minutes from ignition and the right, rear tyre after approximately 14 minutes from ignition [18]. Using the tyre dimensions in question the maximum HRR of the fire in the tyre was calculated to ~0.43 MW and was assumed to be attained after approximately 30 minutes [11]. The weight of the tyre was estimated to ~57 kg. Using a heat of combustion of 27 MJ/kg [9], the energy content of a tyre is calculated to ~1.54 GJ. The HRR of the tyre results in the following expression:

\[
\dot{Q} = 430 \cdot 3.1 \cdot 2.26 \cdot (1-e^{-0.00063 \cdot r})^{2.1} \cdot e^{-0.00063 \cdot r} \quad \text{[kW]} \quad (18)
\]

The fire in the passenger compartment was regarded as an enclosure fire with some ventilation openings, i.e. front and middle door and eventually some windows that are broken. Thus the primary fire spread mechanism will be radiant heat transfer from the flames and the upper gas layer. The passenger compartment is simplified by assuming that it consists of thirteen rows of seats with four seats in each row and with an average distance of ~0.2 m between each row, wall panel of ABS plastic, PVC flooring and needle felt on the walls.

The critical heat flux of a bus seat is assumed to be 7.8 kW/m\(^2\) [21]. For simplicity it is assumed that when the row of seats are ignited the section of wall panel and flooring at the row is ignited as well, as the HRR of a row of seats is much higher than for the wall and flooring section.

A HRR curve – presented by Johansson and Axelsson [19] - was used for each bus seat. Reconstructing it mathematically – subtracting the 30 kW from the burner – resulting in the following expression:

\[
\dot{Q}_{\text{busseat}} = 232 \cdot 2.12 \cdot 2.04 \cdot (1-e^{-0.0075 \cdot r})^{1.12} \cdot e^{-0.0075 \cdot r} \quad \text{[kW]} \quad (19)
\]

The HRR per unit area of the ABS wall panel, PVC flooring and the needle felt was obtained through a report by Johansson and Axelsson [19]. Assuming that the fire environment of the passenger compartment is a two layer equivalent, the calculations of the total heat flux from the fire to adjacent seat rows are separated into two parts:

- Radiant heat flux to the seats from the upper gas layer.
- Radiant heat flux to the seats from the flames.

The two radiant heat fluxes are added to receive the total heat flux.

When calculating the radiant heat flux to the seats from the upper gas layer the following assumptions were made:

- All surfaces are grey, i.e. the emissivity – \(\varepsilon\) – is set to 0.9.
- The upper gas layer is gray and non-reflective, i.e. the emissivity of the upper gas layer – \(\varepsilon_g\) – is set to 0.19.
- The lower layer is transparent to thermal radiation.
- The ceiling and upper parts of the walls (above interface) are at the same temperature as the gas temperature.
- The radiation loss out doors and windows are ignored.

The radiant heat flux from the upper gas layer to the seats was calculated performing a network analysis.

The view factor – from interface plane to floor - is calculated assuming identical, parallel, directly opposed rectangles.

We are facing a pre-flashover situation, thus we will use the correlation of McCaffrey, Quintiere and Harkleroad (MQH) [22] in order to calculate the upper gas layer temperature, \(T_g\). The correlation assumes a two zone approximation (a hot zone with an upper, hot gas layer and fire plume and a cool zone with a lower, cool gas layer) and that the zones are uniform.
Assuming a two-layer ventilation flow and mass conservation, the position of the interface layer was calculated using the following expression for the mass flow rate of fire gases out from openings [22]:

$$\dot{m}_g = \frac{2}{3} \cdot C_d \cdot A_0 \cdot \sqrt{H_0} \cdot \rho_a \cdot \left[ 2 \cdot g \cdot \frac{T_a}{T_g} \cdot \left( 1 - \frac{T_a}{T_g} \right)^{1/2} \cdot \left( 1 - \frac{X_N}{H_0} \right)^{3/2} \right] \quad [kg/s] \quad (20)$$

Where:
- $C_d$ is the ventilation flow coefficient, which is set to 0.68
- $X_N$ is the neutral plane height [m]

Using the plume mass flow rate equation of McCaffrey for the plume region [23] as a near-field plume model would be applicable in this case (i.e. a large fire in a small compartment):

$$\dot{m}_p = 0.124 \cdot \dot{Q} \cdot \left( \frac{z}{\dot{Q}^{2/5}} \right)^{1.895} \quad [kg/s] \quad (21)$$

Where:
- $z$ is the interface height [m]

This leaves us with the following expression if assuming mass balance for the fire gas layer, where the interface height is solved by iteration:

$$0.124 \cdot \dot{Q} \cdot \left( \frac{z}{\dot{Q}^{2/5}} \right)^{1.895} = \frac{2}{3} \cdot C_d \cdot A_0 \cdot \sqrt{H_0} \cdot \rho_a \cdot \left[ 2 \cdot g \cdot \frac{T_a}{T_g} \cdot \left( 1 - \frac{T_a}{T_g} \right)^{1/2} \cdot \left( 1 - \frac{X_N}{H_0} \right)^{3/2} \right] \quad (22)$$

When calculating the incident radiant heat flux to the seats from the flames the same equation was used as for the cab fire in the case of the drilling rig. When calculating the flame area along the full width and on the sides of the seat row, the flame height was obtained through the McCaffrey correlation for the mean flame height [24]:

$$h_f = 2.3 \cdot D \cdot \left( \frac{\dot{Q}}{\rho_a \cdot c_p \cdot T_a \cdot g^{1/2} \cdot D^{5/2}} \right)^{2/5} \quad [m] \quad (23)$$

Using a spreadsheet when calculating the incident heat flux from the upper gas layer and the flames and assuming a depth of 0.4 m for each row, an effective width of 2 m and that both doors (height: 2 m and width: 1 m) and three windows (height: 1 m and width: 2.3 m) are open, the following matrix displays the ignition times of the various rows of bus seats (the rows are numbered starting with the row in the far back and the first row to be ignited is row number six):

<table>
<thead>
<tr>
<th>Row #</th>
<th>Ignition time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>315</td>
</tr>
<tr>
<td>2</td>
<td>273</td>
</tr>
<tr>
<td>3</td>
<td>225</td>
</tr>
<tr>
<td>4</td>
<td>169</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

*Table 1. The ignition times of the various rows of bus seats.*
The calculated maximum HRR of the passenger compartment was 20.4 MW. Verifying the calculated maximum HRR of the passenger compartment with respect to the stoichiometric HRR, results in a maximum HRR of approximately 20 MW. Thus the fire in the passenger compartment was during short interval ventilation controlled and the maximum HRR was adjusted in accordance to this.

![The calculated and the measured HRR curve of the bus fire experiment.](image)

**Figure 3.** The calculated and the measured HRR curve of the bus fire experiment.

The resulting calculated HRR curve for the bus together with the measured curve is shown in figure 4. As can be seen the calculated HRR curve matches the measured HRR curve very well up to the point where the experimental fire was extinguished. The calculated HRR was ~19 MW after 20 minutes, which is within the predicted interval of 15-20 MW.

**DISCUSSION**

The calculated HRR curve of the bus fire matches the measured HRR curve very well up to the point where the experimental fire was extinguished. The front tyres were not accounted for in the calculations and were not ignited during the full-scale experiment, it is unclear at what point the front tyres would ignite and if they would ignite at all. Also, other flammable components such as fluids and hoses were not accounted for in the calculations, but the calculated results manages to effectively match the measured results and is most likely due to the successful reconstruction of the compartments fire and foremost the passenger compartment fire which will clearly dominate the HRR curve.

The calculated HRR curve of the drilling rig matched the measured HRR curve very well and the energy contents of the two curves were almost identical. During the calculations it was noticed that the fire in the hydraulic hoses and the hydraulic oil clearly dominated appearance of the curve.

The results show the potential of the methodologies but additional tests will have to be made in order to be able to develop overall HRR curves for vehicles representative for underground structures, such as flame spread experiments along hydraulic hoses. The work also demonstrates that time observations, photos etc. from actual fires are valuable when developing a HRR curve for a vehicle. Additional work is also needed with respect to the influence of the construction of the vehicle in question - for example the time of failure of a component leading to the fire spread to an adjacent compartment or component – as this will greatly influence the ignition time of the individual components and thus also the overall
REFERENCES

Large Scale Fire Tests for the “Calle 30 Project”

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ABSTRACT

Between 2003 and 2007 an urban network of road tunnels with a total constructed tubes length of 45 km was built in the city of Madrid. This amazing engineering work, known as “Calle30 Project” counted with different kinds of tunnel typologies and ventilation systems. Due to the length of the tunnels and the impact of the work itself, the tunnels were endowed with a great variety of installations to provide the maximum levels of safety both for users and the infrastructure including, in some parts of the tunnel, fixed fire fighting system based on water mist.

Within this framework a large-scale campaign of fire tests were planned to study different aspects related to fire safety in the tunnels including the phenomena of the interaction between ventilation and extinction system. In addition, this large scale fire tests allowed fire brigades of the city of Madrid an opportunity to define operational procedures for specific fire fighting in tunnels and evaluate the possibilities of fixed fire fighting systems. The tests were carried out in the Center of Experimentation "San Pedro of Anes" which counts with a 600 m tunnel with a removable false ceiling for reproducing different ceiling heights and ventilation conditions (transverse and longitudinal ones).

Interesting conclusions on the interaction of ventilation and water mist systems were obtained but also on other aspects including performance of water mist system in terms of reduction of gas temperatures or visibility conditions.

This paper presents a description of the test’s campaign carried out and some previous results obtained.

KEYWORDS: Tunnel, fire, temperature, ventilation, visibility, water mist

INTRODUCTION

Fires occurred in tunnels around the world in the last decades started to raise questions about safety matters in these infrastructures.

Between 2003 and 2007 a total tunnel length of 45 km was built in Madrid. This amazing engineering work, known as “Calle30 Project” counted with different kinds of tunnel typologies and ventilation systems. Due to the length of the tunnels (the largest one up to 4.5 km) and the impact of the work itself, the tunnels were endowed with as many installations as possible to try to ensure the users and the infrastructure’s safety; including in some parts of the tunnel, an extinction system based on water mist, to enhance the structural fire resistance.

Inside the set of actions to improve the safety levels for the tunnels of the “Calle30 Project”, it was developed a large-scale campaign tests to reproduce the events of fire, to study the phenomena of the interaction between ventilation and extinction system and to propose criteria of action to improve the safety of the users.

The tests were carried out in the Center of Experimentation "San Pedro of Anes" located at 22 km from Oviedo and 15 km from Gijon, in Asturias (Spain). The Center, with an approximately surface of 142,000 m², located at the San's Pedro former station, counts with a 600 m tunnel with a removable false ceiling for reproducing different ceiling heights and ventilation conditions (transverse and longitudinal).
The tunnel is built in concrete, with dimensions equivalent to a two-lane road tunnel. Two ventilation stations, a lower gallery for emergency and services, and three emergency exits are available.

According with the requirements for the ventilation system of the Calle30 tunnels; an exhaust system on 450 m duct with dampers 20 meters apart and an extraction air flow rate of 160 m³/s was used. In addition, 6 jet fans were installed to allow the control of the longitudinal air current, so that the system should be able of achieve a longitudinal air velocity of 4 m/s (independently of the fire HRR tested).

The water mist system used in the tests was a deluge system consisting of open spray heads, divided in sections controlled by a sectional control valve, so that when a section valve was opened all the spray heads in the relevant section started the water discharge.

The aspects evaluated during the tests, related with the ventilation and the water mist system, were:

- Evaluation of the effect of the longitudinal ventilation velocity on the performance of the water mist system.
- Evaluation of the performance of the water mist system with fires up to 30 MW of Heat Release Rate (HRR).
- Evaluation of the ability of the water mist system to reduce the gas temperatures at the ceiling and at lower elevations, to limit damage to the tunnel lining and to prevent the fire propagation.

The tests carried out during the first part of the campaign are summarized in the next table.
<table>
<thead>
<tr>
<th>Test id</th>
<th>Cargo</th>
<th>Ventilation strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>336 wood pallets &amp; 5 cars</td>
<td>Longitudinal ventilation with 1 jet fan</td>
</tr>
<tr>
<td>2</td>
<td>144 wood pallets &amp; diesel burner</td>
<td>Exhaust ventilation with 2 fans</td>
</tr>
<tr>
<td>3</td>
<td>144 wood pallets &amp; diesel burner</td>
<td>Exhaust ventilation with 1 fan</td>
</tr>
<tr>
<td>4</td>
<td>120 wood pallets &amp; diesel burner</td>
<td>Exhaust ventilation with 2 fans</td>
</tr>
<tr>
<td>5</td>
<td>24 wood pallets &amp; 3 cars</td>
<td>Exhaust ventilation with 1 fan</td>
</tr>
<tr>
<td>6</td>
<td>336 wood pallets &amp; 5 cars</td>
<td>Longitudinal ventilation with 1 jet fan</td>
</tr>
<tr>
<td>7</td>
<td>3 cars</td>
<td>Longitudinal ventilation with 3 jet fans &amp; exhaust ventilation with 2 fans</td>
</tr>
<tr>
<td>8</td>
<td>3 cars</td>
<td>Longitudinal ventilation with 2 jet fans &amp; exhaust ventilation with 2 fans</td>
</tr>
<tr>
<td>9</td>
<td>280 wood pallets</td>
<td>Longitudinal ventilation with 1 jet fan</td>
</tr>
<tr>
<td>10</td>
<td>120 wood pallets &amp; diesel burner</td>
<td>Exhaust ventilation with 2 fans</td>
</tr>
<tr>
<td>11</td>
<td>120 wood pallets &amp; diesel burner</td>
<td>Longitudinal ventilation with 3 jet fans &amp; exhaust ventilation with 1 fan</td>
</tr>
</tbody>
</table>

Table 1  Tests carried out during the first part of the campaign.

In the next sections, this paper gathers the information, description and results, related with the two first tests presented in the table above, one with longitudinal ventilation (labeled as “Test 1”) and the other with transverse one (labeled as “Test 2”).

TEST’S DESCRIPTION

Cargo’s description

In both tests standard European wood pallets (“euro-pallets”), in “dry” condition, were used. Each pallet was 120 cm x 80 cm x 14.4 cm high, with an average weight of 23.9 kg.

The wood pallets were arranged in stacks, placed on an elevated platform of unburned wet wood pallets topped by a sheet of gypsum board (around 120 cm above the road’s surface).

The stacks of pallets were placed in pairs with the long dimension so that the total width of the cargo was approximately 250 cm and leaving a clear height of approximately 190 cm to the ceiling.

The cargo was ignited with pans of 35 cm diameter, fitted between the wood pallets in the up-wind pair of stacks, with one liter of petrol in each pan (a torch was used to reach into the stack to ignite the petrol).

Due to the slow-growing phase expected, in test 2 a diesel burner was used to “simulate” a vehicle in motion with fire (figure 3). In addition five used cars with the windows broken and the gas tank emptied were involved too as targets and fire loads.

Figure 3  Cargo: “Euro-pallet” stacks’ arrangement, diesel burner and cars

Water mist system’s description

The deluge water mist system consisted on open spray heads along approximately 75 m, divided in three sections of nozzles controlled by a sectional control valve.
Each of the sections consisted of 3 parallel lines spaced between 3.0 m and 3.5 m, with six 6 nozzles spaced around 4 m. Each section of 18 nozzles covered around 24 m of tunnel length. When a section valve was opened all the spray heads in the relevant section started the water discharge with an approximated density of 0.7 l/min/m³.

Figure 4 Water mist system

Measurements

Temperature, air velocity and smoke movement were measured during the tests according to:
1. Near the fire: (around 50 m upstream and downstream) (figure 5)
   • Thermocouples type K in the centerline of the tunnel ceiling, spaced every 5 m and installed 3 to 10 cm below the concrete ceiling (to study the heat load on the structure).
   • Thermocouples type K installed in 4 cross sections of the tunnel at 3 different heights, 2 of the sections at around ±30 m from the fire pace (F1 and F2) and 2 at around ± 45 m (T1 and T2).

Figure 5 Sketch of instrumentation near the fire place

2. Apart from the fire: (100 m and 150 m upstream and downstream) (figure 6)
   • Thermocouples type K (chrome- aluminum) and bi-directional velocity probes to measure the air velocity through the cross-section of the tunnel; installed in 4 cross sections at 6 different heights.
   • Black-white visibility posts every 20 m to study the smoke movement and the thickness of the smoke layer.
   • CCTV system with cameras every 40 m.
3. CO and O2 analyzers were used to estimate a HRR value for longitudinal ventilation tests. A simplified equation was used [2] that neglects the effect of $X_{\text{H2O}}^0$ and $X_{\text{CO2}}^0$, and assumes that the inflowing gases are at ambient as well as the corrections due to CO$_2$ production in the fire (Eq. (1)).

$$HRR = \frac{E \cdot \phi}{1 + \phi \cdot (\alpha - 1)} \cdot \dot{m}_{\text{e}} \cdot \frac{M_{\text{O2}}}{M_{\text{a}}} \cdot X_{\text{O2}}^0$$

(1)

The CO and O2 analyzers were installed only in the tunnel’s section at north portal; but not in the false ceiling (as shown in figure 7).

**RESULTS**

For the correct interpretation of the presented results some aspects must be taken into account:

- Temperatures at 30 m and 45 m upstream and downstream the fire are given at 3 different heights (1.5 m, 3.4 m and 5.2 m)
- Temperatures at 100 m and 150 m upstream and downstream the fire are given at 6 different heights (0.6 m, 1.2 m, 2 m, 2.6, 3.3 m and 4 m).
- In all the graphs “S” stands for “south” and it applies to measurements taken upstream of the fire and “N” stands for “north” and it applies to measurements taken downstream.
- Positive values of air velocity correspond to flow from the south to the north portal.
Table 2  Tests description

Results from test 1

The evolution of the longitudinal ventilation, under forced ventilation of one of the jet fans installed in the tunnel is shown in figure 8. It can be seen how this constant longitudinal air flow is affected by the blocking effect of the fire by lowering the air velocity.

Figure 8  Longitudinal air velocities in the tunnel. Test 1

From the CO and O₂ measurements and using Eq. (1) a maximum HRR of around 18 MW was obtained during the test (figure 9).

Figure 9  HRR for Test 1
Under these circumstances, the temperatures measured around the fire at the ceiling (figure 10) and at 30 m and 45 m upstream and downstream (figure 11) are represented. When the water mist system was turned on, the temperatures fell down significantly; decreasing ceiling’s temperatures from 590ºC to 44ºC.

This gives an idea of how the system is able to control the fire and to reduce the gas temperatures, but not to completely suppress the fire since once the water mist system was turned off the temperatures started to raise.

In figure 12, the reduction of gas temperatures is shown at 100 m and 150 m downstream the fire. Upstream temperatures were not affected due to the longitudinal ventilation which avoided backlayering effects as this test had (for a tunnel of these characteristics and a fire of 18 MW the critical velocity should be around 2 m/s, calculated by Kennedy Model).

During test 1, visibility conditions downstream of the fire were very poor.
Results from test 2

Figure 13 shows the evolution of air velocity at both sides of the fire location. It can be seen, that after the activation of the exhaust fans, the air velocity downstream was around -2.0 m/s and upstream 1.4 m/s.

Figure 13 Air velocities in the tunnel. Test 2

Figure 14 shows the movement and the thickness of the smoke layer along the tunnel during the test. In this figure time is represented in the abscise axis and the tunnel length in the ordinates. The values plotted represent the height of the free-off-smoke zone, where black areas indicate no visibility at the floor level and light-grey zones mean smoke a ceiling level. Before the exhaust system was turned on a smoke layer of around 2 m thick, which means that there was almost no smoke in around 3.5 m from the ground, travelled around 200 m upstream the fire (but not downstream). Once the exhaust system was working the smoke layer pretty much remained 40 m around the fire (up and downstream) till the water mist system was turned on when it cooled down the smoke.

Figure 14 Smoke behavior. Test 2
The temperatures measured around the fire at the ceiling are shown in figure 15 and at 30 m and 45 m upstream and downstream in figure 16. The activation of the water mist system helped to lower down temperatures, being the decrease of the ceiling’s ones from 720ºC to 70ºC.

As it happened in the previous test, the system was able to control the fire and to reduce the gas temperatures, but not to completely suppress the fire, since once the water mist was turned off, the temperatures raised again.

The reduction of gas temperatures at 100 m and 150 m, in this test, are shown in figure 17.

CONCLUSIONS

After analyzing the results of the tests and being aware of their conditions (HRR less than 30 MW, longitudinal ventilation and exhaust ventilation system capacity of 160 m³/s):
• The different longitudinal ventilation during these tests seemed not to affect the water mist system “efficiency”. Ceiling temperatures decrease was in both tests comparable, around 90%.
• The water mist system configuration was able to control the Heat Release Rate (HRR) of a fire of less than 30 MW, although it did not completely suppressed it.
• The water mist system did reduce gas temperatures at the ceiling and at lower elevations near the fire to values enough to limit damage to the tunnel lining and to prevent the fire propagation.
• With a longitudinal ventilation system at distances downstream far from the fire (100 m and 150 m) the water mist system reduced the gas temperatures at lower values too, improving the conditions the tunnel installations would have to support once the ventilation system was working. In the case of the exhaust ventilation, the effect of the water mist system far from the fire was not relevant in terms of temperature.

ACKNOWLEDGMENT

This paper would not have been possible without the initiative of the responsible of the project “Calle 30” tunnels to support this large scale fire tests campaign.

REFERENCES

Experimental study on burning rate in a full-scale train model

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ABSTRACT
A series of tests were carried out in a full-scale train model to calculate the peak of burning rate of combustible carried by passengers, with a new method based on oxygen-consumption which taken the long and narrow space inside the subway into account. The result shows that: Piling-up form, mass and fuel type have great influence on the peak of burning rate in a train, and the peak of burning rate of the combustible carried by passengers is generally between 0.2MW ~ 1.5MW without considering the arson cases and nearly 4.0MW when considering that.

KEYWORDS: fire, subway, burning rate, oxygen-consumption

INTRODUCTION:
Since the subway tunnel has brought great convenience to our life, it is well applied to most countries. But once the fire occurs in subway tunnel and cannot be effectively controlled, it will lead to disaster. A number of serious tunnel fire accidents took place all over the world, such as the Channel Tunnel Fire occurred on 18 November 1996 and Daegu Subway Tunnel fire on 18 February 2003. The tunnel fire disasters are mainly attributed to the complex causes [1], high toxicity and temperature of the smoke [2-4], rapid spreading and difficulties in evacuation, etc. Plenty of research work has been done to enhance subway tunnel fire prevention and control [5-9]. Burning rate in a train is the basic element for these studies. Scholars have carried out many experiments or theoretical estimate on burning rate in a train [10-13]. But great differences are existed among their results, ranging from 1.2 MW to 13 MW. This is mainly because of different trains, different experimental conditions as well as different piling-up forms of the combustible. However, few studies have been done on the combustible carried by passengers, and most studies have not taken the long and narrow space inside the subway into account, which have obvious effect on the burning rate. In this paper, an experimental study is carried out in a full-scale train model, concerning on burning rate of combustible carried by passengers.

NOMENCLATURE
$\Delta H_{c,\text{mass},O_2}$ is the heat released from burning when unit oxygen is consumed,
$\Delta H_{c,\text{mass},O_2} = 13.1 \times 10^3 \text{KJ/Kg}$;
$m_{O_2,0}$ is the mass flow of oxygen of air into the train;
$m_{O_2}$ is the mass flow of oxygen of smoke out of the train;
$S_{\text{smoke}}$ is the area of smoke overflow at the opening;
$X_{O_2,0}$ is the volume fraction of oxygen of the environment air;
$X_{O_2}$ is the volume fraction of oxygen of the smoke;
$u_{\text{smoke}}$ is the velocity of overflow at the opening;
$\rho_{O_2}$ is the density of oxygen of the overflow.
\( x \) is the horizontal direction at the opening
\( z \) is the vertical direction at the opening
The subscript indicates different gas, the smoke layer is denoted without the subscript 0, and the environment gas is denoted with the subscript 0.

1. EXPERIMENT DESIGN
The experiment is carried out in a full-scale train model with 22.7 m long and placed inside a simulated tunnel, which was a train of Shenzhen Metro, as shown in Figure 1. The height of the train is 2.26m and the cross section of which is as shown Figure 2. On both sides of the train, there are 5 doors with the height of 2.0 m and width of 1.6 m, and 4 windows with the height of 0.6 m and width of 1.0 m. At two ends of the compartment, the openings are designed to link with other compartments, with the height of 2.0 m and width of 1.6 m.

In the experiment, all the side doors are closed in order to simulate the combustible burning environment in real train. To effectively calculate the total amount of smoke, only one end door is opened and all the smoke overflows from it. The combustible burning rate can be calculated by measuring the parameter of the smoke from the openings. In the experiments, the fire source is located in the central area, as it is indicated in Figure 3. The arrangement of measuring instruments at the opening is showed in Figure 2. There are 6 groups of K-type thermo-couples used to measure the temperature distribution in the train, especially in the smoke layer. Thermo-couples in each group are vertically arranged, with the distance of 20 cm between each other. 5 groups are set inside the train and the other one is at the opening. A group of 4 hotwire anemometers is located at the opening, with the distance of 30 cm between each other and the first anemometer is 15 cm away from the top of end door. A group of O₂ and CO concentration measuring instrument is set 20 cm outside the end door.
and 20 cm from the doorhead, to ensure the instrument in the overflow.

![Diagram of fire and measuring instruments](image)

**Figure 3: The sketch of fire and measuring instruments**

According to the investigation of the typical combustible and luggage carried by passengers in Shenzhen Metro, three kinds of typical combustible are employed in this experiment: carton with wastepaper inside, suitcase with cotton fabric clothes inside, Handbag with clothes inside. Considering arson and the quantity of combustible carried by passengers, 9 groups of tests are designed, as shown in Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Combustible</th>
<th>The number and size of combustible</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Carton with wastepaper inside</td>
<td>2×0.30m×0.40m×0.40m</td>
<td>8kg</td>
</tr>
<tr>
<td>2</td>
<td>Carton with wastepaper inside</td>
<td>2×0.40m×0.35m×0.33m</td>
<td>10kg</td>
</tr>
<tr>
<td>3</td>
<td>Carton with wastepaper inside</td>
<td>9×0.40m×0.35m×0.33m</td>
<td>20kg</td>
</tr>
<tr>
<td>4</td>
<td>Handbag with clothes inside</td>
<td>18×0.40m×0.35m×0.33m</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Handbag with clothes inside</td>
<td>3×0.40m×0.30m×0.1m</td>
<td>5kg</td>
</tr>
<tr>
<td>6</td>
<td>Suitcase with clothes inside</td>
<td>18×0.40m×0.30m×0.1m</td>
<td>15kg</td>
</tr>
<tr>
<td>7</td>
<td>Blanket</td>
<td>1×0.75m×0.50m×0.35m</td>
<td>6kg</td>
</tr>
<tr>
<td>8</td>
<td>Carton with paper and alcohol on surface</td>
<td>18×0.40m×0.35m×0.33m</td>
<td>Carton: 20kg Alcohol: 4L</td>
</tr>
<tr>
<td>9</td>
<td>Alcohol</td>
<td>Pool fire: 1.0m×1.0m</td>
<td>7L</td>
</tr>
</tbody>
</table>

### 2. IMPROVEMENT MEASURING METHOD BASED ON OXYGEN-CONSUMPTION PRINCIPLE

For traditional oxygen-consumption method, smoke collecting hood and exhaust fan are used to collect smoke. However, because of the long and narrow structure in the train and shortage of fresh air, its burning status is different from that in heat release calorimeter platform (based on ISO 9705). However, what draws the researchers’ most concern is the real burning status of the combustible carried by the passenger in a train. Installing smoke collecting hood and exhaust fan at the overflowing opening will have obvious influence on the combustible burning status in the train. Thus, a new method is employed to measure the real burning rate.

After a long-distance vertical flow in the train, the combustible smoke takes on a relative stable movement at the opening, as shown in Figure 4. According to the study of Yaqiang Jiang [14], after a certain distance from the source, the distribution of smoke temperature and velocity in the vertical flow differs only with the height change, while smoke concentration distribution changes little along the height direction, which can be considered to be same in the smoke. By measuring the distribution of smoke temperature and velocity at the opening, and the area of the opening, the smoke mass flow can be calculated. With the smoke concentration, the burning rate can be obtained from improved burning rate calculation method.
3. IMPROVEMENT CALCULATION METHOD BASED ON OXYGEN-CONSUMPTION PRINCIPLE

Assuming that the train wall is adiabatic, without smoke leakage, and all the heat released from the burning can overflow out of the train through the opening. According to oxygen-consumption principle, 13.1×103 KJ heat can be released with consumption of 1 kg O2. The burning rate can be calculated by:

\[
\dot{Q} = \Delta H_{\text{mass, O}_2} \left( \dot{m}_{O_2,0} - \dot{m}_{O_2} \right) = \Delta H_{\text{mass, O}_2} \cdot \int_{S_{\text{smoke}}} \left( X_{O_2,0} - X_{O_2} \right) u_{\text{smoke}} \rho_{O_2} \, dx \, dz
\]

Assuming that the components in the smoke layer are fully mixed, the volume fraction of oxygen maintains well-distributed in different locations. So the oxygen-consumption factors can be defined as:

\[
\phi = \frac{X_{O_2,0} - X_{O_2}}{X_{O_2,0}}
\]

The mass flow of oxygen can be expressed as:

\[
\dot{m}_{O_2} = (1 - \phi) \dot{m}_{O_2,0}
\]

The volume flow rate of air into the train is:

\[
\dot{V}_0 = \frac{\dot{V}_{O_2,0}}{X_{O_2}} = \frac{\dot{m}_{O_2,0}}{\rho_{O_2,0} X_{O_2,0}}
\]

The volume fraction of nitrogen of air into the train is:

\[
X_{N_2,0} = 1 - X_{O_2,0} - X_{CO_2,0}
\]

The volume flow rate of nitrogen of air into the train is:

\[
\dot{m}_{N_2,0} = \rho_{N_2,0} \cdot X_{N_2,0} \cdot \dot{V}_0 = \rho_{N_2,0} \cdot (1 - X_{O_2,0} - X_{CO_2,0}) \cdot \frac{\dot{m}_{O_2,0}}{\rho_{O_2,0} X_{O_2,0}}
\]

The volume flow rate of smoke out of the train is:

\[
\dot{V} = \frac{\dot{V}_{O_2}}{X_{O_2}} = \frac{\dot{m}_{O_2}}{\rho_{O_2} X_{O_2}}
\]

The volume fraction of nitrogen in smoke out of the train is:

\[
X_{N_2} = 1 - X_{O_2} - X_{CO_2} - X_{CO}
\]

And the volume fraction of nitrogen in smoke out of the train is:

\[
\dot{m}_{N_2} = \rho_{N_2} \cdot X_{N_2} \cdot \dot{V} = \rho_{N_2} \cdot (1 - X_{O_2} - X_{CO_2} - X_{CO}) \cdot \frac{\dot{m}_{O_2}}{\rho_{O_2} X_{O_2}}
\]

As the nitrogen is mass conservation during the reaction, The following equation holds:
Assuming that all of the gas conform the ideal gas law, the oxygen-consumption factors can be expressed as:

\[
\phi = \frac{X_{O_2,0} \cdot (1 - X_{CO_2,0} - X_{CO,0}) - X_{O_2} \cdot (1 - X_{CO_2,0})}{(1 - X_{O_2} - X_{CO_2} - X_{CO}) \cdot X_{O_2,0}}
\]

And Eq. (1) can be expressed as:

\[
\dot{Q} = \Delta H_{c, \text{mass}, O_2} \cdot \int \phi X_{O_2,0} \cdot \frac{\rho_{O_2,0} T_0}{T} u_{\text{smoke}} \cdot dx \cdot dz
\]

\[
= \Delta H_{c, \text{mass}, O_2} \cdot \phi X_{O_2,0} \cdot \frac{\rho_{O_2,0} T_0}{T} \sum \int u_{\text{smoke}} \cdot dx \cdot dz
\]

Because the test data is discrete space, it is necessary to change the integration of area into discrete type:

\[
\int_{S_{\text{smoke}}} \frac{u_{\text{smoke}}}{T} \cdot dx \cdot dz \rightarrow \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{u_{\text{smoke}, i, j}}{T_{i, j}} \Delta x_i \cdot \Delta z_j
\]

In the above Equation, subscript \(i\) and \(j\) represent the grid node number in the width and height direction respectively, \(m\) and \(n\) represent the total number of grid in width and height direction respectively, \(\Delta x_i\) and \(\Delta z_j\) express the size of grid in the width and height direction respectively.

And Eq. (12) can be expressed as:

\[
\dot{Q} = \Delta H_{c, \text{mass}, O_2} \cdot \phi X_{O_2,0} \cdot \frac{\rho_{O_2,0} T_0}{T} \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{u_{\text{smoke}, i, j}}{T_{i, j}} \Delta x_i \cdot \Delta z_j
\]

4. THE EXPERIMENTAL RESULT

The peak of the burning rate of combustible carried by passengers is a key focus in subway fire, thus this paper mostly pay attention to the peaks of the burning rate of different combustible in these tests. Temperature and velocity distribution in vertical direction are divided into 20 meshes, with the size of 0.1 m. The parameter of each grid can be obtained by third-order spline interpolation. The peak of burning rate in these tests can be calculated by Eq. (11), (14). The temperature and velocity interpolation at the opening of Test 6 in the peak stage of burning rate are shown in Figure 5. Figure 6 and 7 is the curve of CO concentration and temperature changing with time. The parameter and the peak of burning rate at the opening are shown in Table 2.

![Figure 5 The interpolation result at the opening of Test 6](image)
Figure 6 The curve of concentration of CO changing with time at the opening (Test 6)

Figure 7 The curve of temperature changing with time at the opening (Test 6)

Table 2 Burning rate and detail of the tests

<table>
<thead>
<tr>
<th>Test NO.</th>
<th>The mass flow of smoke (kg/s)</th>
<th>Maximum concentration of CO (ppm)</th>
<th>Minimum concentration of O₂ (%)</th>
<th>Maximum concentration of CO₂ (%)</th>
<th>the oxygen-consumption factors (φ)</th>
<th>The peak of burning rate (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.916</td>
<td>147</td>
<td>20.52</td>
<td>0.73</td>
<td>0.0206</td>
<td>506</td>
</tr>
<tr>
<td>2</td>
<td>18.07</td>
<td>62</td>
<td>20.96</td>
<td>0.29</td>
<td>0.0094</td>
<td>469</td>
</tr>
<tr>
<td>3</td>
<td>15.28</td>
<td>69</td>
<td>20.4</td>
<td>0.94</td>
<td>0.0347</td>
<td>1471</td>
</tr>
<tr>
<td>4</td>
<td>6.783</td>
<td>25</td>
<td>20.74</td>
<td>0.41</td>
<td>0.0149</td>
<td>279</td>
</tr>
<tr>
<td>5</td>
<td>13.52</td>
<td>29</td>
<td>20.77</td>
<td>0.54</td>
<td>0.0176</td>
<td>661</td>
</tr>
<tr>
<td>6</td>
<td>7.072</td>
<td>58</td>
<td>20.92</td>
<td>0.28</td>
<td>0.0119</td>
<td>233</td>
</tr>
<tr>
<td>7</td>
<td>6.702</td>
<td>345</td>
<td>20.77</td>
<td>0.43</td>
<td>0.0131</td>
<td>241</td>
</tr>
<tr>
<td>8</td>
<td>27.55</td>
<td>73</td>
<td>20.03</td>
<td>1.43</td>
<td>0.0508</td>
<td>3878</td>
</tr>
<tr>
<td>9</td>
<td>9.892</td>
<td>5</td>
<td>20.83</td>
<td>0.4</td>
<td>0.158</td>
<td>434</td>
</tr>
</tbody>
</table>
5. DISCUSSION
The alcohol pool fire with diameter of 1m in Test 9 is the comparative trial. In this test, the maximum burning rate is 434 kw, with the maximum CO concentration of 5ppm, which indicates that the methanol is full burning. And the result is in good agreement with the previous research results [15]. Thus, the new burning rate measuring method is of considerable accuracy.

For carton fires
Because of different sizes and piling-up forms, the three tests (1, 2, 3) are in different burning status, with respective heat release of 506 kW, 469 kW and 1.47 MW.
In Test 1, four cartons are piled up together, two large ones and two small, the larger cartons are taller than others, which is helpful for fire spreading, so the burning is fiercer.
In Test 2, nine cartons are used, having the same volume with small cartons in Test 1, and the distance between each other is much farther. However, the burning condition is not very fierce, so the peak of burning rate is lower than that in Test 1.
In Test 3, 18 cartons are used with much closer distance. All the cartons are burning almost at the same time, so the peak of burning rate is much greater than that in Test 1 and 2. From the comparison of the three carton fire tests, it can be concluded that not only the mass of the combustible, but also the size of carton and the distance between them have great influence on the peak of burning rate.

For handbag fire
There are 3 handbags in Test 4 and 18 ones in Test 5, their peak of burning rate are 279 kW and 661 kW. In Test 4, those handbags are filled with goods and piled up closely, and the burning condition is much fiercer. Although the total amount of combustible is just one-sixth of that in Test 5, the peak of burning rate is almost half of that in test 5. From the comparison of the two handbag fire tests, it can be concluded that the peak of burning rate is far from linear growth as the total mass. Thus, the burning rate of large combustible cannot be estimated simply by linear amplification through small-scale tests, which may have great error in the subway fire.

For suitcase and blanket fire
For Test 6, it is hard for closed suitcase to catch fire, therefore, the suitcase was open in the test so that the combustibles can be ignited directly. The peak of burning rate is about 233kW. Two blankets are used in test 7. Although the mass is bigger and the blanket will catch fire more easily at the early stage, the cotton surface burns and forms a layer of carbon coke afterwards. It is difficult to achieve full burning for the blanket’s internal and it is presented a long period of smoldering fire. So the peak of burning rate has remained at a low level, only 241kW.

For arson with alcohol
In Test 8, about 4 L alcohol is sprinkled into the 18 cartons to simulate arson. The total burning area is about 6.0 m2, and the burning takes place almost at the same time as the ignition. The burning is rather fierce, with the peak of the burning rate of 3.8 MW. This is mainly because alcohol is dipped into the carton, which speeds up the burning and makes the peak of burning rate increase greatly. And large fire with high burning rate pose a serious threat to passengers in the train.
6. CONCLUSION

Based on oxygen-consumption principle, a new method is developed to measure the burning rate of combustible, with consideration of the special burning environment in the train. Experimental results show that this method has considerable accuracy when compared with previous research results. The peak of burning rate of the combustible carried by passengers in a train is generally between 0.2MW ~ 1.5MW, without considering the arson cases. Piling-up form, mass and fuel type have great influence on the peak of burning rate in a train. It is undesirable to estimate the burning rate of large combustible simply by linear amplification through small-scale test in subway fire. As for arson, if 4L alcohol is sprinkled into the carton, the peak of burning rate of carton fire can rise up to nearly 4.0MW. This will pose a serious threat to the subway. So it is recommended to strictly control the quantity of flammable liquid carried by each passenger.

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Large-scale Commuter Train Fire Tests – Results from the METRO Project

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ABSTRACT
Three fire tests were performed under and inside commuter train carriages in a tunnel. Both tests initiated inside the carriage developed to fully flashover conditions. The time to flashover was significantly different between the two cases. In the test with the original seats and linings the maximum heat release rate (HRR) was 76.7 MW and occurred 12.7 min after ignition. The maximum HRR in the case where more modern seats and aluminium lining were used, occurred after 117.9 min. The main reason for the difference was the difference in initial combustion behaviour between the case with combustible wall and ceiling lining, and the case with aluminium as the exposed interior surface. In the case with combustible lining a ceiling flame was developed, radiating towards the seats and the luggage spreading the fire more quickly than in the case without exposed combustible lining. When the growth rate of the fire was rapidly increasing, a flame was observed at the ceiling. The maximum HRR calculated from the experimental results are significantly higher than those obtained in other documented test series. The luggage in, under or between different seats is presumed to increase the fire spread significantly in both cases. This was obvious from results performed within the same project prior to the full-scale tests.

KEYWORD: metro, train, full-scale experiments, fire tests, tunnel

INTRODUCTION
The society is highly dependent on access to mass transport systems in order to facilitate transportation of people in populated urban areas. One example of such a metro system is the one in the Stockholm area. Fires, incidents or terror attacks not only potentially cost human lives and injuries, but also damage the environment, influence citizens’ daily life and represent a significant cost in economical terms. Authorities and engineers working on safety and security aim to provide users with a high level of confidence in public systems, but safety and security come only at significant cost and it is often necessary to compromise between cost and benefits. We could, e.g., install water spray systems in the entire metro system to prevent the development of a fire, but this is sometimes unrealistic from a cost-benefit point of view.

Numerous fires and terror attacks have occurred in metro related systems throughout the world. A total of 289 people where killed and 265 severely injured in an accidental fire in the subway of Baku, the capitol of Azerbaijan, 28th of October 1995 [1]. Similarly, some 198 people were killed and 146 injured in the Daegu subway arson attack of February 18, 2003 [2].

The mass transport system must be constructed so that people sense that they are safe and secure when travelling. A lack of confidence in the system is devastating for both society and mass transport companies. Knowledge of the consequences of a fire incident or a terror attack in a metro system is therefore of utmost importance. There is a great need to improve the knowledge in many different
fields of fire safety and security in metro systems. Therefore, a large research project (METRO) is presently ongoing where a number a large-scale test have been performed. The METRO project (www.metroproject.se) is an interdisciplinary collaborative research project between universities, research institutes, tunnel infrastructure owners and fire departments in Sweden. The project is a three year undertaking, running until the end of 2012. The main objective of METRO is to create a safer environment for passengers, personnel and first responders in the event of fire or terror attack in underground mass transport systems. A central part of the project is large-scale fire tests with commuter train carriages in a tunnel. The main aim of the large-scale test is to illustrate in a mass transport system the limitations, consequences and risks when such a carriage starts to burn, or is subject to a terrorist attack. Such large-scale tests can give information on fire spread and development, the limit for flashover, radiation towards people, structures and equipment, conditions and possibilities for the rescue service personnel, and much more.

The large amount of resources needed (personnel, material, equipment, transportation, etc) to perform large-scale fire tests with trains means that the number of full-scale tests that have been performed is limited. Still such full-scale tests are very important both for understanding of the fire behaviour and for comparison with computer simulations and model-scale tests. One example of test performed with a metro car is from the extensive EUREKA 499 test series [3-4]. In that test series, a German metro car was used giving a maximum HRR of 35 MW. In the same test series, tests were performed with different types of railway cars with maximum HRR between 13 MW and 43 MW [5]. Given the range of HRR and the diversity of railway carriages and tunnel dimensions, there is clearly a need for further large-scale data.

In this paper the set-up and results of the large-scale fire tests performed within the METRO project are presented.

**EXPERIMENTAL SET-UP**

The full scale tests were performed in the old Brunsberg tunnel, located between Kil and Arvika in western Sweden. This abandoned, 276 m long tunnel lies on a siding about 1 km long. It was taken out of service when a new tunnel was constructed close by to reduce the sharpness of a bend in the route. The cross-section of the tunnel varies along the tunnel and to get a better view of this variation the cross-section was registered at 21 different positions along the tunnel. The tunnel height varied in these measurements between 6.7 m and 7.3 m with an average of 6.9 m. The width at the ground level varied between 5.9 m and 6.8 m with an average of 6.4 m.

For the full-scale fire tests the project received two commuter train sets of the type X1, donated by the Stockholm Public Transport (SL). Each train set consists of one motor carriage and one manoeuvre carriage. In the fire tests, only the manoeuvre wagon from each train set was used, see Figure 1.
The manoeuvre carriage was approximately 24 m long. There was a driver’s compartment at one end and the length of the passenger compartment was 21.7 m. The width of the inside of the carriage was 3 m and the height along the centreline was 2.32 m. The height at the wall was 2.06 m. The horizontal part of the ceiling was approximately 1.1 m wide.

During the test series, three fire tests were performed, one test with a fire initiated directly under the carriage and two fire tests where the fire was initiated inside the carriage. The latter two ultimately involved the entire carriage in the fire. For test 1 and test 2 the X1 train was used with original shape and material (see Figure 1), and the same carriage was used in both tests. The carriage used in test 3 was refurbished to be similar to a modern C20 wagon (used in the Stockholm metro. The seats were refitted using X10 seats (relatively similar to C20 seats) and the walls and ceiling were covered by aluminium, see Figure 2. This meant that the width at the floor level was 2.99 m and the smallest width between the rounded walls below the windows was 2.84 m. Note that the old walls and ceiling materials were retained behind the aluminium lining.

Figure 2  Interior design of the X1 train that was refurbished to look like a C20 train inside.

The carriage used in each test was positioned (centred) 96 m from the eastern entrance of the tunnel, see Figure 3.

Figure 3  A plan view over the instrumentation in the tunnel.

The data acquisition was comprehensive. Gas temperatures at numerous positions, heat release rate (HRR), gas concentrations and smoke inside the carriage and the tunnel, as well as radiant fluxes and gas velocities, were measured. In Figure 3 the measurement positions in the tunnel are presented.
Where single thermocouples are indicated they were positioned 0.3 m from the tunnel ceiling. In the thermocouple tree downstream of the carriage (P33), the thermocouples were positioned 0.83 m, 2.14 m, 3.45 m, 4.76 m and 6.07 m from the ground, in addition to the one 0.3 m from the ceiling. The air velocity was measured with a bi-directional probe 50 m upstream of the wagon, 3.45 m from the ground. All the sensors indicated in Figure 3 were placed in the tunnel. Not shown in the figure are all the sensors inside the carriage. Inside the carriage, temperature was measured at many positions, both as single thermocouples near the carriage ceiling and in thermocouple trees. Furthermore, CO, CO₂, and O₂ were sampled and analyzed in one position at three heights. The smoke density was also measured with a laser and photo cell system at three heights. In total were there 67 sensors or sampling points inside the carriage. Further, the details of the measurement station (P38) are not shown in Figure 3. At this station there were a total of 26 sensors or samplings points (temperature, velocity, optical density, CO, CO₂, O₂).

A controlled air flow was needed in the tunnel to control the smoke from the fire, for the safety of personnel and protection of equipment, and to guide all smoke towards the measurement station. The latter was needed to make it possible to estimate the HRR using oxygen consumption calorimetry. The necessary air flow was obtained using a mobile fan of type Mobile Ventilation Unit MGV-L125/100FD. The created air velocity in the tunnel was before the ignition 2 m/s – 2.5 m/s.

It has been shown in fire tests carried out by the authors in a fire laboratory using 1/3 of a train carriage that luggage plays a very important role for the fire development [6]. Further, in investigations of some of the most hazardous fire accidents in railway and metro systems in modern time it has been shown that the luggage carried on by train passengers plays a very important role in the fire development [1, 7-8]. Therefore, when planning for the full scale fire tests, the influence of the transitional fire load in mass transport systems carried on by passengers was one of the most important parameters to evaluate. To obtain a good estimation of what passengers in the Stockholm metro and commuter trains carry with them on the trains, a field study was carried out by Mälardalen University [9]. The field study showed that 87 % of all passengers in the commuter trains carried bags with them on the train and 82 % in the metro. The luggage that was used in the full scale test corresponds to an assumption that approximately 81 % of the passengers carried luggage and a loading of one passenger per seat available (98 seats) in the carriage. In total 79 pieces of luggage were used with an average mass of 4.44 kg. This corresponds to a total transitional (extra) fire load of 351 kg. The different types of bags were filled with clothes and paper (reports and brochures). If an average energy content of 20 MJ/kg is assumed the extra fire load corresponds to 7.2 GJ.

**TEST PROCEDURE**

**Test 1**
The purpose of the fire scenario in Test 1 was to evaluate the fire spread underneath the railway car in case of a fire in for example the breaks or electrical device. On the same time it was important that the fire did not spread to the inside of the carriage since it was to be used in a second fire test. Therefore, the temperature in the floor was measured during the test. The fire source was a pool of heptane positioned under the ATC receiver. The pool area was 350 mm × 350 mm × 35 mm. The pool contained 3.2 L of heptane. The distance between the top of the pool (edge) and the ATC receiver was 155 mm. The test was performed inside the tunnel and with an air velocity over the pool fire under the carriage of approximately 2-3 m/s. The HRR from such a pool fire was measured in the laboratory (without ventilation) to increase to a plateau at 300 kW after 1 min. After 3 min the HRR increased again to a maximum of approximately 500 kW after which the HRR decreases until it was extinguished after approximately 6 min.

**Test 2 and 3**
The scenario for these two tests aimed to simulate an arsonist that ignited a seat in a corner. An empty milk container (paper with an inner plastic lining) was filled with 1 L of petrol. The milk container was placed on a plywood board (36 cm × 36 cm × 1.2 cm). Three small ignition sources (fibre board with added paraffin) were used. The ignition was achieved by placing the small ignition sources at different locations which ignited the spilled petrol from the empty milk container. One of the small
ignition sources was placed on the seat just outside the plywood board and two on the floor. The small ignition sources were 23 mm × 30 mm × 15 mm in size. When pulling a string attached to the milk container, it tumbled over and the petrol flowed out on the seat and floor and ignited by the burning fibre boards. The fire was then allowed to develop and spread to the luggage and other combustible material in the wagon. At the time of ignition the three doors on one side (below referred to as door 1, door 2 and door 3, counted from the front of the train) were open. During the tests the other three doors fell out and the windows broke, which meant that during the intense part of the fire all six doors and all windows were open.

RESULTS

Test 1
The heptane pool fire did locally ignite train dirt/paint at the surface (the protection plates are engulfed in the flames in Figure 4) of a nearby ATC-unit located over the fire, but the fire did not spread further and self-extinguished approximately 13.5 minutes after the pool fire burnt out.

Test 2 and 3
The ignited petrol in one corner of the carriage spread on the floor and to nearby luggage and other material. The initial development was similar in the two tests, but very soon the development differed significantly (see Figure 5). In Test 2 the fire continued to develop very fast and soon the entire carriage was involved in the fire (see Figure 7). The gases near the 0.29 m from the ceiling near the position of ignition reach a temperature of 600 °C after approximately 4 min. The corresponding conditions were reached in the other end of the carriage after approximately 11.5 min. In Test 3, on the other hand, the initial development stopped and the fire spread slowed down. The fire did, however, not extinguish completely, but continued on a low and relatively constant level.

Since one of the aims of the fire tests was to study the effects (condition in the tunnel, radiation, etc) of a fully developed fire it was decided to assist the fire development by igniting some additional pieces of luggage. Two L of Diesel fuel was added to each of five pieces of luggage in the vicinity of door 1, i.e. 10 L in total. However, when the first of these pieces of luggage (very close to door 1) was ignited approximately 110 min after the original ignition, the fire fighter igniting the luggage saw flames on the ceiling and had to exit the carriage without igniting the other prepared pieces of luggage. The fire had spontaneously spread to the driver’s cabin. This then spread the fire back again to the passenger compartment shortly after the decision was made to intervene in the fire progress. The fast temperature increase (0.88 m from the driver’s cabin; 0.29 m from the ceiling) started approximately 103 min after ignition (see Figure 8). At the time 108.4 min the temperature in this
position raised above 600 °C. At the time 103.8 min after ignition, the temperature was still higher in
the driver’s compartment than in the passenger compartment, but the flashover of the driver’s
compartment did not occur until the time 105 min, i.e. after the temperature has started to increase
in the passenger compartment, but before the passenger compartment was fully involved in the fire. At
the time 110 min after ignition, the temperature near the ceiling inside door 1 was approximately
500 °C.

Figure 5  Left: HRR from Test 2 and Test 3 with real time scale. Right: HRR from Test 2 and Test 3
with the time scale in Test 3 shifted.

Figure 6  Developed backlayering in Test 2 (left) and large flames and progressing backlayering
in Test 3 (right). Photograph courtesy of Per Rohlén.

The fire development in Test 3 after the fire spread to the passenger compartment was very similar to
the one in Test 2. The HRR curves are presented in Figure 5. In the left figure the curves are shown
with the real time from the tests, while in the right figure the time scale for Test 3 is shifted so that the
time for the increase corresponds to the one in Test 2. As can be seen in the figure, the general shape
of the two fire curves are almost the same, although the time for the maximum HRR is not exactly
the same. The maximum HRR in Test 2 was calculated to be 76.7 MW (12.7 min after ignition), while the
corresponding value for Test 3 was 77.4 MW (117.9 min after ignition), i.e. in both tests the maximum HRR was calculated to be approximately 77 MW. In the left figure of Figure 5 the HRR calculated from oxygen consumption calorimetry is included for comparison. The period of fire growth and the maximum HRR are very similar for the two methods of HRR calculation. The same applies for the period of decrease. However, there is a period after the maximum HRR where there is a difference between the two methods. Photos from Test 2 and Test 3 are shown in Figure 6.

As mentioned above, all doors fell out during both tests. In Test 2, some of the power cables supplying the instrument downstream of the carriage were actually destroyed so the data registration at the measurement station downstream of the fire was not active after a certain time into the test. The consequence was that the HRR could not be calculated using oxygen calorimetry from this time (9.4 minutes after ignition). Instead a method based on temperature measurement was used [10-13]. Since the oxygen calorimetry was available in Test 3, these two methods could be compared and showed good agreement. The calculations and the comparison are described in detail in the test report [13]. The HRR results presented in Figure 6 are all calculated with the temperature method.

**Figure 7** Gas temperature near 29 cm from the ceiling in the wagon in Test 2. The distance x is measured from the wall towards the driver’s cabin.

**Figure 8** Gas temperature near 29 cm from the ceiling in the wagon in Test 3. The distance x is
measured from the wall towards the driver’s cabin.

The estimation of the total energy content in the material in the carriages is uncertain due to limited information on many of the materials. Integrating the HRR curves in Figure 5 can give additional information on the total energy. For Test 2 the energy released during the first 60 min was approximately 64 GJ, while the released energy during the first 185 min in Test 3 was approximately 71 GJ. Since the fires were not extinguished at these times the total energy content should be higher than these values.

The gas temperature inside the carriage reached approximately 1000 °C in both Test 2 and Test 3 (see Figure 7 and Figure 8) and although the large difference in fire development, as discussed above, the temperature development for the parts when the entire wagon gets involved in the fire are similar to each other. In Figure 8 the period of initial fire spread in the beginning of Test 3 is well illustrated reaching a long period of low and relatively constant temperatures before the start of the fast fire spread.

![Figure 9](image1.png)  
**Figure 9** Gas temperature near the ceiling in the tunnel in Test 2.

![Figure 10](image2.png)  
**Figure 10** Gas temperature near the ceiling in the tunnel in Test 3.
In the tunnel, the maximum temperature measured near the tunnel ceiling was approximately 1100 °C both in Test 2 and Test 3. However, the maximum temperature was somewhat higher in Test 3: approximately 1120 °C measured above the centre of the carriage, while the maximum temperature in Test 2 was approximately 1080 °C, measured at the position +10m (10 m downstream the centre of the carriage. The time resolved temperature results are presented in Figure 9 and Figure 10. Note that the time scales in the two figures are significantly different. The maximum temperatures in three positions above the wagon are summarized in Table 1. The gas temperatures near the ceiling in Test 1 were not affected by the fire.

<table>
<thead>
<tr>
<th>Test</th>
<th>Position -10 m (°C)</th>
<th>Position 0 m (°C)</th>
<th>Position +10 m (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>911</td>
<td>1073</td>
<td>1081</td>
</tr>
<tr>
<td>3</td>
<td>702</td>
<td>1118</td>
<td>980</td>
</tr>
</tbody>
</table>

CONCLUSIONS
Three fire tests were performed under and inside commuter train wagons in a tunnel. Both tests initiated inside a carriage developed to fully flashover conditions. In the test conducted with the original seats and linings, the maximum heat release rate (HRR) was 76.7 MW and occurred 12.7 min after ignition. In the test conducted on the refurbished carriage, the maximum HRR occurred after almost 118 min and was approximately 77.4 MW.

The main reason for the difference in fire growth rate between these two tests was due to the involvement of the combustible wall and ceiling lining in the test conducted in the old style X1 carriage. This would indicate that there is a greater opportunity for passengers to react to a developing fire in a modern carriage than in an old carriage.

The maximum HRR calculated from the experimental results are significantly higher than those obtained in other documented test series. The luggage in, under or between different seats is assumed to increase the fire spread significantly in both cases. Clearly, it is necessary for train owners to consider this transient load when conducting risk assessments and designing response tactics.

ACKNOWLEDGEMENT
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Full-scale Experiments for Heat Release Rate Measurements of Railcar Fires

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ABSTRACT

This paper describes experiments performed to measure the heat release rate of train car fires from ignition to burnout. Two tests are presented: a test using an intercity railcar and a test using a subway car. For the tests, the cars were moved inside a tunnel facility and placed on stands to simulate realistic conditions. Thermocouples were installed inside the train car to provide an accurate picture of the temperature conditions inside the car so that an insight of the fire development can be obtained. A number of cameras have also been placed inside the car and the tunnel providing live video during the test. Other instrumentation included heat flux meters for measuring heat fluxes inside the train car and the tunnel and instruments for measuring smoke density. The paper provides details of the experimental set-up and the instrumentation as well as the procedure used to perform the tests. It also presents and discusses the results of the two tests.

KEYWORDS: fire heat release rate, tunnel fires, train fires

INTRODUCTION

Fire safety in tunnels has received considerable attention lately as a result of a number of accidents that occurred in recent years and due to the increased use of underground tunnel facilities for the transportation of people and goods. In Europe, 21 full-scale tests involving road vehicles, railcars and a combination of fire loads (wood cribs, heptanes and plastics) and two tests using half a passenger train car with internal fittings were conducted. The results of the tests for the railcars identified important parameters that affect fire development in railcars [1, 2]. The size of the railcar fires tested was estimated to be in the range between 15 to 20 MW. Another European project identified the fire risks in European trains, defined the most relevant fire scenarios, selected suitable test methods and proposed a classification system for the various products used. For the tests, they used a 10 m³ enclosure constructed inside a passenger rail vehicle [3]. They report that after the windows broke the fire became fuel-controlled, which contradicts the findings of White et al. [7] who reported that the fire after flashover is ventilation controlled.

A major research program on fires in trains for the US Federal Railway Administration (FRA) [4-6] was conducted by the National Institute for Standards and Technology (NIST) in the USA. The aim of the project was to demonstrate that heat release rate test methods in conjunction with hazard analysis techniques could be used to assess fire safety in passenger railcars. The duration of the full-scale tests conducted was limited to minimize damage to the railcar to allow repeated tests. Only one test reached conditions approaching flashover.

A full-scale fire experiment has been conducted outdoors on a typical Australian passenger train, in which the fire was allowed to become fully developed involving all combustible materials within the
It was found that ceiling and upper wall linings are more critical for fire spread than seats and lower wall linings. The fully developed fire went to flashover 140 s after ignition and spread inside the vehicle very rapidly. From this test it was concluded that the peak heat release rate was ventilation controlled and that many common methods of estimating train fire HRR are not valid and that further research into ventilation of train fires is required.

The heat release rate of fires involving intercity and subway railcars is an important parameter used for the design of the fire protection systems in tunnels and subway stations. The size of the heat release, for example, is used to determine the critical velocity in tunnels. The critical velocity is the velocity required to prevent the flow of smoke upstream. The amount of air flow required to achieve this velocity is then used to design longitudinal ventilation systems for tunnels. The objective of the ventilation system is to maintain the upstream side of the fire free of smoke so that occupants can evacuate safely. Failure of the ventilation system to prevent backflow may result in smoke moving upstream endangering passengers. Determining the heat release rate of railcars is not easy as it requires large-scale test facilities capable of withstanding these high intensity fires. The test facility is also required to have instrumentation for measuring the properties of the products of combustion used for calculating the heat release rate. One such facility is the recently constructed fire research laboratory of Carleton University located 50 km west of Ottawa. This facility houses a tunnel, an atrium and a burn hall.

**DESCRIPTION OF THE FACILITY**

The tunnel of the Carleton University facility is 10 m wide, 5.5 m high and 37.5 m long. It is equipped with a mechanical exhaust system that consists of three fans capable of exhausting a total of 132 m$^3$/s of gas. The exhaust fan system is designed to draw smoke from the tunnel through a large fan chamber. The fan chamber is equipped with the instrumentation needed for measuring the heat release rate of large fires using oxygen consumption calorimetry. Oxygen calorimetry requires accurate measurements of the mass flow rate, CO$_2$, CO and O$_2$ concentrations of the exhaust gases. This is achieved by strategically placing the instrumentation at the end of the upper chamber of the lab just before smoke enters into the fan chamber. Two fans are located at the east end of the facility at the fan chamber level, and one fan is located at the attic level as shown in Figure 1.

![Figure 1. Schematic diagram of Carleton laboratory facility [8]](image)

**HRR measurement system**

A measurement system has been developed and installed in the facility for measuring the heat release rate of tunnel fires. The system uses oxygen calorimetry for accurate and reliable measurements under different ventilation conditions. The oxygen calorimetry requires accurate measurements of the mass flow rate, CO$_2$, CO and O$_2$ concentrations. The fan chamber is long enough for the velocity
profile of the flow to be fully-developed so that the flow is reasonably uniform at the end of the chamber. The HRR measurement collects data at the end of the upper chamber (5.66 m wide by 2.94 m high), by directing all combustion products through this measurement area, where the instrumentation measures the required gas properties. Figure 2 shows a schematic of the HRR measurement system.

Figure 2. Schematic diagram of HRR measurement system [8]

Methodology of oxygen consumption calorimetry

The heat release rate measurement system uses the oxygen consumption calorimetry by Janssen [9] and Parker [10]. The heat release rate is computed using Eq. (1).

$$Q = \left( E_{O2} - (E_{CO} - E_{O2}) \right) \frac{(1-\theta)}{25} \frac{x_{Ar}}{x_{O2}} \varnothing \frac{m_{e}}{1+\theta(\alpha-1)} \frac{M_{O2}}{M_a} (1 - X_{H_2O}^o) x_{O2}^o$$

(1)

Where:

$$\varnothing = \frac{x_{O2}^o(1-x_{CO}^o-x_{Ar})-x_{Ar}^o(1-x_{CO}^o)}{(1-x_{Ar}^o-x_{CO}^o-x_{Ar}^o)x_{O2}^o}$$

(2)

$$X_{H_2O}^o = \frac{RHP_0(T_0)}{p_a} = \frac{RH}{p_a} \exp(23.2 - \frac{3816}{46 + T_0}) \approx \frac{RH \times 2.5 \text{ kPa}}{101.5 \text{ kPa}} = 0.0123$$

(3)

$$M_a = M_{dry}(1 - X_{H_2O}^o) + M_{H_2O}X_{H_2O}^o$$

(4)

Molar fractions of water vapour in the incoming air ($X_{H_2O}^o$) can be calculated using Eq. (3). RH is relative humidity, $p_0(T_0)$ is saturation pressure of water vapour at ambient temperature $T_0$, and $p_a$ is air pressure (Pa). The molecular weight of incoming air needs to be calculated taking into account water vapour concentrations using Eq. (4) developed by Janssens [9].

Mass flow rate calculation

The accuracy of the oxygen calorimetry depends on correct measurements of the mass flow rates. In
general, the shape of the velocity profile of a fully-developed turbulent flow in a pipe is uniform over the cross section, yet the velocity gradually decreases near the walls due to wall friction. For this reason, a correction factor ($\zeta$) is required when calculating the mass flow rate of the flow in a duct [11].

$$\dot{m}_e = \zeta AV \rho$$

The correction factor is directly related to the velocity profile of the flow. The correction factor for the fully-developed turbulent flow through the large rectangular fan chamber must be found experimentally by examining flows under various conditions. To calibrate the system and determine the correction factor, a series of tests was conducted using propane burners that could provide known heat release rate fires. From the test results, a calibration factor of 0.9 for the HRR measurement system was found. Details of the calibration tests are described in Ko [12].

**Velocity calculation**

Bi-directional probes are often used to measure velocities in fire tests because the measurement is quite accurate for low velocity and high temperature flows found in medium- and large-scale fire tests. In addition, they are insensitive to small changes in orientation (angle) and sooty environments. The measured pressure difference can be converted to a velocity using Eq. (6).

$$V = \frac{1}{k_p} \sqrt{\frac{2\Delta p}{\rho}}$$

The HRR measurement system uses bi-directional probes that were fabricated using copper tubes, as shown in Figure 3. Based on the calibration of the bi-directional probes under limited conditions that can be encountered in the laboratory, the probe constant ($k_p$) was found to be 1.1, which is close to the asymptotic value of 1.08 suggested by McCaffrey and Heskestad [13].

![Figure 3. Bi-directional probe dimensions used in the current study (D=24.6 mm, L=46.25 mm, D’=6.3 mm, and L’=7.6 mm)](image)

**Instrumentation**

Accurate measurement of mass flow rate of gases is challenging due to the variation of the flow velocity inside the large chamber of the facility. To obtain good representation of the flow velocity and other parameters across the entire cross-section of the chamber, the instrumentation in the fan chamber was designed based upon extensive analysis of various CFD simulations as well as manual velocity measurements. All simulations, as well as the manual measurements, indicated that for any
fire scenarios, the temperatures were relatively uniform across the measurement area. Due to the large distance between the test section and the measuring station, smoke mixes well by the time it reaches the measurement area. The profiles of the gas concentrations were also uniform over the measurement area. As a consequence, the location of the thermocouples and the gas sampling locations at the measurement section are not critical.

While temperature and gas concentrations are uniform over the measurement area for any scenario, the velocity profiles were found to be affected by the exhaust fan speed. For velocity measurements, various probe combinations were examined using the velocity data obtained from measurements and simulations, at every 0.25 m over the measurement area (a total of 231 measurements at each test/simulation). A total of 28 combinations were compared using different number of probes from 2 to 30. From the analysis, an optimum probe combination using 4 probes was found, which showed an error of less than 6% for various conditions, comparable even to the combinations with 20 or 30 probes.

Figure 4 shows the final instrumentation for velocity, temperature, and gas concentrations over the measurement area in the fan chamber. Four bi-directional probes were installed at the locations found from the analysis. The probes are connected to the transducers which measure the pressure differences and convert them to electrical signals. Six thermocouples (Type J) were installed at locations shown in Figure 4. A steel gas sampling grid was installed to cover the measurement area of the fan chamber as shown in Figure 4. The gas enters through the holes on the downstream side of the steel tube and is mixed into a single outlet. The sample gas moves through a cotton soot filter, a condenser coil for cooling and a Diorite gas drying unit. Then, the sample enters the gas analyzer. A detailed diagram of the measuring devices used for temperature, velocity, and gas concentrations is shown in Figure 5.

![Figure 4. Instrumentation](image-url)
Real time calculation and display system

Using Labview (version 8.6), a real-time HRR calculation and display system was developed. The computed HRR is displayed on the computer monitor with a delay, which is inevitable due to the gas analyser and the large scale of the facility. Delay time for the gas analysis system, which represents the time for the gas analysis system to pump gases through the sampling line and to analyse gases through the chemical process in the gas analyzer itself, was found to be 45 seconds when the sample gas was pumped at a constant flow rate of about 1.5 l/min. The delay time of 45 seconds was programmed in the real-time HRR calculation and display system. Thus, the delayed data of O₂, CO₂ and CO concentrations were programmed to be shifted so that they are synchronized with the measured temperatures and velocities [14]. In the Labview program, the signals were conditioned at a frequency of 2000 Hz, collecting 400 samples, yielding an average value every 0.2 s. To process the large amount of data, a time step of 1.5 s was set in the program to process data and log calculations so that it matches with the delay time of 45 s (i.e. 30 time steps to match the 45 seconds).

Uncertainty of HRR measurement system

From the uncertainty analysis conducted with data obtained from the calibration test program, the combined uncertainty of the system measurements was found to be about 10-15%. The details of calculations of the combined uncertainty in the HRR estimations, as well as the uncertainty associated with each measurement variable are described in Ko [12].

Description of the cars

Two train car tests were carried out: a test to measure the HRR of a train coach car and a test to measure the HRR of a subway car. Table 1 gives the dimensions of the two cars as well as their weight and fire load. The coach train tested is shown in Figure 6 (a). This train is an intercity train with a length of 23 m, a width of 3 m and a height of 3.7 m. The total weight of the train is 38 tons. The estimated fire load of this car was 50 GJ. Figure 6(b) shows the subway car used for the tests. The subway car had a length of 19.7 m, a width of 3.15 m and a height of 3.45 m. The estimated fire
load of the subway car was about 50% of the rail car at just over 23 GJ.

Table 1. Physical characteristics of the train cars

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Coach car</th>
<th>Subway Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (ton)</td>
<td>38.0</td>
<td>24.0</td>
</tr>
<tr>
<td>Length (m)</td>
<td>23.0</td>
<td>19.7</td>
</tr>
<tr>
<td>Width (m)</td>
<td>3.0</td>
<td>3.15</td>
</tr>
<tr>
<td>Height (m)</td>
<td>3.7</td>
<td>3.45</td>
</tr>
<tr>
<td>Fire load (GJ)</td>
<td>50</td>
<td>23</td>
</tr>
</tbody>
</table>

(a) Train car  
(b) Subway car

Figure 6. Train cars used for the tests.

Test setup

The tunnel ceiling and walls were insulated, and the walls were also lined with corrugated metal sheets to protect them from thermal damage. Along the tunnel wall, a water spray system was installed to cool the walls. The exhaust fan system was initially set to 50%, and then the fan speed was increased to 100% in 3 min and in 6 min after ignition for the coach test and the subway test, respectively. In the coach test, 4 side doors (2 on each side) were open (see Figure 7). In the subway test, all 4 sliding doors on one side were open. The doors on the other side were left closed.

Figure 7. Door condition of coach train test

In the measurement system, the HRR per unit mass of O$_2$, $E_{O2}$, was set to 13.1 MJ/kg (suggested by Huggett [15]) and the expansion factor, $a$, was set to 1.10 (suggested by Parker [10]). These values were suggested for most fires where the composition of the fuel is unknown. The relative humidity
(RH) was set to 0.5.

A sand propane burner that is often used for the room corner test (ISO 9705) was used as the ignition source. The HRR of the burner was 75 kW for the first 3 minutes and 150 kW for the following 8 minutes.

RESULTS AND DISCUSSION

Figure 8 shows two photos of the coach car during the early stages of fire development. The first photo was taken at 260 s when the first two windows just broke and the size of the fire was about 5 MW, and the second was taken at 400 s when the fire size grew to 10 MW. Both photos show that flames issue from both sides of the car and they are pushed forward due to the ventilation system.

Figure 9 shows two photos of the subway car: one at 267 s; and the other at 345 s. At those times the fire size was 1 MW and 5 MW respectively.

Figure 8. Train car fire at (a) 260 s and (b) at 400 s.

Figure 9. Subway car fire (a) at 267 s and (b) at 345 s.

Figure 9 shows the measured heat release rate of the coach car. The fire starts to grow after about 100 s from ignition and by 300 s it reaches 10 MW. From there it grows slowly to 15 MW as more windows break. After the breakage of all windows, the heat release rate reaches the maximum value of 32 MW (at 18 min after ignition).
Figure 10 shows the measured heat release rate of the subway car. The fire takes more time to intensify than the coach car fire; however once it starts to grow it does so very quickly. The maximum heat release rate of 52.5 MW was reached in about 9 min after ignition. It took only 140 s for the fire to grow from 1 MW to 52.5 MW. This rapid fire growth is a result of the fact that four doors were open from the start of the fire so adequate ventilation was there to sustain such growth. The duration of the subway car fire was shorter than the coach fire due to the higher heat release rate and lower fuel load.

CONCLUSIONS

This paper described the facilities used to perform full-scale fire tests to determine the fire development and heat release rate of traincar fires in tunnels and presents details on two tests performed to measure the heat release rate of an intercity coach car and a subway car. Both cars were
The heat release rate measurements presented for the two cars show clearly that fire development and maximum heat release rate is governed by the ventilation conditions that exist during the fire. The intercity car which had a much higher fire load density reached a lower maximum heat release rate than that of the subway car, which had a lower fire load density. The duration, however, of the subway fire was much less than that of the coach fire due again to the lower fire load density.

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On Bayesian Probabilistic Networks for Risk Analysis of Road Tunnels

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ABSTRACT

Quantified Risk Analysis (QRA) has become a cornerstone in the design and in particular in case of retrofit of road tunnels. Classical methods use event threes for QRA. However due to the manifold of parameters and their mutual influencing, adequate event trees can only be developed for simple cases. In the EU-directive 2004/54/EC [3], 15 safety relevant parameters are defined. Assuming that each of these has 4 states, the resulting number of dependencies is more than one billion, which cannot be catered for employing event trees. Consequently, the here presented novel method is based on Bayesian Probabilistic Networks, which also permits to cater of the inter-dependency of the parameters.

The method was developed as a Best Praxis for Risk Analysis of road tunnels on behalf of the Norwegian and Swiss road authorities [10]. Two separate Bayesian Probabilistic Networks are incorporated in the model: one for conventional traffic accidents with possible subsequent fires (see Figure 3) and another for transports of dangerous goods (see Figure 4).

The tunnel of concern is divided into sections each with constant risk profile e.g. invariant with respect to slope, traffic, lanes and all other relevant parameters. Portal zones as well as intersections are therefore always treated particularly.

The methodology has been implemented in a computer code TRANSIT: Tunnel Risk Analysis on a Segmental basis by using Influence diagram Technique.

In addition to presenting the QRA method, the results of case stories are presented. One of these is the retrofit of a road tunnel where following measures are analysed:

- Shortening the escape route distance from 600 m to 300 m
- Creation of a continuous slut gutter for road surface drainage
- Increase the height of the traffic envelope
- Update the tunnel ventilation to current requirements

Moreover, the situation with bidirectional traffic in one tunnel tube during the refurbishment period compared with the current normal employment having unidirectional traffic in both tubes is analysed.

Additionally, the importance of knowing the duration of traffic congestion and the daily traffic distribution is demonstrated.

The cost effectiveness of each measure is calculated based on the present value method of each measure compared with the equivalent capital benefit using the marginal cost principle. It is also
illustrated that some measures may not seem cost efficient but can still be of benefit as e.g. the usage in terms of transport of dangerous goods may change.

**KEYWORDS:** QRA, quantified risk analysis, tunnel, Bayesian probabilistic networks, upgrade, retrofit, cost efficiency, transports of dangerous goods, Transit.

**INTRODUCTION**

The demand for subsurface transport is increasing. This leads to complex underground systems with numerous stakeholders with different expectations and requirements in terms of capacity, reliability, availability, maintainability and safety.

Quantified Risk Analysis (QRA) is increasingly gaining importance in order to quantify the safety of road tunnels and hence to balance the requirements and expectation of various stakeholders. Various reasons demand a QRA to be conducted. One reason may be that the tunnel has a particular characteristics e.g. as defined in the EU-directive 2004/54/EC on the minimum requirements for the safety of road tunnels [3]. Moreover, when upgrading existing tunnels meeting current standards may be very costly or technically impossible. Finally, several new subsurface road systems display features beyond the current experience e.g. underground roundabout that cannot easily be assessed.

Cooperation between the federal road authorities of Switzerland (FEDRO) and Norway (NPRA) was initiated aiming at developing a joint “best practice” methodology and a corresponding tool for the risk assessment of road tunnels [10]. A software tool was developed which takes basis in the proposed methodology. This tool is called TRANSIT. The present paper describes the methodology and presents the application of the methodology.

**CONVENTIONAL APPLICATIONS OF ROAD-TUNNEL RISK ASSESSMENT**

Building on the theoretical foundation developed by the JCSS in 2008, Faber et al. [4] developed a methodology for an uniform risk assessment for the Swiss road network. The results of this project form the framework and precondition for an efficient, transparent and communicable treatment of risks and they facilitate that risks from different sources are treated in the same manner and assessed on the same basis so that they are comparable, may be aggregated and transparently documented and communicated.

PIARC has been one of the main initiators for promoting safety in tunnels and has among others initiated the ERS2 project in collaboration with OECD for harmonizing the risk analysis and regulation of transport of dangerous goods. This topic has been ratified by UNECE and the ADR prescribes the risk analysis methodology for determining five predefined groups of restrictions for transport of dangerous goods through road tunnels.

In the report PIARC C3.3 Risk Analysis for Road Tunnels PIARC [8], PIARC has followed up on the risk analysis methods used in Europe. Several methodologies and tools for the risk assessment in roadway tunnels exist already. The most common are TuRisMo (Austria), TuSi (Norway) BASt model (Germany), HQ-TunRisk, TunPrim/RWSQRA (Netherland), QRAM (OECD – PIARC) and ASTRA ADR (Switzerland). All these methodologies have their advantages in specific fields. A review and analysis of these methodologies has showed that the requirements with regard to the modelling of specific events (e.g. accidents and fire) neither from the Directive 2004/54/EC of the European Parliament nor from FEDRO and NPRA are fully met, Hoj and Horn [5]. The methodologies fail to model all events or relevant indicators are not considered. Another aspect is that in some methodologies the level of detail is not sufficient for the ranking of different decision alternatives to reduce the risk.
NEW APPROACH: BAYESIAN PROBABILISTIC NETWORKS (BPN)

Introduction
The general approach utilized in TRANSIT differs significantly from the approach used in the other models mentioned above. The major difference is that the system is modelled and analysed using Bayesian Probabilistic Networks (BPN’s) which results in a hierarchical indicator based risk model.

Simplified, BPN’s can be considered as an advancement of event trees. They provide the possibility to fully represent simple event trees but also dependencies between different indicators and consequences can be considered, see illustrative example Figure 1. They are also efficient in regard to the graphical representation of complex systems so that they facilitate to make plausibility checks in regard to causal relations between different indicators. Bayesian Networks represent the current state of the art in the risk assessment.

Bayesian Probabilistic Networks (BPN) have been developed in the mid of the 1980ies with the motivation to deal with information from different sources and interpret and establish coherent models (Pearl [7]). Today, Bayesian Networks are widely used in systems with artificial intelligence, expert systems for diagnosing diseases (Kahn et al. [6]) but also in the engineering sector Deublein et al. [2] and in natural hazards management (Schubert et al. [9]). They are used due to their flexibility and efficiency in regard to system representation.

[Diagram of a Bayesian Probabilistic Network showing indicators, events, and consequences in a tunnel segment.]

Figure 1  Simplified illustration of a generic system representation using a BPN.

Generic risk representation
The road tunnel users are exposed to various risks which have different causes. The largest contributor to the risk is collisions and other types of ”normal traffic accidents”. Fire events as consequence of accidents or due to technical problems with engine or brakes are also events which must be considered in road tunnel risk assessments. Finally, rare events with potential large consequences, such as events with dangerous goods transports, must be considered as well.

In general, risk to users in the tunnel has to be considered in both the planning phase and during the operational phase of tunnels. Two different classes of measures can be differentiated: one class concerns the reduction of the exposure, i.e. the reduction of the accidents and fire frequency and the other class concerns the reduction of the consequences when a fire or an accident occurs. The main criterion in the planning phase of such measures is the cost efficiency of the measures. In order to judge the efficiency of measures, the influence of the measure on the risk has to be quantified.

A key feature of this methodology is that the uncertainties and the dependencies of the parameters, which are explicitly considered for the modelling of event frequencies and consequences, are
The system constituents are modelled using so-called risk indicators which can represent the system in a generic manner, i.e., all possible configurations of the system can be represented by using an appropriate choice of the indicators. From this definition, it is clear that the choice of the indicators plays a major role in the risk assessment and of course, any choice cannot be exhaustive. These Key Performance Indicators (KPI) can be used to establish a generic system representation for a risk model for a generic tunnel segment.

The risk model for the segment is generic, that means that one risk model for all possible characteristics in a tunnel is used. The model becomes specific by introducing evidence on the specific parameters, such as annual average daily traffic (AADT), the fraction of heavy goods vehicle, etc., in the model and by performing inference calculations.

For a specific tunnel segment some or all of the considered KPI’s are known and this knowledge can be transferred in the model by introducing evidence in the generic model. In this sense, the model becomes specific for this specific segment (see Figure 2). The same generic model can be used to calculate the risk under specific conditions. The risk can be calculated for each single segment as well as for the entire tunnel. Segments with higher risk in the tunnel can be identified and specific risk reducing measures for these segments can be identified.

Bayesian Networks for accidents, fires and dangerous goods accidents

The risk model is established by employing Bayesian Probabilistic Networks. The BPN developed for accidents and fires in tunnel is shown in Figure 3. It contains 39 nodes and 58 links. Each node represents an indicator whereas some of the indicators are observable (O), some indicators are logical observable (I) and some indicators are logical non-observable (G). The notes denoted with (R) are the outcome of the network. The links between the nodes represent the relation between the nodes. This relation can be a probabilistic or deterministic function or a function estimated by expert opinion.

Each of the nodes contains a different number of so-called states. These states represent the different possible characteristics of the node which can be observed in reality. The node “number of lanes” contains 3 states, i.e., one lane, two lanes and three lanes per direction. By knowing the number of lanes and the number of vehicles per hour, the level of service can be calculated. One kernel node in the network shown in Figure 3 is the node AMF. This node represents the “Accident Modification Factor” (AMF). The hypothesis is made that one basis or mean accident rate for the tunnel can be calculated over the entire network. Under different circumstances, this accident rate might be higher or smaller than the average rate. The AMF represents the difference of the accident rate in a specific segment from the mean value of all existing segments in the entire road network.

If it was possible to observe directly the different indicators in the data acquisition, the use of AMF would be obsolete. This would mean dedicated statistics for all combinations of traffic, tunnel lay-out, geometry, tunnel equipment etc. Since the tunnel designs are too diverse and the accidents, injuries and fatalities are too infrequent such statistics can hardly be established for all combinations. The
The concept of an accident modification factor (AMF) has the clear advantage that the models can be used and the results be extrapolated to conditions which are not directly observable. When statistics becomes available for some of the combinations, the existing prior distribution can be updated with this new information. The AMF is a normalized function of one or more indicators \( i \), i.e. 
\[ AMF = f(i_1, \ldots, i_n) \]
with a definition range of \([0, \infty]\). The AMF are assessed with different methods and models for the different considered indicators.

The Bayesian Network to model dangerous goods events in the tunnel is shown in Figure 4. This network can easily be simplified for the purpose of illustration. If one neglects all risk indicators describing the site and object specific characteristics, i.e. all “O” nodes, then the main node has the name Dangerous Goods Incident. This node contains all relevant and representative events and the rates per vehicle kilometre specified by PIARC. From this node, three general links go to the three principle hazards, i.e. pool fire, explosion and toxic events. Given a specific principle event and given the specific characteristics of the KPI’s the expected number of fatalities and injuries can be calculated.

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Figure 3 Bayesian network for accidents and fire events due to general traffic conditions.
EXAMPLE OF APPLICATION

Introduction
As part of a competition for the elaboration of a new methodology for the risk analysis of national road tunnels in Switzerland, the Federal Road Administration (FEDRO) had defined following test case in order to evaluate and compare the approaches by the competitors under realistic conditions.

Tunnel key parameters:
- Two 4.6 km long tunnel tubes with inclination of 1% and -3.5% (respectively 3.5% and -1%), which are operated in unidirectional traffic, see Figure 5.
- 56’000 vehicles per day, 11 % heavy-goods vehicles and annually 300 hours with congested traffic.

Following measures were to be investigated:
- M1: Reduce egress-route distance from 600 m to 300 m; investment costs 5 million CHF
- M2: Provide drainage according to current standard using continuous slots; investment costs 10 million CHF.
- M3: Increase the traffic space height from 4.50 m to 5.20 m; investment costs 130 million CHF.
- M4: Refurbish tunnel ventilation to current state-of-the-art concentrated smoke extraction at fire location with remote controlled dampers instead of the distributed smoke extraction; investment costs 13 million CHF and annual maintenance costs of 260’000,-- CHF.

Having upgraded the tunnel according to these measures, the tunnel would meet current Swiss standards.

Moreover, following situations should be examined:
- M0: Tunnel in current condition i.e. prior to upgrading
- MB: Tunnel in construction period operating only one tunnel tube with bidirectional traffic
- ME: Tunnel subsequent to upgrading the tunnel with the measures M1 to M4

Figure 5 shows the eight homogenous segments (including the two outside the tunnel portals) that were used for the Quantitative Risk Analysis.
Current condition (prior to upgrade)
As seen in Figure 6, the computed accident rates are higher in the portal zones than inside the tunnel. Moreover, the computed accident rates vary with inclination and hence increases at about 2900 m.

For the transports of dangerous goods, the computation for the current condition shows that the tunnel is just acceptable according to the statutory order for hazardous incidents, see Figure 7. The 300 h annually with congested traffic causes a plateau in the risk profile at 30 to 70 fatalities.

In order to assess the sensitivity, computations were carried out with other daily traffic profiles than those specified for the test case. Assuming a traffic profile that is typical for commuter traffic with morning and evening peaks then the cumulated exceedance frequency of number of fatalities would be beyond the statutory order for hazardous incidents. Consequently, mitigation measures for the transports of dangerous goods had to be considered. Daily traffic profiles can hence play an important role.
M1: Reduction of egress distance from 600 m to 300 m
Reducing the egress distance from 600 m to 300 m has a positive effect on the consequences i.e. the number of injured and fatalities. However, observing the base egress probability, this effect becomes much stronger at egress route distances below, say, 200 m, see Figure 8.

This measure causes an about 10 % reduction in consequences in terms of injuries and fatalities for normal traffic incidents. In case of transports of dangerous goods, this reduction is merely about 6 %, as this measure has no influence on the consequences caused by explosions.

![Base escape probability as a function of the distance between escape routes.](image)

M2: Drainage system with continuous slot according to current standard
TRANSIT considers the effects of the longitudinal and transversal slope of the road, the type and the efficiency of the drainage system. The prime benefit of installing a state-of-the-art drainage system is to reduce the size of the spillage pool and hence the heat-release rate of the fire, which predominantly is relevant for the scenarios with transports of dangerous goods in which case the fatalities were calculated to be reduced by 33 %. The influence in case of normal traffic incidents is negligible. Therefore in case of this test case, the overall risk is less reduced.

M3: Increasing the height of the available traffic space from 4.50 m to 5.20 m
According to EU-guide line 96/53/EG, which is also applicable for Switzerland, the maximum height of vehicles is 4.00 m. With an available traffic space height of 4.50 m, a safety margin of 0.50 m already exists. The main reason to heighten the available traffic space is therefore to facilitate passages of special transports. Moreover, the danger of collision between part of a vehicle and the tunnel equipment is reduced. Consequently, the probability of incidents and the consequences of such are reduced. On the other hand, they have insignificant influence on the risks due to transports of dangerous goods.

The number of incidents would be reduced by about 4 % and the number of fatalities by 2.4 %. The exposure i.e. in the case the frequency of fires would by this measure be reduced by about 0.6%.

M4: Tunnel ventilation with concentrated in lieu of distributed smoke extraction
A modern smoke-extraction system according to the Swiss guideline would extract 160 m$^3$/s over a distance of 200 m and at the same time ensure control the longitudinal flow in the tunnel so that the smoke does not flow beyond the extraction zone. This is much more efficient than earlier smoke-extraction of semi-transverse and transverse tunnel-ventilation systems that extracted the smoke over long distances at a rate of 80 m$^3$/s,km. The old system would therefore extract 16m$^3$/s over 200 m and not control the longitudinal flow in the tunnel.
The modern concentrated smoke extraction increases the possibilities of self-rescue in case of fire. It has an influence on the consequences but not on the probability of an incident.

According to the computations, the number of injured in case of fire would be reduced by 85 % and the number of fatalities by 80 %.

**Comparison of the measures**

Table 1 compares the costs and efficiencies of the measures. Although refurbishing the tunnel ventilation is associated with high costs, this is the most efficient measure (290 %). Also the reduction of the escape-route distance from 600 m to 300 m proves to be efficient.

Heightening the available traffic space (from 4.5 m to 5.2 m) as well as constructing a continuous slot drainage system are inefficient in terms of the limiting cost principle. Nevertheless, the state-of-the-art drainage system carries other advantages such as enabling transports of dangerous goods and could therefore in terms of a societal cost-benefit analysis still be considered to be a beneficial measure.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Investment costs [million CHF]</th>
<th>Reduction in fatalities [%]</th>
<th>Efficiency of measure [%]</th>
<th>Cost efficiency of measure according to limiting cost principle</th>
<th>Particular advantages for permission of transports of dangerous goods</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1: Egress distance 300m (instead of 600 m);</td>
<td>50</td>
<td>4.4</td>
<td>138</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>M2: Drainage with continuous slot</td>
<td>10</td>
<td>0.1</td>
<td>2</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>M3: Increase available traffic space from 4.50 m to 5.20 m</td>
<td>130</td>
<td>1.6</td>
<td>2</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>M4: Tunnel ventilation according to current standard</td>
<td>13</td>
<td>39.9</td>
<td>290</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

A sound methodology is developed and presented in this paper representing the best practice in the field of traffic safety assessment of road tunnels in accordance with the state of the art in the field of risk assessment. The methodology facilitates the risk-based decision making with respect to risk-reducing measures during the planning and during the operation of the tunnel. The methodology gives comparable and reproducible use-independent results.

The general approach in this project differs significantly from other methodologies for the risk assessment in roadway tunnels. Bayesian Probabilistic Networks (BPN), which are used to model the events, are a best practice methodology in the field of risk assessment and they facilitate the assessment according to recent scientific standards. TRANSIT represents the tunnel system in a generic manner, i.e. risks are assessed in segments, which are defined as a function of the tunnel and traffic characteristics. TRANSIT facilitates the risk assessment on different levels of detail. If only a
few details on the tunnel and traffic characteristics are known, the analysis can still be performed. Missing information on risk indicators is replaced by a priori distributions. When more specific information is available, the level of detail of the analysis can be increased.

The test case has demonstrated that varies measured can be quantified such that the most cost-efficient ones can be selected. In some cases, less cost-efficient measured should nevertheless be considered as they may influence the usage of the tunnel e.g. allowing for transports of dangerous goods.

When using QRA for decision making, a sensitivity study of the parameters should be conducted. In the presented test case, the daily traffic profile had a significant influence on the estimated risks due to transports of dangerous goods.

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Assessment model for the transport of dangerous goods through road tunnels

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ABSTRACT

In many cases decisions have to be made with respect to the safety level that has to be maintained in tunnels. In this paper the central question is how one can decide between (a) a tunnel with limited allowance for dangerous goods and a deviation route for the prohibited goods or (b) a tunnel allowed for all dangerous goods and possibly equipped with additional safety measures. In principle these type of decisions should be taken, at least partly, by comparing the costs and benefits of the various alternatives. This paper gives an outset of such an approach and discusses the needs for further research.

KEYWORDS: dangerous goods, risk analysis, social cost benefit analysis, transport, road tunnels.

INTRODUCTION

At present, many road tunnels in the Netherlands are not open for the transport of all dangerous goods. The obvious reason is that dangerous good transport may lead to fires and explosions and thus to serious accidents in tunnels, endangering the lives of many people and in extreme cases possibly the integrity of the tunnel structures itself. However, the alternative routes that have to be taken may pose other groups of persons at risk and is an economical loss in itself. So the question arises whether it makes sense to allow free transport in a larger set of tunnels or maybe all.

Current rules and laws are limited to safety and not very well structured to deal adequately with those type of decisions. In the Netherlands there are requirements with respect to internal safety, external safety, structural safety, rescue operations and so on. Those rules have been developed more or less independently from each other and there is no guarantee that they will be consistent in all circumstances. What is needed is an integrated inventory and assessment of risks for a set of feasible alternative solutions.

This paper summarises the set up of such an approach, based on a number of research projects carried out in the last decade [1, 4-7]. The basis of the method is a social cost-benefit analysis (SCBA) over the (remaining) life time of the structure. A simplified case study will be presented to illustrate the ideas.

DISCUSSION OF AVAILABLE ASSESSMENT METHODS AND MODELS

In this section we will discuss three earlier methods developed and used for the assessment of infrastructure: the OEEI, TNO and DARTS methods.

The OEEI model

The OEEI guideline (Research program Economical Effects Infrastructure, in Dutch: Onderzoeksprogramma Economische Effecten Infrastructuur) describes a method for the assessment of large
infrastructure projects, based on the social costs and benefits of the different alternatives [3]. Difference is made into direct effects, indirect effects, external effects and imponderables. Direct effects are directly related to the infrastructure under consideration, e.g. maintenance costs or reduced travel time. Indirect effects are effects on the remainder of the economy, even cross-border effects. For the case at hand these effects are not applicable. External effects are the unintentional and unpriced effects on the common well-being, e.g. environment and safety. That the effects are unpriced does not mean that the consequences are unpriced as well. For example, the unpriced effect of noise nuisance may lead to lower prices of houses. Imponderables are effects that cannot be expressed in money, such as “distribution effects”. Distribution effects mean that the effects, positive as well as negative, are not distributed equally between groups of stakeholders, such as users, residents, etc. [1]. The structure and methodology of the OEEI model can be used as a basis for the assessment model.

The TNO assessment model

In the 1980’s TNO has developed an assessment model to decide upon the preferred route for the transportation of (classes of) dangerous goods and to assess whether the corresponding risk is acceptable. The model gives insight in the risk in terms of victims and in the economical costs and has been described in [4, 5, 6, 7] and has been, amongst others, applied in [8, 9].

![TNO assessment procedure diagram]

Basically the routes and surrounding area up to 250 m from the route are segmented and both the population density and the economical value of the buildings are determined. Most of this information is available after execution of a risk analysis for internal (RWS-QRA [10]) and external (RBMII [11]) safety. However, the TNO risk analysis model additionally indicates the material damage based on scenarios with explosives, flammable gasses, toxic liquids and toxic gasses. The model takes into account the following aspects:

- Number of victims per year:
  - Victims on the road/in the tunnel due to traffic incidents with dangerous goods involved;
  - Victims in the surrounding area due to traffic incidents with dangerous goods involved;
  - Victims due to traffic incidents without dangerous goods involved.

- Economic costs:
Material damage due to traffic incidents with dangerous goods involved;
Material damage due to traffic incidents without dangerous goods involved;
Additional transport costs associated with the longest of the two alternatives;
Damage due to transport;
Economic damage due to irreparable damage to the tunnel.

The results of the calculations are the expected value of the number of victims and the economic costs for every alternative. The expected value for large incidents is calculated separately, to include risk aversion. It is also possible to include a factor representing the acceptable value to prevent one victim. The analysis concludes with a sensitivity analysis, to get insight into the robustness of the preferred alternative.

The principle of the model is suitable as basis for the new assessment model. It focuses on the risks resulting directly from the alternatives, but does not include indirect or external effects, such as damage to the environment. An advantage is that risk aversion is included. A disadvantage is that the risk analysis is somewhat out-of-date and needs updating. The weighing method however can certainly be applied.

The DARTS model

Within the European Research project “Durable And Reliable Tunnel Structures (DARTS), a comprehensive decision tool has been developed [12]. The model is quite alike the OEEI model, but focuses on the attribution of costs to certain stages of development of the tunnel (design, construction, etc.) and on the detailed composition of the costs. The methods for the determination of costs are usually qualitative. The environmental effects have been subdivided in 11 aspects, which is too detailed for the case at hand, and will therefore not be treated here. For the assessment of the costs of the environmental aspects, several methods are supplied, such as:

- Contingent valuation method: the “willingness to pay” for a specific environmental issue or the compensation needed to counteract that effect;
- Travel costs method: the “willingness to pay” to travel to and through the nature to enjoy it;
- Hedonic price method: a method based on the difference in price between goods with or without the environmental effects (e.g. same house, with or without noise nuisance).

The DARTS model focuses on risks during construction, which is not relevant for the case at hand. Furthermore, additional (OECD) scenarios are taken into account, which are not applicable for this case as well. However, the principle of this method can be used as a basis for the new assessment model.

PROPOSED MODEL

Based on the study of the three assessment procedures we may distinguish four main steps [1]:

1. **A system description**

The first step is to describe the system characteristics of both the tunnel and the deviation route. These characteristics may be:

- Type of transport of dangerous goods (allowed categories);
- Tunnel system: lay-out, structure and installations;
- Safety measures: preventing as well as mitigating measures;
- Procedures;
- Emergency services;
- Education and training;
• Length of the deviation route vs. length of the tunnel;
• Road type(s) of the deviation route;
• Surrounding area: industrial area, residential area, etc..

2. Formulation of alternatives

For the case of the transport restrictions for dangerous goods the basic alternative is the current situation: a tunnel with limited allowance of dangerous goods transport and a deviation route for the transport of the dangerous goods that are not allowed through the tunnel. Most tunnels in the Netherlands, 21 out of 25, are currently ADR 2011 category C or D [13]. Category C poses limitations on dangerous goods that can cause a very large explosion, a large explosion or the release of a large quantity of toxic substances. In addition to category C, category D poses also limitations to dangerous goods that can cause a large fire.

The second alternative, the alternative that will be compared to the basic alternative is in first instance the situation where all dangerous goods transport takes place through the tunnel and the deviation route is not longer used for dangerous goods transport. In that way the tunnel under consideration becomes a category A tunnel: no limitations to the transport of dangerous goods.

After the first comparison it may turn out that the second alternative does not perform according to the minimum requirements for internal, external or structural safety. Then a third or even more alternatives may be introduced. These alternatives are as alternative two, but with a package of (safety) measures added to perform according to the requirements. The optimization of the package of measures is an iterative process.

3. Evaluation of relevant costs and benefits

The costs to be evaluated are presented in the list below. Benefits are included as costs with a negative value.

1) Financial costs
2) Traffic related costs
3) Risk related costs
4) Environmental costs (pollution, emission, noise, etc))
5) Interests of stakeholders/Distribution-effects
6) Risk perception

For the first three items a further subdivision into various items has been presented in the tables 1 to 3. Items 4 to 6 have not been further developed in this paper. The interested reader is referred to [1] and [12].

An interesting point of course is the way the loss of human lives is taken care of in a Social Cost Benefit Analysis. In this study we will consider a two step procedure. Based on [15, 16] a “value” for a casualty of 2 million Euro is considered in the economic calculation. Secondly it is required that the loss of human lives fulfils the requirements following from internal and external safety criteria, in principle both for Individual and Social Risk. In some countries, like for instance the Netherlands, those criteria may even be part of the law.

4. Comparison

In the last step the various alternatives are compared and a decision is taken. A possible decision might be to develop and consider a number of other promising alternatives.
Table 1: Financial costs

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>Basic costs of construction and standard package of safety measures.</td>
</tr>
<tr>
<td>Operation</td>
<td>Costs involved with labour, energy, cleaning, etc.. Differences in costs will occur due to differences in safety measures.</td>
</tr>
<tr>
<td>Maintenance and repair</td>
<td>Inspection, maintenance and repair of the construction and the installations of the tunnel.</td>
</tr>
<tr>
<td>Additional measures</td>
<td>Costs for technical as well as organizational measures (e.g. training and education of emergency services).</td>
</tr>
</tbody>
</table>

Table 2: Traffic related cost

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detour</td>
<td>The costs of driving via the deviation route consists of the fuel, maintenance and debit of the vehicles.</td>
</tr>
<tr>
<td>Travel time</td>
<td>The travel time costs consist of the (difference in) time that it costs to take the deviation route or the shorter route through the tunnel, expressed in money. The time gained is dependent of the difference in the length of the route, the speed (limit) and traffic build-up.</td>
</tr>
<tr>
<td>Additional measures for trucks</td>
<td>These costs concern measures at the source of unsafety, the trucks, such as reinforced tanks, compartmentalization and coating. The benefits of these measures not only benefit the safety of the tunnel, but also the remainder of the transportation route. The costs therefore need to be attributed by kilometre for example. One could choose to multiply the costs per kilometre with a weighing factor for tunnels, since they usually benefit more than the open road.</td>
</tr>
<tr>
<td>Enforcement</td>
<td>Currently certain types of dangerous goods are not allowed through the tunnel. This ban needs to be enforced, for example by the police. Furthermore the trucks may be controlled on the deviation route for not complying with the speed limits. Allowance of dangerous goods makes enforcement less or unnecessary.</td>
</tr>
</tbody>
</table>

Table 3: Risk related costs

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal risk</td>
<td>The internal risk needs to comply with the current rules and regulations regarding tunnel safety. In the current draft of the new Dutch law the limit for group risk is posed on $0.1/N^2$ per kilometre per year.</td>
</tr>
<tr>
<td>External risk (tunnel)</td>
<td>The external risk, the risk of victims in the neighbourhood of the tunnel as a result of an accident in the tunnel, should comply with the current rules and regulations.</td>
</tr>
<tr>
<td>External risk (deviation route)</td>
<td>The external risk should comply with current rules and regulations. The expected value of the number of victims will be generated according to CPR14 and CPR 18 with RMBII or risk curves.</td>
</tr>
<tr>
<td>Material damage</td>
<td>These are the costs involved as a result of traffic accidents, such as damage to vehicles.</td>
</tr>
<tr>
<td>Structural damage</td>
<td>Repair or reconstruction of the tunnel or of buildings in the neighbourhood of the deviation route as a consequence of an accident.</td>
</tr>
<tr>
<td>Medical costs for injured people</td>
<td>Medical care of injured people is usually twice the costs involved with deceased people. The number of injured people is usually much higher than the number of deceased persons.</td>
</tr>
<tr>
<td>Economical damage after closure of the tunnel</td>
<td>The costs related to unavailability and limited accessibility as a consequence of a closed tunnel for repair or reconstruction due to an accident in the tunnel. The costs are largely dependent of available alternative routes.</td>
</tr>
</tbody>
</table>
CASE STUDY

In this paragraph a case study is presented according to the steps of the assessment model presented above. It is a simplified version of the example in [1]. The calculations for this case study are based on the combination of the existing risk analyses. The order of magnitude of the output is realistic, but some of the results may be less logical or less fitting, due to the combination of methods. Furthermore some of the numbers are estimated, because no acceptable basis existed. Discounting future costs to the present has not been done for the sake of a clear example.

1. System description

The tunnel has a length of 2.4 km and consists of two tubes with two lanes. The safety measures are the standard measures.

Per day 77000 vehicles pass the tunnel, of which 37% trucks. About 3% of the trucks transport dangerous goods and only 3.7% of those trucks transport goods (compressed gas and so on) that are not allowed to pass the tunnel. So every day 0.37*0.03*0.037*77000 = 0.0004*77000 = 32 vehicles per day or about 11500 vehicles per year need to make a detour. The detour is 15 km.

2. Alternatives

The basic alternative consists of a category C tunnel where dangerous goods involving gas or highly flammable materials are prohibited. The second alternative is a category A tunnel where all traffic is allowed but with no additional measures taken.

3. Relevant aspects

Only traffic and risk related costs will be considered in this example. Other costs are either the same for both alternatives or have a negligible influence. Costs are calculated for a period $T = 50$ a, say the anticipated lifetime of the structure. For simplicity no discounting is performed.

Traffic related costs

a. Detour

The fuel costs are estimated to be 0.19 €/km and 0.05 €/km for maintenance and depreciation. Given a deviation route of 15 km and a yearly average of 11500 vehicles, the costs are 2.1 Million Euro during the lifetime of the tunnel.

b. Travel time

UNITE [14] states the value of travel time for a heavy goods vehicle (HGV) to be 43 €/hour. Based on the type of roads and their length and average speed of the deviation route, an average travel time of 15 minutes has been estimated. This brings the travel time benefits over the lifetime of the tunnel on 6.2 million Euro.

Risk related costs

The average number $N$ of serious accidents leading to explosions or big fires during the life time $T$ if all traffic is allowed in the tunnel will be in the order of magnitude of

$$N = \lambda nLT$$

Where $\lambda$ is the probability that a serious accident leading to fire or an explosion will occur per driven vehicle kilometre in mixed traffic, $n$ is the traffic intensity, $L$ the length of the tunnel and $T$ the period
under consideration, in our case the design life time. Taking:

\[ \lambda = 5 \times 10^{-11} \text{ (veh.km)}^{-1}, \quad n = 77,000 \text{ veh/day}, \quad L = 2.4 \text{ km and } T = 50 \text{ a} \]

We arrive at:

\[ N = 5 \times 10^{-11} \times (77000 \times 365) \times 2.4 \times 50 = 0.17 \]

One might also say that the probability of having a serious accident in the tunnel is 17%.

Once an accident with trucks containing atmospheric or pressured gas has occurred, various scenarios may develop. In principle there may be just a fire, a gas explosion, or a cold or a warm BLEVE. Pressures on tunnel elements and consequently resulting damages may vary, depending on a large set of details. In [1] the likelihoods and consequences for a number of these scenarios have been investigated. The result has been summarised in Table 4. It has been assumed that the tunnel will collapse partly at explosion pressures above 250 kPa and that full collapse may occur at BLEVE pressures higher then 450 kPa.

Table 4: Risk calculation given a fire accident

<table>
<thead>
<tr>
<th>Event</th>
<th>Conditional Probability</th>
<th>Damage class</th>
<th>Damage [M€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire (large)</td>
<td>0.46</td>
<td>Small</td>
<td>3</td>
</tr>
<tr>
<td>Explosion &lt;250 kPa</td>
<td>0.04</td>
<td>Small</td>
<td>3</td>
</tr>
<tr>
<td>Explosion &gt;250 kPa</td>
<td>0.10</td>
<td>Medium</td>
<td>25</td>
</tr>
<tr>
<td>BLEVE &lt;450 kPa</td>
<td>0.05</td>
<td>Medium</td>
<td>25</td>
</tr>
<tr>
<td>BLEVE &gt;450 kPa</td>
<td>0.35</td>
<td>Large</td>
<td>255</td>
</tr>
</tbody>
</table>

Calculating the products of probabilities and damages and adding them we arrive at an expected damage \( E_D \) of 95 M€. Multiplying with the expected number of serious events \( N = 0.17 \) we arrive at a risk of

\[ \text{Life time Risk} = N \times E_D = 0.17 \times 95 = 16 \text{ M€} \]  

The number of casualties can be calculated in a similar way. For the basic alternative one should also calculate the number of casualties caused by the 15 km detouring dangerous good transports. In this example a net number of 2 additional live losses resulted [1].

4. Comparison

The economic gain of having less detours is (rounded off) 8 Million Euro while the loss due to the extra risk is 16 million Euro. In addition there is an expected additional loss of lives, which will increase the 16 to 20 million Euro if the 2 M€-value mentioned before is adopted.

The conclusion is that in this case the tunnel should not be set open to all types of traffic. Of course this might be different if for instance the detour would have been larger or if additional measures could be taken without too much effort. In [1] this has been elaborated to some extent.

CONCLUSIONS AND RECOMMENDATIONS

The assessment model as presented in this paper has been based on the structure of the OEEI guideline and the components of the TNO, the DARTS and the RWS-QRA models. The systematic approach seems to be feasible for facilitating decisions regarding the allowance of all dangerous goods through tunnels. However, the assessment model is an outset that needs to be further
developed, for example by means of case studies.

In the outset for the assessment model, the following knowledge gaps have been identified:

1. The current outset for the assessment model does not include the option of weighing factors. It should be possible to incorporate weighing factors in the model. Furthermore the quantification of the weighing factors, which is dependent of the stakeholders as well, should be determined.
2. The structural damage as a result of the scenarios that are identified in the RWS-QRA model, cannot yet be quantified. Especially the structural damage as a result of explosions, but also as a result of toxic substances, is an important knowledge gap. The costs involved with structural damage, for example for repair or as a result of collapse of the tunnel, are unknown.
3. The current RWS-QRA model only quantifies victims, but not injured people. Quantification of the number of injured people is important for the further development of the assessment model.
4. The current RWS-QRA model does not include explosion scenarios in a proper way and needs to be improved.
5. If safety measures need to be taken, these can be applied to either the tunnel or the trucks. At the moment it is not possible to quantify the (part of the) costs that are involved with the application of safety measures to trucks.

It is important that procedures and methods are developed further in order to reduce the degree of arbitrariness and inconsistency in choosing between alternatives. This does not only hold for the closure of vehicles for certain type of transports but equally for all other type of safety related decisions.

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Fire Ventilation Upgrades: Can a retrofit be detrimental to Fire Life Safety?

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ABSTRACT

Technological advances have provided improved materials and equipment, a greater understanding of fire and fire growth, and the methods to enhance life safety in a fire event. When undertaking upgrades or renovations to subway or underground rail systems, the goal is to improve both the social utility and life safety for the user. In doing so, it is customary to upgrade the system to the latest Codes and Standards. However, if an integrated approach is not adopted, performance of critical components of the safety systems could be compromised, particularly if improvements among civil works, and mechanical and electrical equipment are not coordinated, procedures are not updated, or if the upgrade takes place in stages.

This paper discusses an integrated approach that was undertaken for system upgrades to two mass transit systems. The approach established goals for upgrading the tunnel safety systems and the tunnel ventilation system, and provided an accurate assessment of the existing system and equipment. In the process, it was determined that unless undertaking a complete system upgrade, a sequenced or partial approach could degrade the current life safety of the systems. This leads to the conclusion that the benefits of a sequenced upgrade need to be continually checked to ensure that improvements are actually delivered – not just assumed to be delivered due to the system performance being upgraded. It also reaffirms that appropriate training must be developed and maintained to ensure the appropriate response in an emergency event.

KEYWORDS: Emergency Ventilation Systems, Fire Ventilation Upgrade, Tunnel Fire Simulation
INTRODUCTION

Throughout the world there are thousands of road and rail tunnels used by hundreds of millions of people on a daily basis. Many of these tunnels in service are older and in many cases do not meet the required safety standards of modern tunnel systems. Two transit large bodies that have been operating for at least half a century have recently planned a Fire Ventilation Upgrade (FVU) in hopes of improving safety and security for patrons. Much of the older existing tunnels in these systems fail to comply with the stringent safety standards associated with modern design. In the case of tunnel ventilation, the capital cost of bringing systems into compliance can be extremely high, with complex implementation logistics.

Besides the constraints of the as-built system, for one transit body it was stipulated that the ventilation upgrade involve various alternatives, and it was encouraged by another transit entity that a phasing plan be developed for the upgrade to be implemented in stages. This paper discusses the ventilation upgrade strategies to provide an acceptable level of safety. A typical design approach was taken, and the metrics and assessments will be discussed. In both cases, consideration of much more than equipment alone was needed to achieve the goals of the studies.

BACKGROUND: A 'Typical' Ventilation Upgrade

Analysis and design of ventilation for a retrofit involve much of the same approach as for a new tunnel system. The goals of a ventilation upgrade are to achieve safety goals at a low relative cost while minimizing impact on operations. A general set of guidelines for such design are:

1) Assess the existing ventilation system in total:
   Procure as-built drawings or survey the site, collect field data and equipment information/working status, inquire of future plans in nearby areas, measure the system capabilities.

2) Establish criteria appropriate for the design:
   Revisit the worst-case scenario, potential fuels, and vehicles in the tunnels and stations; consider relevant codes and standards; develop evacuation requirements; obtain approval from the authority having jurisdiction (AHJ) and owner/operators.

3) Develop a simulation plan:
   Determine the worst-case locations for design fires and a tentative plan for addressing each scenario.

4) Create a model and perform the initial tunnel simulation:
   Accurately represent the tunnel system calibrated to field data and incorporating connected entities, size the fans, estimate ventilation equipment alternatives, estimate construction alternatives.

5) Determine what is required to make the system reasonably safe:
   It is at this stage of results that alternatives and risk are assessed to produce the best design moving forward. Start to develop drawings and cost estimates in greater detail. Confirm concepts with civil, electrical, mechanical teams and the operator and AHJ. Are operational considerations being evaluated that might reduce the likelihood of a fire ever starting?

6) Develop detailed models for station simulation:
   Prepare input for computation fluid dynamics (CFD) models. Optimize ventilation equipment sizing, perform additional tunnel studies for patron comfort, develop equipment operating schedules, prepare tunnel data for field tests.

7) Perform CFD testing of stations:
   Perform evacuation modeling of tunnels and/or stations. Evaluate tenability with respect to the evacuation requirements.

8) Construct the ventilation upgrades:
   Ideally, revenue service can continue with little or no impact to passenger travel.
CODE REQUIREMENTS

National Fire Protection Association (NFPA) 130 (Standard for Fixed Guideway Transit and Passenger Rail Systems) represents the most directly applicable fire standards for rail tunnel systems. The application of the complete standard is valid to new tunnels and extensions of existing systems; however, the portion of the standards dealing with emergency procedures is applicable to both new and existing facilities. In both studies, NFPA 130 was used as a goal to design to, and also in assessing tenability conditions as outlined in the Annexes. Additionally, applicable local fire, building and electrical codes and/or health regulations supersede NFPA 130 and address underground public spaces in the stations, and were therefore stipulated in planning documents.

The upgrade of transit rail tunnels can be complex, difficult and expensive to incorporate. One of the challenges was to ensure that construction access for the installation of fan and electrical equipment be from easily accessible points, preferably at street level.

STARTING POINT

For both transit entities, a decision for a ventilation upgrade had been made in addition to other risk mitigation measures, and criteria had been determined. It was accepted that in the event of a train fire, sufficient flow may not be generated to prevent back-layering in the evacuation path in tunnels, given the restrictions on space and power for new equipment. For one study, some additional applicable local building and health standards were adopted. It was also accepted that the vehicle type had not changed significantly, justifying a higher heat release rate of potential combustibles versus newer, fire-hardened trains. Furthermore, 1-D Subway Environment Simulation (SES) models existed in some form so updating them for either project was not as major an effort as creating these models from scratch, but which required confirmation of the accuracy of the software input. The initial tunnel simulation stage (point 4 above) of the studies was therefore a challenge, more with respect to data management, as the number of alternatives was great for each system. Moreover, at this stage of analysis the phasing was considered in the iterative process for one of the systems.

As older subway systems are typically complex networks of tunnels and stations, located in heavily urbanized areas, there is generally little room for emergency ventilation shafts and fan rooms, so any available space was considered for use in the FVU efforts. The original ventilation systems for these subways were primarily designed for removal of dirt and heat associated with normal operation of trains and mitigation for the piston effect on patron comfort. Passive street vents that exist in both systems present an issue due to the difficulty of closure during a fire event, the effects of weather on nearby equipment and the problem of finding a suitable location for new ventilation fans.

Based on site surveys, collected data and previous studies, the worst-case fire scenario was determined for each ventilation zone to provide the most conservative sizing of equipment. For each proposed ventilation equipment modification, a set of simulations including response at each fire location determine the overall performance of the enhancements. One measure of a worst-case fire scenario is the likelihood that back-layering can be prevented; a calculated critical velocity in a tunnel is based on tunnel grade, tunnel height, tunnel sectional area, density and temperature at the fire site, the fire heat release rate, ambient air values and gravity, and represents the flow at which back-layering for a specified fire intensity is prevented. Back-layering is the flow combustion products in the opposite of the intended ventilation direction.

Fire was the primary design factor for estimating ventilation capacity, and the different fire locations considered such factors as tunnel area, grade, length of tunnel segment, ventilation zones, proximity to portals, fire location on the train, etc.

One-dimensional modeling was initially used to simulate alternatives and assess ventilation performance. This is an iterative process that can be used in parallel with more complex three dimensional analysis once a cohesive system design takes root.
**FVU Construction Options**

For the first stage of analysis, a set of construction and equipment options was proposed to be tested. The options ranged from the simple replacement of fans with the newest functioning equipment to a total reconfiguration of the ventilation system to provide compliance with current NFPA criteria, that included purchasing land for new construction, much above-grade and track level demolition and construction, and new equipment. Additional hybrid construction alternatives based on the simple and NFPA compliant construction options. For each construction option, models representing each upgraded system were analyzed at each fire location proposed in the simulation plan. Results were then compared to the revised critical velocities at each fire location and provided to the client with a rough estimate of cost for evaluation. For each construction option or ventilation alternative, the key metrics had to be revisited to ensure that, for instance, revised fan capacity was indeed based on the revised worst-case scenario, or that for such a location, the critical velocity was calculated from the characteristics of the upgraded location.

Important to note is that depending on the preferred construction option, the worst-case fire location may change, and if tunnel separation walls are added or removed, critical velocity may need to be recalculated for subsequent analysis, as presented in Figure 1.

During the survey of one project, before the creation of the base model, it was decided that all available space was to be seriously considered for FVU purposes. As such, a task was determining the greatest capacity that would fit into any space allocated for ventilation, the greatest capacity to replace existing fans, and how to include other flow control measures. Additionally, a phasing plan was presented as a result of initial analysis.

Because the system is a network of inter-related components affecting flow, the initial analysis step is critical. In both FVU projects, simply replacing equipment with the biggest and newest available equipment at each ventilation plant location did not necessarily improve control of smoke near a fire incident, precisely because of the interoperability of the components of the system. Given the space constraints, a bias was found tending to force flow in a predictable, yet uncontrollable ways. Balancing ventilation capacity, adding dampers, walls, baffles or portal doors to direct flow, and investigating alternatives within an iterative performance-based design framework were necessary to improve ventilation performance, hence Fire Life Safety, in the initial analysis. Overlooking the integrated nature of the tunnel ventilation system could lead to uncontrolled flows if unchecked.
EQUIPMENT PHASING

After determining the locations of existing and new equipment, and the potential benefits from a ventilation upgrade, phasing and other options were considered for fan replacement priority.

The priority of ventilation equipment upgrade was based on several factors, including:

- The number of zones dependent on the ventilation equipment. Equipment that is used in 3 or more zones would have a higher priority than equipment that only impacts a single zone.
- The current ability of the ventilation equipment to service a fire incident. Equipment that is unable to control airflow, or can do so to only a limited degree, has a higher priority than equipment that can manage flow at or approaching critical velocity in the impacted zones.
- The ability and need to reverse the fan. If the fan needs to operate in supply and exhaust, but is a single directional fan, upgrade is a higher priority.
- The percent improvement obtained with practical replacement. A fan where upgrade would provide a very large improvement in performance would have priority over one which provided only minimal improvement or none at all.
- The ability of the ventilation equipment to service a train fire incident. A fan where practical replacement would meet criteria would have a higher priority than equipment where upgrade would still not provide the needed capability.

Figure 1: Typical Construction Options Table for FVUs
• The ability of the fan to service a wayside fire incident. A fan that could at least service a wayside fire (lower HRR) with upgrade would have higher priority than one that could not.
• The ability to service a train fire incident with full capability replacement.

Other factors include the cost to replace the equipment, the cost to provide electrical power, and the availability of space.

Thus, a Fan Replacement Sequence table (shown in Figure 2) was created for the purpose of determining which fans, located along the subway lines, would benefit the ventilation system the most when replaced. Each fan plant in the system was identified by its location with the existing fan capacity and the direction of flow. The operating status and condition of the fan was noted for each fan and damper, also indicating any other existing problems such as electrical or exposure issues that may prevent the delivery of the required air flow. Also included in the table were critical fire locations, the intended fan capacity upgrade, fan operating mode and estimated flow results.

Based on the information compiled in the table, weighting of the various factors led to an engineering judgment precedence that was assigned to aspects of the existing ventilation system, and would be unique to any transit entity. Fire location, condition of equipment, existing capacity of equipment, existing versatility of equipment, potentially new locations for equipment, and existing equipment performance relative to critical velocity were each assigned weighting values. The precedence was chosen with the lowest sum of values as having the least precedence.

The first was whether the existing fan is working or not working. Precedence was also given to operating mode. Also considered was whether construction of new fan plant is needed, and/or the addition of a fan in an existing natural ventilation shaft. Percent of critical velocity achieved by existing fan capacity at each fire location was given a rank. The final precedence given to percent critical velocity was determined by adding the ranks for each fire location where the fan is used. A similar factor was based on the amount of gain in critical velocity that will occur with fan replacement. The total precedence is then determined by adding the precedence of all of the aspects of the ventilation system considered. The final fan replacement priority grouping was then based on the total precedence value.
Table: General Replacement Sequence Table for FVUs

<table>
<thead>
<tr>
<th>Location</th>
<th>Fan ID</th>
<th>Fan/Louver Number</th>
<th>Operating Status</th>
<th>Existing Fan Capacity kcfm</th>
<th>Proposed Fan Capacity kcfm</th>
<th>% Increase in proposed fan capacity at existing location</th>
<th>No. of fire Loc</th>
<th>Existing fan working mode</th>
<th>Operating Status</th>
<th>Added fan single or reverse dir</th>
<th>As-Is Runs</th>
<th>% Increase in proposed capacity</th>
<th>Total</th>
<th>Fan replacement precedence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 1</td>
<td>Fan ID1</td>
<td>Fan Stationing 1</td>
<td>O</td>
<td>R</td>
<td>93</td>
<td>25.0 X</td>
<td>3</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>50</td>
<td>1</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>Location 2</td>
<td>Fan ID2</td>
<td>Fan Stationing 2</td>
<td>K</td>
<td>E</td>
<td>120</td>
<td>112.0 S</td>
<td>3</td>
<td>10</td>
<td>S</td>
<td>S</td>
<td>75</td>
<td>3</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>Location 3</td>
<td>Fan ID3</td>
<td>Fan Stationing 3</td>
<td>O</td>
<td>E</td>
<td>90</td>
<td>90.0 X</td>
<td>2</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>68</td>
<td>2</td>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>Location 4</td>
<td>Fan ID4</td>
<td>Fan Stationing 4</td>
<td>X-F</td>
<td>NA</td>
<td>10</td>
<td>10.0 X</td>
<td>3</td>
<td>10</td>
<td>S</td>
<td>X</td>
<td>50</td>
<td>1</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>Location 5</td>
<td>Fan ID5</td>
<td>Fan Stationing 5</td>
<td>X-F</td>
<td>NA</td>
<td>110</td>
<td>30.0 S</td>
<td>3</td>
<td>10</td>
<td>S</td>
<td>X</td>
<td>60</td>
<td>1</td>
<td>15</td>
<td>2</td>
</tr>
</tbody>
</table>

Points Definition:

- 0: Existing fan working
- 10: Existing fan not working
- 0: No change in fan direction required
- 3: Change in fan air flow direction required
- 15: Construction of new fan plant
- 2: Addition of fan in natural vent shaft
- 0-25: Highest (+) % Crit Vel to Lowest (-) % Crit Vel
- 0-49: % Increase in proposed fan capacity
- 100-149: Motor work
- 150-199: Electric problem
- 200-249: Key way bad
- 250-299: Standing water
- 300-349: Other problem
- 3: Number of fire locations fan used, max 8
If a precedence is used when installing upgrade equipment, it is important to evaluate the state of the system at each stage to identify areas of vulnerability. The phasing plan provides another opportunity to optimize the ventilation system and ensure that performance and Fire Life Safety is indeed improved at all points within the subway. The staging analysis of the CTA system again demonstrates the inter-related nature of ventilation equipment and environments and the importance of revisiting critical metrics during FVU design iterations.

**FINAL ANALYSIS**

Detailed three dimensional CFD ventilation modeling allows for fine tuning of the design and determination of the fan and damper configuration for different modes of operation. Results from this phase of analysis are necessary to evaluate tenability criteria in stations or other more complex spaces than tunnels. It provides output to compare variables in the evacuation paths to criteria over time. Because the models are complex and resource-intensive, only the area immediately surrounding the simulated incident are studied (the incident station) but usually no more. Because of the focus of the CFD analysis, the remainder of the subway system is estimated through boundary conditions.

If a potential bias among inter-related ventilation components is not captured in the 1-D modeling, unless a potentially vulnerable area is included in the CFD analysis, it will not be represented at this stage of the design. However, if a bias is captured within the domain of a 3D study, it should prompt a reassessment of the FVU design.

The ultimate objectives for emergency tunnel ventilation systems are to provide tenable routes for passenger evacuation and fire-fighter access, and to help limit damage to facilities. The approach to be adopted for evacuation analysis should be defined as early as possible, and an iterative process should be used to evaluate potential the fire ventilation upgrade as a complete system. At the final design stage, known limitations of construction alternatives and phasing will be well-documented, and open communication within the design team is critical to ensure that there is buy-in from the client and the AHJ. While the engineers take ultimate professional responsibility for the design, it is important that key decisions are put through a series of reviews associated with approval of design concept through deliverables such as the design criteria document, ventilation simulation plan, iteration results and analysis reports.

**CONCLUSIONS**

A fire ventilation upgrade to emergency ventilation systems for existing transit tunnels presents unique challenges. The design steps and typical considerations associated with upgrading existing facilities include a detailed assessment of the existing system, applicable standards and codes, development of suitable criteria, consideration of risk analysis, and the development and application of accurate simulation models. Thorough communication with all players will ensure the best-integrated product. Considering the subway network as a set of inter-related components is necessary, a facet of iterative analysis, and will aid in identifying areas where system safety can be improved; otherwise, subtle equipment bias in particular environments can be misleading. Frequently, innovative solutions are needed to meet design and installation objectives. The importance of reassessing metrics and performance for various ventilation alternatives, construction options, or FVU equipment phasing plans must be stressed.

While satisfying the most recent tunnel code revisions in full may not be necessary, it is the duty of the designer to ensure that evacuation and Fire Life Safety is addressed as intended, and to the highest degree possible.
REFERENCES


ABSTRACT

Internationally, there would appear to be a lack of consistency as to how risk analysis is undertaken for major tunnel projects, and some real challenges in terms of risk data.

The type and level of risk analysis needed depends to some extent on the complexity of the tunnel. It also critically depends upon the legal and regulatory provisions of specific countries. It may involve fire and life safety considerations. However, in a number of countries it also needs to consider environmental issues, risk to disruption and other factors as part of a regulated process.

This article describes a methodology for a risk analysis and it gives ideas regarding an approach for risk analyses for major tunnel projects.

The methodology described in this paper forms part of a greater framework for risk management, which is touched upon in the article but not examined in any depth in this paper. It is important that the reader understands this broader process and does not see this methodology as a standalone process.

This methodology has been used and accepted by authorities on a number of international tunnel projects, as a key part of QRA studies for fire and life safety.
INTRODUCTION

The following article gives a short introduction about risk analysis for tunnels (life safety), where current practice is at the moment, and what we as authors consider important issues to consider and develop.

Internationally, there would appear to be a lack of consistency as to how risk analysis is undertaken for major tunnel projects, and some real challenges in terms of risk data.

While the EU Directive for road tunnels [1], and the TSI document for rail tunnels [2], highlights the need for risk analysis, there is no prescribed framework or methodology that should be followed internationally. Several European countries have established methodologies, and PIARC is understood to be continuing the work on guidance documents for future use.

The type and level of risk analysis depends to some extent on the complexity of the tunnel. It also critically depends upon the legal and regulatory provisions of specific countries. It may involve fire and life safety considerations. However, in a number of countries it also needs to consider environmental issues, risk to disruption and other factors as part of a regulated process.

BASIC METHODOLOGY

In general all types of risk analysis studies follow the same broad process. A basic methodology for risk analysis is set out in Figure 1 below. It shows a clear route from the project start to a final deliverable (the Risk Analysis Report).

Figure 1 \hspace{1cm} Basic Methodology
The first step “Project Context / Design” is the most important one. Before starting the design and implementation of a framework for managing risk, it is important to evaluate and understand both the external and internal context of the project and the client’s expectations, since these can significantly influence the design of the framework [3]. Part of this step is to clearly understand the project, and the external and internal parameters that need to be taken into account. That sets the scope for the remaining process; in other words establishing the context.

In this process of establishing the context is it very important to identify all stakeholders and in that way understand their objectives and concerns. A few important points that help establish the context are shown below, but a more detailed description can be found in [3]. The following are considered key points:

- the social and cultural, political, legal, regulatory, financial, technological, economic, natural and competitive environment, whether international, national, regional or local

- key drivers and trends having impact on the objectives

- relationship with, perceptions and values of stakeholders; for example regarding acceptable risks, good design, vital safety requirements, etc.

- form and extent of contractual relationships

Returning to Figure 1, there are two key questions to be answered in relation to the framework or methodology to be utilized for a tunnel risk analysis:

1. Is a qualitative or semi-quantitative risk analysis only required, using a risk matrix approach or similar? Or does this need to be extended into a full, Quantitative Risk Analysis approach (QRA)?

2. Is the QRA to be undertaken on a comparative basis, with the design compared on a risk basis with an acceptable benchmark, eg. PIARC [4], NFPA502 [5] design? Or have the regulations, or a stakeholders and authorities group set quantitative risk acceptance criteria in terms of individual risk, F-N curves or other criteria?

Once these questions are answered, the process of setting up event trees, determining frequencies for each event path, as well as establishing consequences through modelling and other means is fairly straightforward.

HAZARD AND SCENARIOS

A significant issue in risk analysis is the importance of the hazard analysis and scenario development upon which the QRA is based. This is considered to be the key part once the context has been established and the scope/process has been agreed among the stakeholders.

This part requires good communication and collaboration with the different stakeholders. It would normally include workshops and consultation with stakeholders and authorities as well as design team members and other experts. When this part has been worked through in detail only then can the foundation of the QRA be properly established. If done poorly this has the potential to drive the QRA to justify either an unsafe design or to an over-conservative and potentially costly design solution. This indicates that this part of the analysis is a very delicate process.

Arup has developed a methodology [6] for hazard analysis and scenario development for fire and life safety that is illustrated in Figure 2 below. The methodology is based on previous work [7]. It is equally applicable for other hazards, such as toxic or flammable gas or liquid releases.
Figure 2  Methodology: Hazard analysis and Scenario development

The methodology described above can be considered to be divided into two key parts: 1. Workshops to establish all possible fire scenarios, and 2. The use of event tree analysis to screen and group these possible fire scenarios.

The event tree analysis screens and groups the fire scenarios into three different groups. These are based on return periods. The event trees with their base frequencies and probabilities of each event yields the frequency of each scenario expressed as fires/year, or alternatively as a return period in terms of years per fire.

For the purposes of fire engineering analysis and design, all fire scenarios are divided into one of three groups, depending on their return period. The groups of scenarios are:

- Group 1 - Design Fire Scenarios (return period of less than 100 years)
- Group 2 - High challenge Design Fire Scenarios  (return period of more than 100 years but less than 10,000 years)
- Group 3 - Extreme events (return period of more than 10,000 years)

The first group is for design and are the basic and more common fire scenarios expected; the proposed design should be able to cater for these scenarios. The second group of scenarios is for sensitivity analysis (but could also serve for design); how well will the proposed design respond to these less frequent but higher consequence scenarios? The fire engineering analysis must show that safety is achieved or the risk is less than ALARP when a high challenge fire scenario is used to test the design.

The third group is not for design; the extreme events (rare events but which may have high consequences) are not for design but must be recognized as events for which data must be provided for the project QRA. An example might be a scenario involving an LPG tanker having a BLEVE in a road tunnel. The consequences of such an event in a tunnel would be very high, but cannot be cost effectively designed to prevent consequences. The strategy must be one of mitigation through detection of LPG tankers before they get into the tunnel and provide off-ramps to prevent their tunnel entry.
This methodology not only considers fires for a range of vehicle types, but also considers failure cases for detection, emergency ventilation and suppression, as well as other systems. It defines the worst credible scenario as the event having a one in 10,000 years return period (when group 2 is used for design). It also highlights the need to at least consider extreme events and mitigation measures, even if these events are beyond the limits of reasonable design.

ALARP PRINCIPLE

ALARP is an important principle that normally forms part of the risk analysis. It is very important that from the beginning of the project define and agree acceptance criteria for design. There will most likely be some of the design fire scenarios or the high challenge design fire scenarios that do not meet the preset acceptance criteria, for these cases the ALARP principle must be used. The “ALARP process” must include all the relevant stakeholders. What is reasonable to one stakeholder might not at all be reasonable to another. Close collaboration is needed.

The principle is shown in Figure 3 below.

![ALARP principle](image)

Figure 3 ALARP principle

When using this principle is necessary to keep in mind that if it is possible to reasonably argue that the fire risk has not been increased at all or not significantly increased by the “lack of” a design measure or the incorporation of mitigation measures then the design solution may be acceptable. This is the starting point for the process.
FIRE SAFETY SYSTEMS

Active fire safety systems are of high importance when it comes to life safety. They are also important when it comes to the risk analysis process and specifically when looking at failure probabilities.

Any type of active life safety system should be as robust and as simple possible. When a system becomes too complex it will, in many cases, have an increased failure probability. A typical example is the difference between a longitudinal ventilation system and a transverse ventilation system for emergency smoke management. The former has a number of jet fans located in the tunnel it would normally be designed to lose some number of them to failure and still be able to achieve the required critical air velocity in fire conditions. It can basically be seen as on/off system (starting up jet fans, or jet fans going into fire mode), this would be considered a simple and robust system.

On the other hand, a semi-transverse or transverse ventilation system is a lot more complex; specific sections of the tunnel need to be able to work properly (closing and opening of ventilation zones and dampers), and extraction rates need to be balanced against inlet air, etc. These systems can become quite complex. From a failure probability point of view these more complex ventilation systems would be more likely to be less robust and have a higher failure rate on demand than the simple longitudinal ventilation system.

The design of the different life safety systems is also very important. A good design will increase the robustness of the system and this is important from a risk point of view. Another as important part as the design is the maintenance of the systems, without a good maintenance regime the benefits of good design will shortly be lost, and this will also increase the life safety risks.

Sometimes optimization of design through value engineering (when this is based only on decreasing the cost) may also increase the life safety risks. For any type of optimization process the general aim of maintaining a robust system for which a good maintenance regime can be used must be kept in mind.

CCF

An important part of any risk analysis is a common-cause-failure (CCF) study. This is directly applicable to the life safety systems. The ideal situation would be to have totally independent systems i.e. no system dependencies which could cause simultaneous failures and thus a significant increase in overall risk. A typical example could be how the life safety systems are powered by one single power back up source, if this one source fails (due to bad maintenance, ageing, etc,) all systems will be lost.

Again the key to deal with this is to apply good design and of course be aware of the CCF concept. For more details regarding CCF information can be found in [8].

DATA CHALLENGES

There are three major challenges with risk analysis data regarding tunnels. They are:

1. There is some data for incidents in road tunnels, from PIARC, for example. However, it is mostly data looking back at incident rates dating back around 20 years. This data appears to be dominated by major European and North American road tunnels. It is very likely that this data overstates the likelihood of incidents in modern, well designed, uni-directional road tunnels, based on recent anecdotal evidence.

2. There is even less reliable data for rail tunnels, apart from some for metro systems. In particular, there is very little useful data on incident frequencies for freight, dangerous goods and long distance passenger trains.
3. On the consequence side, data in relation to the extent of tunnel damage, and the time for closure, repair and re-commissioning is even more sparse for both road and rail tunnels, although some recent attempts [9] have been made to quantify some data using the information in Beard and Carvel [10].

RISK DOCUMENTS

For readers that are not familiar with risk management and interested in the subject the following documents can give information:

- Risk Analysis for Road Tunnels, PIARC [11]
- Risk Management – Principles and guidelines [3]
- Risk Management – Risk assessment techniques [12]
- Combined Qualitative and Quantitative Fire Risk Analysis – Complex Urban Road Tunnel [13]

CONCLUSION

The paper has shown a methodology that has been used and accepted by authorities on a number of international tunnel projects, as a key part of QRA studies for fire and life safety.

Regarding any type of life safety systems a good design and maintenance regime is very important and has a significant effect on the life safety risk. Common-cause-failures are very important and should be thought of early on in the design process, and also later on for the maintenance regime.

It is also clear that a good deal more research is required in the area of risk data for tunnels.

REFERENCES


Fixed fire fighting systems for tunnels – SOLIT² Research Project

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ABSTRACT
This paper discusses first the background of fixed fire fighting systems (FFFS). In particular water mist systems are discussed giving the extensive test and research background. The research has been very much experimentally driven since other ways like CFD cannot replace this yet. Also the view of existing standardisation and engineering guidance is given. This has changed drastically during the last decade as increased knowledge about tunnel fires has been gained.

The practical aspects of installation of FFFS are explained in a separate chapter using two case studies demonstrating the state-of-art technologies used in the most recent installations. New Tyne Crossing is used as an example of road tunnel protection and Eurotunnel (Channel tunnel) as a rail tunnel example. Both tunnels have been commissioned in 2011. The investment decisions in both case study tunnels were based on cost benefit analysis, which is a completely new aspect FFFS can provide in addition to increased life safety. The integration of technologies to high profile tunnels is discussed in more detail. In particular modern safety and reliability engineering tools like RAMS analysis and their impact to the case studies are shown.

The main emphasis of the paper is in the SOLIT² Research project which represents the very latest technology and findings about FFFS in tunnels. SOLIT² stands for Safety-of-Life-in-Tunnels and follows the first SOLIT program carried out 2005-2007. SOLIT² is a new research program that was funded by German ministries for studying tunnel fire safety. The previous SOLIT project demonstrated the effectiveness of FFFS against tunnel fires and, together with the UPTUN research program, results changed the view towards active systems like FFFS. The new SOLIT2 project has not its main focus in FFFS, but in the holistic overall view of all tunnel safety systems with active fixed fire fighting systems. SOLIT² Fire tests were carried out in summer 2011 and preliminary results are shown in this paper.

KEYWORDS: Fixed fire fighting systems (FFFS), water mist, heat release rate (HRR), SOLIT

FIXED FIRE FIGHTING SYSTEMS (FFFS) – BACKGROUND, TESTING AND STANDARDISATION

Fixed fire fighting systems (FFFS) mean an active way to fight fires in tunnels. Fixed fire fighting systems represent a new way to improve fire safety compared to conventional technologies. The approach using active fire fighting by a fixed installation has been used for decades in Australia and Japan. The technology was selected following the building protection regulations and those for low-pressure deluge (“sprinklers”) [1]. However, the main drawback has been the lack of full scale testing of low-pressure deluge systems. FOGTEC, being the first company, did comparison tests recently between low-pressure deluge and high-pressure water mist, which is the main stream in Europe [2]. The background of using high-pressure water mist technology in Europe follows the extensive full scale fire testing funded by the European Union and individual governments during the last decade. A number of catastrophic fires in Europe a decade ago were the initial trigger for the development of fire safety in tunnels. Many things like design fire sizes, design temperatures, and safety concepts for tunnels have changed. Also active fire fighting is a technology that has been developed as a solution to large HGV fires. The following table illustrates briefly the main tests that...
have been carried out in Europe with high-pressure water mist technology. FOGTEC high-pressure water mist technology was used in these tests.

Table 1 Full scale fire tests with HGV mock-up [3].

<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>Project/Program/Organisation</th>
<th>Class A – HGV tests (up to)</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-2006</td>
<td>EU</td>
<td>UPTUN – Upgrading Methods for Fire Safety in Existing Tunnels</td>
<td>30MW</td>
<td>~60</td>
</tr>
<tr>
<td>2005-2006</td>
<td>Germany</td>
<td>SOLIT – Safety of Life in Tunnels</td>
<td>200MW</td>
<td>55</td>
</tr>
<tr>
<td>2009-2012</td>
<td>Germany</td>
<td>SOLIT² – Safety of Life in Tunnels 2</td>
<td>100-150MW (30-100MW Class B)</td>
<td>15</td>
</tr>
<tr>
<td>2010</td>
<td>UK</td>
<td>UK Highways Agency</td>
<td>100MW</td>
<td>20</td>
</tr>
<tr>
<td>2010</td>
<td>France / UK</td>
<td>Eurotunnel</td>
<td>200MW</td>
<td>4</td>
</tr>
<tr>
<td>2006</td>
<td>Spain</td>
<td>Madrid Bomberos</td>
<td>25-150MW</td>
<td>10</td>
</tr>
<tr>
<td>2006</td>
<td>Spain</td>
<td>Madrid Municipality – M30</td>
<td>25-150MW</td>
<td>3</td>
</tr>
</tbody>
</table>

The fire tests have shown that predicting the results of full scale fire tests is very difficult by any other means than experimentally. Accuracy of CFD is still limited and needs to have verification by experimental results. Particularly when water mist is introduced into the models. However, the test data received from fire tests have improved also the accuracy of CFD, but still do not remove the need for experimental tests. Water mist systems still get criticism that the testing background is limited. The comparison is often made with the ventilation systems where design is often verified only by CFD or small scale tests 5-10MW in the real installation. Probably the largest ventilation tests have been in combination with testing water mist systems during preburning time or in free burning reference tests. These tests have also shown some deviation between modelling and real data. For example smoke stratification with longitudinal ventilation above 30-50MW heat releases is often seen to be too positive with CFD.

Figure 1  Eurotunnel full scale fire tests 2010 – Over 200MW HRR before activation of water mist system [3]

Although the new knowledge has increased, thanks to extensive experimental testing, the standardisation of fixed fire fighting systems has followed slowly. There are not clear standards or rules that would guide either type testing of systems or setting of installation rules. On the other hand, it must be also remembered that the view of PIARC one decade ago was against active systems in tunnels, which now has changed completely [4]. Wrong assumptions were corrected by PIARC and a separate report about fixed fire fighting systems, “An assessment of fixed fire suppression systems”, was published in 2008 [5]. However this report is already slightly outdated in its technical and
commercial specs compared to state-of-the-art systems being currently installed. NFPA502 is the first standard that included a chapter about FFFS in the latest edition 2011 [6]. NFPA502 gives basic information and engineering requirements for the systems to be installed in tunnels. So far the best engineering based approach has been generated in the UPTUN research program. “Engineering guidance for water based fire fighting systems for the protection of tunnels and subsurface facilities” sets basic engineering practices for systems to be installed into tunnels [7]. Lately also the French CETU published a new report “Water mist in road tunnels” in 2010 [8]. CETU report gives very comprehensive description of state-of-art technologies. Basically the message of all the guidelines or standards referred to is that fixed fire fighting systems should fulfil certain requirements that are listed in the next table. The table also lists the means whereby water mist technology has fulfilled these requirements in full scale fire tests. Other technologies naturally have different results, but missing test data is the main hindrance for those.

<table>
<thead>
<tr>
<th>REQUIREMENT</th>
<th>METHOD</th>
<th>EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvement of self-rescue conditions</td>
<td>- Immediate cooling of fire and surrounding volume</td>
<td>Tunnel users have safer conditions for evacuating themselves or having better survivability conditions in case of being trapped.</td>
</tr>
<tr>
<td></td>
<td>- Reduction of smoke production, better visibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Binding smoke and soot</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Less toxic gases</td>
<td></td>
</tr>
<tr>
<td>Improvement of access of fire services</td>
<td>- Limiting heat release rate (HRR)</td>
<td>Fire and rescue services have easier access to the fire to fight the fire. Access can be done from both sides of fire with normal protective equipment. Systems increase fire fighters safety significantly.</td>
</tr>
<tr>
<td></td>
<td>- Immediate cooling of fire and surrounding volume</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Reduction of smoke production, better visibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Blocking radiant heat</td>
<td></td>
</tr>
<tr>
<td>Prevention of fire spread</td>
<td>- Limiting heat release rate</td>
<td>Fire will be limited to the initial vehicle, which is very essential in case of HGVs (trucks).</td>
</tr>
<tr>
<td></td>
<td>- Immediate cooling of fire and surrounding volume</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Blocking radiant heat</td>
<td></td>
</tr>
<tr>
<td>Limiting damages to tunnel structure</td>
<td>- Immediate cooling of fire and surrounding volume</td>
<td>Tunnel structure and other equipment will not be under same time / temperature exposure as used without system. Enables shorter recovery time after fires.</td>
</tr>
<tr>
<td></td>
<td>- Blocking radiant heat</td>
<td></td>
</tr>
</tbody>
</table>

**FIXED FIRE FIGHTING SYSTEMS (FFFS) – INSTALLATIONS AND EXAMPLE CASES**

Extensive fire testing and excellent results with realistic HGV fire loads have led to installation of fixed fire fighting systems in tunnels. There are tunnels that are protected with modern high-pressure water mist systems in Spain, Italy, the Netherlands, Austria, France, the UK and Russia so far [1]. Additionally more are to come in the near future. However, the discussion related to fixed fire fighting systems has recently been more focused on system performance than engineering requirements for the systems. The recent tunnel projects have shown that proper engineering and material selection is a very vital part of system reliability. The official guidance for such is very limited and UPTUN R251 engineering guidance is the only engineering related document. The positive development in Europe has been that system reliability and life cycle costs (LCCs) have become an important part of the tendering process. Normally full RAMS studies are required as part of the system design process and the manufacturer needs to ensure certain design availability [1]. This is important for the tunnel operator since a fixed fire fighting system is normally part of critical safety systems. Having a critical safety system out of operation can lead to traffic limitations or closing the tunnel. Using reliability engineering tools is common in aviation, rail and automobile industries but in tunnel or fire safety engineering it is a completely new thing, which has started only in recent years. Two example cases about installation of FFFS in tunnels are shown in following chapters.

**Example case (road tunnel) – Tyne crossing (2011)**

The Tyne crossing provides a connection under the River Tyne in Newcastle, UK. The crossing has two tunnels, the existing road tunnel was opened in 1967 (reopened 2011 after refurbishment) and the new tunnel was opened in 2011. The tunnels are a vital part of the Tyne and Wear road network carrying 38,000 vehicles per day whilst the forecast is to rise to 43,000 per day by 2021.
The decision to incorporate a FFFS system, specifically a high-pressure water mist system, to protect the road tunnels of the New Tyne crossing made the project a pioneer for applying the highest fire safety standards in the UK. Tyne tunnels were the first tunnels in the UK having an active fire protection system. The feasibility studies recommended using high-pressure water mist technology. Neither foam additives nor low-pressure deluge systems were considered to be suitable for the tunnels. The drainage capacity gave also some limits for the flow rate of high-pressure water mist technologies. Tyne tunnels have recently been mentioned as the safest in the UK.

The selected water mist system for Tyne tunnels had to have independent full scale fire tests passed with 100MW HGV fire mock-up. Additionally, the operator specified the technical requirements had to follow UPTUN R251 Engineering guidance. The new Tyne tunnels comprise many different cross-section types made with different tunnelling methods including cast iron lining, cut and cover, sprayed concrete lining and immersed parts.

The technical concept in Tyne tunnels is having three adjacent sections, each 25m in length, triggered simultaneously in case of fire. Only deluge nozzles are used in order to provide full flow rates for every activated section thus maximizing the effect of water mist from the beginning of activation. The total pump capacity of water mist system is 3300l/min at 140bar. After detailed analysis, the tunnel operator decided to activate system immediately after detection. The concept was tested with a full scale emergency test. The human behaviour was a special focus during this test.

The investment decision was made on a cost-benefit analysis. According to the independent study by the experts the installation of the fixed fire fighting system will provide benefit-to-cost over the assessment period of tunnel operation [9]. Additionally FFFS will increase the life safety of tunnels and provide safety for fire services in case of fire. Following the Tyne crossing more road tunnels will be protected in the UK. For example, the M25 Dartford crossing will have a high-pressure water mist system incorporated.

**Example case (rail tunnel) – Eurotunnel (Channel tunnel)**

The Eurotunnel (Channel tunnel) is an over-50km rail link under the Channel between Calais in France and Folkestone in England. Up to 450 trains crossdaily through the two tubes of the tunnel carrying either passengers, goods or car/trucks in shuttles.

After the severe fires on trucks shuttles in 1996 and 2008, Eurotunnel decided to reinforce the safety strategy with new SAFE (project name) fixed fire fighting systems. The systems are based on high-
pressure water mist technology that has already been tested in several research projects and installations in Europe. Also other technologies were considered but high-pressure water mist was identified to be the most suitable technically and commercially. Eurotunnel did not want to have any major modifications to the infrastructure of the tunnel, which would have been the case for example with a conventional low-pressure deluge system [10]. The technical specifications followed primary UPTUN R251 Engineering guidance together with Eurotunnel’s own requirements for tunnels. Also RAMS studies were required for the water mist system. A full scale fire test program was organised for the type testing of the selected water mist technology. The fire scenario represented the worst expected situation with truck shuttles. The size of tested fires was extremely high, for example, heat release rates in excess of 200MW were measured before activation of the water mist system. During vast test programs together with experienced fire brigades one could see that even with fully developed HGV fire loads with heat release rates from 100-200MW the water mist system was able to ease the rescue of persons for the fire brigade and allow for control of the fire and rapid extinguishing. All general aims set for the FFFS as required by the standards and reference guidance were fulfilled. Additionally detailed requirements of Eurotunnel in terms of performance e.g. temperature, fire spread, cooling, easing fire services were achieved and Eurotunnel with its own stakeholders were very satisfied with the test results. For example, temperatures around the fire with 200MW HRR were reduced from 1100°C to below 50°C within two minutes after triggering the system and the fire was brought under control.

The Eurotunnel SAFE installation concept comprises installation of FFFS in in total four sections in two tunnels. Due to the significantly larger potential fire load in the truck shuttles, the SAFE stations serve primarily to protect these truck shuttles. SAFE stations are located at both ends of intervals 3 and 4 in the tunnels, about 10 kilometers from the portals. Each SAFE station is 870 meter long and divided into 29 sections, each 30 meters long, three sections will be activated in the case of fire [10].

The Eurotunnel SAFE system was started in 2010 and commissioned in late 2011. The installations
were done within very limited and short installation slots because the tunnels were kept open for traffic. Only high grade stainless steel was used in the installation following UPTUN R251. The connecting method was 100% welding in the running tunnels, because of vibrations in the tunnel. Mechanical connections (fittings/couplings) require maintenance and have the possibility to be loosened by such vibrations. The total pumping capacity including redundancy is 4000l/min @ 115bar in one SAFE station.

A number of different kinds of tests have already been carried out during the commissioning of the SAFE system. For example, the water mist system has been extensively tested together with powered 25kV catenary (in a real incident the power is cut off). No negative or dangerous effects have been noticed in these tests. Additionally tests with water mist distribution and ventilation as well as visibility and evacuation have been carried out with very positive results. The SAFE stations include also very sophisticated control (SCADA), detection, and video surveillance systems that were supplied by FOGTEC.

Figure 5 Commissioning spray test of Eurotunnel SAFE system 2011

SOLIT² RESEARCH PROJECT – LATEST EXPERIMENTAL RESULTS

SOLIT² (Safety Of Life In Tunnels) research program represents the latest knowledge in the field of active fire fighting in tunnels. The first SOLIT project was finished in 2007 and the focus at that time was to see if fixed fire fighting systems are able to fight large 100+MW design fires. The previous UPTUN tests had been carried out only with 30MW design HRR, which used to be the standard and common knowledge in past. The first SOLIT project demonstrated the effectiveness of fixed fire fighting systems, in particular high-pressure water mist, in large fires. Therefore the second SOLIT² was launched with different focus in 2009. The aim of SOLIT² is to study the interaction between fixed fire fighting systems and other safety installations with a holistic approach. The main aim is to study the possible compensation of other safety systems by installing an active fire fighting system. This is done primarily by full scale fire tests, but also by utilising and developing CFD models, especially for understanding water mist, fire and ventilation. Additionally the SOLIT³ project will focus on the life cycle cost evaluation and compiling proper design rules for active fire fighting systems. The project is funded by the Federal Ministry of Economics and Technology in Germany. The total budget of the project is about 4 million euro. The majority of the budget was used in the full scale fire test campaign in May-June 2011. In total over 6000 euro pallets, 8000 liters of diesel and 1200m³ of water were used in this massive fire test campaign [11].
SOLIT² - Fire tests

The fire tests were organised in the TST (Tunnel Safety Testing) test tunnel in San Pedro de Anes, Spain. The test tunnel is artificial and has a total length of 600m. The tested cross-section corresponded to a typical two lane tunnel. The water mist system was built at 60m distance into the tunnel. The first part of the testing was the optimisation of the water mist nozzle lay-out and flow rates. After this the water mist system parameters were kept unaltered throughout the fire test campaign as the focus was not to test water mist systems but other systems in combination with it. The test tunnel offered the possibility to test both longitudinal and transversal ventilation. The tunnel ventilation system provided longitudinal air velocities between 1-6m/s. The semi-transversal ventilation could extract 120m³/s via a ventilation building and duct above false ceiling (air velocity up to 30m/s). The semi-transversal ventilation system is dimensioned for maximum 30MW HRR fires.

![Figure 6 TST test tunnel in Spain during fire tests](image)

The measurement system in the fire tests was massive. There were in total 152 different sensors in the test tunnel recording each fire test [12]. Additionally many visual and experimental recordings (e.g. by fire services) were used. Sensors were recording for example:

- Temperatures
- Heat radiation
- Air velocities
- Gas concentration (O₂, CO₂ and CO)
- Pressures and flow rates
- Air humidity

The weather data from outside was recorded for each test. Also the humidity of solid fire load was measured. Furthermore the temperatures distribution and visibility conditions were recorded with normal, infra-red and thermal cameras. Most of the temperatures were measured from the air, but some temperature sensors were embedded into the tunnel structure or test materials in order to see the real impact.

The fire mock-ups consisted of two main scenarios. A. Large 100+ MW HGV solid fire and B. Large pool fires up to 100MW. A separate fire target representing a second “truck” was used 5m downstream of the mock-up. Prevention of fire spread was one of the pass / fail criteria. Water mist was normally activated 4 minutes after ignition with solid fires, which represents delayed detection and activation in real case. In one scenario the system was activated with a massive 12 minutes delay.
SOLIT\textsuperscript{2} - Preliminary results

Fire test results showed that fixed fire fighting systems can have very positive impact for the performance of the ventilation system. Many tests were carried in order to study this interface. Also CFD simulations are used for deeper understanding and there will be more results been published very soon. However, one of the major findings was studying back layering and ventilation system capabilities with and with water mist system. A comparison test with pool fires was set up. A “small” 30MW free burning fire was compared to a large 100MW fire having water mist system activated. The comparison tests were carried out on longitudinal upstream side air velocity of 3m/s. The fire test results showed very extensive backlayering effect with free burning 30MW fire starting 5 minutes after ignition. 100MW fire having water mist activated did not reveal any backlayering during the test even though fire was initially much greater. This basic result suggests that ventilation systems dimensioned to maximum 30MW can be used to much higher design fires together with water mist system.

The effect of water mist on HRR was studied more with solid fires. The typical heat release rate behaviour is presented in the following graph. The measurements suggest that water mist system can have a significant impact on the development of fire by slowing and suppressing it.
Though HRR reached the 25MW level, temperatures around the fire were kept in control, which probably is the most important function of active fire fighting systems. This prevents fire spread and protects fire services approaching the fire. The following graph shows the temperature measurements at the fire target 5m downstream side from the fire mock-up. Different graphs show different heights in the tunnel cross-section. As the results show, the temperatures stay well under the 100°C level throughout the test after activation of water mist. There is one measurement that increases during the test and this is the temperature directly under the ceiling. This value increases as the fire is burning closer to the target (downstream end of mock-up) and fumes are passing this location. However there is no temperature increase at the level of fire target and therefore also fire spread was prevented. The impact of temperature on the tunnel structure, concrete and equipment was part of the testing. The embedded temperature sensors recorded temperatures inside the concrete and equipment. For example pipe temperatures and temperatures inside the section valve protection box were collected. Additionally, sample pieces of concrete were used in the fire tests.

**SOLIT² - First conclusions**

The preliminary assessment of SOLIT² fire tests results confirmed the efficiency of water mist systems in tunnel fires. Very important data was collected for studying and understanding the interfaces of different parts of fire safety systems. This data can be used for developing more accurate numeric models as well as assessing compensation possibilities with water mist systems. The preliminary results already suggest that compensation is very possible, but later studies will reveal the quantitative values when life cycle costs are finished. These results are expected later in 2012 [12]. The fire tests demonstrated that even with very large fires, much safer evacuation conditions for
people and working conditions for fire services can be achieved with a water mist system.

**CONCLUSIONS**

Fixed fire fighting systems (FFFS) are nowadays a technology which has been very widely tested in full scale fire tests. This applies especially for high-pressure water mist, which is the mainstream in Europe. Low-pressure deluge systems have been tested only once by FOGTEC in recent years. The positive test results have changed the standardisation and fixed fire fighting systems are nowadays commonly accepted technology to enhance fire safety in tunnels. However, systems must have a full performance proof through full scale fire tests before being allowed to install in tunnels. Existing standardisation sets basic requirements for fixed fire fighting systems. These are A. Improvement of self-rescue conditions, B. Improved conditions for fire & rescue services, C. Preventing fire spread from one vehicle to another, and D. Preventing/limiting structural damages to tunnel. The absolute values for these should be set in the risk analysis that should be carried out for every tunnel individually. However, existing standards do not give clear instructions to the engineering aspects. UPTUN R251 engineering guidance is the only exception so far.

Fixed fire fighting systems have been successfully installed already in a number of tunnels in Europe. Example cases given, Tyne crossing and Eurotunnel, show two completely different applications of such. The specialities of these projects were that the investment decision in both cases was based on cost benefit analysis.

The SOLIT² research project represents the latest knowledge in the field of tunnel fires with fixed fire fighting systems. The massive research project focuses especially on the holistic approach studying the interfaces of fixed fire fighting systems to other safety systems. The compensation of other systems by having a water mist system is possible according to the first results. Fixed fire fighting systems can lower the design criteria of many other parts of safety systems e.g. passive protection, ventilation. More results will be published during 2012.

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Effectiveness Analysis of a Fire Detection System Configured as a Multi-Function Portal Aimed at Protecting Railway Tunnels

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ABSTRACT

In Italy there is a relevant number of long tunnels, some of which are more than 50 years old, consequently more likely to determine potential threat for people in case of a fire involving passenger trains. According to the fire statistics, Italian tunnels fire risk level can be considered as “residual”; nevertheless early stage fire detection system has become a topic issue nowadays as a key factor aimed at increasing the railway tunnels safety.

A new system concept has been defined, implementing two basic safety functions: the first is aimed at detecting early stage fires on rolling stock and the second is aimed at detecting wrong loads displacement on freight trains.

Both of the functions are based on the use of sensors aimed at performing appropriate measurements to be processed and evaluated according to specified criteria. After the definition of the functional requirements, a series of evaluations and analyses have been carried out in order to address the system development and realization.

FIGHTING TUNNEL FIRES

Italian railway emergency procedures are defined according to a fire fighting philosophy through the following statements:

- It should be stopped, as far as possible, any train with a fire on board before entering a (long) tunnel;
- if a train is travelling through a tunnel and a fire on board has been detected, it should leave the tunnel before stopping, as far as possible, or
- for specific situations (i.e. fire ignition on a high speed line passenger train, like high speed line Bologna - Florence equipped with ERTMS L2 train control system) the train must continue travelling after a fire detection alarm, directly to the first “egress place” displaced along the tunnel.

The first sentence can be inferred from this consideration: if there is the opportunity for a train with a (dangerous) fire principle on board to stop before entering a long tunnel, the driver must brake and stop the train, avoiding risks related to a fire development within an enclosure and to the exposition of egressing passengers to a fire threat. The application of such procedure implies a decision to be taken by the driver (and the emergency management) about the possibility of fire spreading.

The second instance can be inferred through the following considerations:
- avoiding air flux inversion or even significant air velocity reduction along the train with an already developed fire on board generally implies a fire spread limitation;
- determining a stop of a passenger or a freight train with a fire on board within a (long) tunnel implies:
in case of a passenger train, an egress of people potentially exposed to untenable conditions along the tunnel

in case of a freight train, the spread of the hazard factors to a significant portion of the tunnel and possibly the consequent involvement of passengers on board of another train already entered the tunnel.

The application of the above described philosophy can be applied by effective fire detection systems (and adequate automatic train protection system for the third instance).

The basic principle which is requested to a detection system is the possibility of a quick response of the Tunnel Safety Management System to the incoming fire threat; nevertheless, because of the large breaking space needed by a train, in a range of 1 - 3 km, according to deceleration values, generally within a range of 0.3 to 0.5 m/s², speed of travel, train mass distribution and the brake delay time, a short response time by the fire detection system can be of great importance for the emergency management.

The system must provide alarms according to priority levels corresponding to appropriate threshold levels, the highest of which determines a direct (automatic) intervention on the signaling system and the consequent stop of the train. Direct intervention on signaling system implies the highest integrity level required for the safety function (i.e. fire detection), in fact any false alarm would be of unacceptable impact on the operation, and consequently one of the activities to be carried out within the system development involves the quantitative evaluation of the false alarm rate and the containment within acceptable values through the adoption of adequate architectures and appropriate methods aimed at minimizing systematic faults.

HAZARD ANALYSIS

Fires potentially involving rolling stock can ignite through a wide range of different sources, according to the type of wagon and equipment on board, together with the operational condition and the materials characteristics.

Detailed fire statistics can be investigated for a deep understanding of the fire ignition phenomena potentially involved, according to the rolling stock type and characteristics; the same data can be appropriately treated in order to infer quantitative factors to be applied to the probabilistic risk analysis. Causal analysis based on railway fire statistics investigation
has been performed, in order to identify concomitant (precursor) events leading to any of the significant fire ignition sequences.

The following tables describe the resulting classification of the fire related events, observed and appropriately reported according to specified protocols within the last 15 years on the Italian railway system; each of the identified ignition causes has been correlated to the observed outcomes and consequences, according to the available statistics. The field “HRR peak”, indicated within the following tables, is to be regarded as a conservative HRR peak value determined taking into account the wide variety of rolling stock and their differences in terms of materials, layout and each of the significant epistemic uncertainties; hence it must not be considered as a statistic inference.

<table>
<thead>
<tr>
<th>ID</th>
<th>Rolling stock</th>
<th>Rail car</th>
<th>Ignition displacement</th>
<th>Causes</th>
<th>Immediate consequences</th>
<th>Possible loss of Traction</th>
<th>Possibility of Emergency Brake Activation</th>
<th>Pro growth</th>
<th>HRR peak</th>
<th>Detection by Internal Devices</th>
<th>IR camera detection</th>
<th>Hot Box detection</th>
<th>High Sensitivity Smoke detector</th>
<th>Statistical weight [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H81</td>
<td>Locomotive</td>
<td>Loco</td>
<td></td>
<td>Traction system</td>
<td>Inductance overheating</td>
<td>Y</td>
<td>N</td>
<td>slow</td>
<td>50</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>59</td>
</tr>
<tr>
<td>H82</td>
<td>Air conditioning system</td>
<td>Fan overheating</td>
<td></td>
<td></td>
<td></td>
<td>Y</td>
<td>N</td>
<td>slow</td>
<td>10</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>20</td>
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<tr>
<td>H83</td>
<td>Electrical equipment</td>
<td>Contactors short circuit</td>
<td></td>
<td></td>
<td></td>
<td>Y</td>
<td>N</td>
<td>fast</td>
<td>10</td>
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<td>H84</td>
<td>Underfloor equipments</td>
<td>Brake blocks overheating</td>
<td></td>
<td></td>
<td></td>
<td>Y</td>
<td>N</td>
<td>slow</td>
<td>50</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>5</td>
</tr>
<tr>
<td>H85</td>
<td>Rolling</td>
<td>System failure</td>
<td></td>
<td></td>
<td></td>
<td>Y</td>
<td>N</td>
<td>slow</td>
<td>10</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 1 – Hazard analysis results from railway fire database
Table 2 – Hazard analysis results from railway fire database

<table>
<thead>
<tr>
<th>ID</th>
<th>Rolling stock</th>
<th>Ignition displacement</th>
<th>Causes</th>
<th>Immediate consequences</th>
<th>Possible loss of traction</th>
<th>Possibility of emergency brake activation</th>
<th>Fire growth</th>
<th>HRR peak</th>
<th>Detectability by internal devices</th>
<th>IR camera detection</th>
<th>Hot arc detection</th>
<th>High sensitivity to smoke detection</th>
<th>Statistical weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF18</td>
<td>Passenger train</td>
<td>exterior</td>
<td>electrical fire, short-circuit, etc.</td>
<td>smoke generated by passenger coach</td>
<td>Y</td>
<td>N</td>
<td>slow</td>
<td>10</td>
<td>X</td>
<td>Y</td>
<td>10</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>HF19</td>
<td>Locomotive</td>
<td>exterior</td>
<td>traction system</td>
<td>electric fire</td>
<td>Y</td>
<td>N</td>
<td>slow</td>
<td>10</td>
<td>X</td>
<td>Y</td>
<td>10</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>HF20</td>
<td>Freight train</td>
<td>exterior</td>
<td>electrical equipment</td>
<td>electric fire, short-circuit</td>
<td>Y</td>
<td>N</td>
<td>fast</td>
<td>10</td>
<td>X</td>
<td>X</td>
<td>5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>HF21</td>
<td>Freight train</td>
<td>interior</td>
<td>mechanical failure</td>
<td>smoke generated by passenger coach</td>
<td>Y</td>
<td>N</td>
<td>fast</td>
<td>10</td>
<td>X</td>
<td>X</td>
<td>5</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 – Hazard analysis results from railway fire database

DEALING WITH UNCERTAINTY

The detection principle can be regarded as the measurement of any of the expected hazard factors, determined by the establishment of a fire within a certain domain under control and a
consequent evaluation with respect to reliable threshold values, in order to provide alarm whenever the criteria are met.

All of the hazard factors and the corresponding intensity of the expected values can be regarded as proportional to the HRR so that the measurement reliability can be reasonably related also to the intensity of the quantities to be measured.

Focusing on the determination of appropriate threshold values, for the significant quantities to be measured in order to provide reliable fire alarms, we can identify a wide source of uncertainties affecting both the performance criteria and the quantities measurement.

The heat flux measurement, significant for the determination of the temperature of the external surface of the train, is strongly influenced by the emissivity of the materials characterizing different train surfaces, according to the treatment, painting, dust, state of the wear; typically the value of this parameter is not available and quite variable, according to the spectral band and temperature range.

In turn, if performance criteria based on the temperature measurent are adopted care must be take about threshold values determination, taking into account uncertainty sources related to the difficulty of identify ignition displacement (internal/external) and to the possibility that some parts of the train can be normally operating at higher temperatures (e.g. axlebox, brake shoe, engine, pantograph, etc.).

Moreover, influences of the environment factors on the hazard behavior (i.e. gases and smoke concentration and distribution, heat flux, gas temperature, etc.) are generally significant: long exposure of the railcars to the sunlight can determine significant effects on surface temperature; in turn, considering internal fire ignition scenarios (e.g. a sleeping car), the effect of the HRR on the external surface temperature can be negligible for a significant period of time after the ignition, while the tenability conditions for the passengers could be already over the acceptability limits.

The latter observation clearly determines a wide spread around the reference values for the temperature to be assumed as fire alarm thresholds.

According to the basic concept of our detection system, to be installed along the railway line (before tunnel portals), we can figure out the system to be performing measurements outdoors on trains travelling at a speed in a range of 120 to 300 km/h according to the type of line and rolling stock (typically 120 km/h for freight trains and 160 – 300 km/h for passenger trains); this last circumstance determine difficulty related to the data acquisition and processing, which can be very time consuming according to the amount of data, the complexity of the algorithms and the HW capability.

The hazard analysis carried out showed that most of the significant fire scenarios can be hardly visible in an early stage to most of the thermograph sensors or gas detectors displaced wayside the railway line, especially when the ignition occurred underneath shielding surfaces (e.g. within the interior of a coach or sleeping car, within containers, etc.).

Infrared thermography is based on the heat flux measurement radiating from the external surface or from the uncovered parts of the train which can be involved in dangerous overheating and consequent fire ignition, according to the rolling stock hazard analysis; such heat flux measurement is typically affected by significant uncertainty related to the unknown emissivity value of the radiating materials.

Fire ignitions originated underneath vehicle surfaces looks the hardest challenge for an outdoors detection system: according to the expected dynamics of such fires, sensors should identify temperature (if above a threshold value) on the external surfaces of the wagons, or
temperature gradients, revealing a small fire within wagons.

![Thermography of a train](image)

**Figure 2 – Thermography of a train**

In order to deal with the relevant number of aleatory variables affecting the measurement process and the need of determining reliable performance criteria, a tradeoff between sensors-system capabilities (higher measurement reliability could lead to unreasonable costs for the system purpose) and appropriate probabilistic data processing should be carried out. Acquiring large amount of data from field (e.g. temperature and heat flux measurements on travelling rolling stock) and defining appropriate correlations between aleatory variables can be a valid alternative solution to the application of unreasonably expensive sensors and maybe the only way of defining a system characterized by the highest integrity level for the safety functions to be implemented.

Through appropriate algorithms applied to the acquired data, simulation models of the sensing principles and appropriate usefulness indicators, it is then possible to select the best (more convenient) technology to be implemented and the optimal way of performing the measurements during the operation and data processing.

**RISK ANALYSIS**

In order to address optimized fire detection system development a risk analysis has been performed.

**Ignition sources classification**

Rolling stock fires recorded and stored within database has been classified according to the following key issues:

- technical cause/arsen;
- type of railway car where the fire originated;
ignition source and displacement over the railcar. The risk analysis carried out is based on accident database statistics, which has been utilized in order to calculate fire hazard rate according to specific conditions, as the type of carriage and combustible materials involved, the ignition displacement, the description of the fire spread, the event of “loss of traction” by the locomotive as a fire consequence or the occurrence of a derailment within the tunnel.

Experimental HRR curve together with fire modeling results have been also taken into account in order to identify correlations between fire ignition cause and displacement, type of train and carriage involved and representative HRR curves, expressed in terms of ignition phase duration, fire growth, HRR peak value (HRR level-off value) and total duration.

The goal is to address detection performance criteria according to the scenarios having predominance on the global fire risk level.

Consequences analysis
In order to quantify the expected outcomes of a fire occurring within long tunnels a series of fire simulations has been performed, predicting the smoke and hazard factors behavior and the interaction with environmental factors as the pressure difference at the tunnel portals, which consequently determines the air velocity profile, influencing in turn the smoke stratification and the visibility and the tenability conditions, significant for the egress evolution along the tunnel.

The expected HRR is strongly dependent to the type of rolling stock involved in a fire; according to the types of carriage, experimental curves available and fire simulations performed we can identify three classes of HRR peaks:

- 10 MW (passenger car);
- 50 MW (freight train or locomotive);
- 150 MW (freight train carrying flammable liquid or gas).

Each of the identified classes of HRR has been correlated to specific fire growth rate and decay according to the type of carriage and ignition displacement.

Numerical simulations aimed at predicting the smoke and heat spread along the tunnel have been performed, simulating the case of a fire occurred on a train which stopped within the tunnel after a loss of traction occurred; it has been carried out through the whole set of significant parameters:

- tunnel lengths (i.e. 1000, 4000, 9000, 16000 m)
- tunnel sections (i.e. single bore - double track / double bore)
- pressure differences at the portals;
- displacement of the stopped train with respect to the tunnel portals and intermediate exits (influencing the length of the egress path).

The hazard factors behavior within the tunnel has been predicted through the series of fire simulations above mentioned; data related to the evolution of smoke concentrations, heat flux and gas temperature along the egress path have been utilized to calculate FED, according to the egress dynamics and eventually identifying a number of expected fatalities for each scenario.

The results of such series of fire simulations and consequences analysis determined a number of reference scenarios, further extended through the application of appropriate statistic
methods as uncertainty treatment related to the aleatory variables involved. In order to take into account the possibility for a second train crossing through a double track tunnel to be involved in the fire scenario, previously determined by a first train stopped within the tunnel, the following assumption has been made:

- a 10 MW fire occurred on a passenger train do not determine further involvement of a second train crossing through the tunnel (travelling on the adjacent track);
- a 50 MW fire occurred on a freight train can determine a further involvement of a passenger train if the latter train is stopped within the tunnel and a passengers egress occurred (the involvement is considered as occurring because of the smoke and heat spread along the egress path where the passengers are walking toward the exits);
- a 150 MW fire occurred on a freight train can determine
  - direct involvement of a train crossing on the adjacent track because of the large intensity of the hazard factors spreading and radiating from the fire source;
  - involvement of passengers as in the previous case referred to a 50 MW fire.

According to the parameters and cases above identified and described in the following table there is the scheme of the total number of fire scenarios globally investigated.

![Table 4 – Fire scenarios considered for the quantitative risk assessment](image-url)

Further class of risk analysis parameters has been considered in order to take into account the possible unavailability of the emergency lighting system within the tunnel during the egress and the unavailability of the sidewalk as well, in order to consider within the global risk level old tunnels not yet retrofitted.

A fire on board of a train can also determine a derailment, according to some concomitant circumstances; the ignition displacement and the fire load is a key factor in the determination of the precursor of such an accident evolution.

For example, a fire occurred under-floor of a wagon can determine the involvement of the bogies, the mechanical component temperature can the reach dangerous values so that a structural collapse or abnormal forces at the wheel-track interface can occur.

**Detection sub-model**

Within the above described risk model a basic sub-model has been implemented, aimed at quantifying risk reduction. According to the operational scenarios, a class of expected HRR curves has been generated.
through a Monte Carlo simulation, in order to identify potential fire ignition scenarios to be checked through the passage at the check point (detection system) displacement, along the line to which the tunnel belongs.

The ignition probability density function is assumed to be independent to the train displacement with respect to the tunnel; it is also assumed that after the train stop at the last station it is expected that any possible failure potentially leading to a fire ignition has been detected (and removed) by the personnel.

A fire ignition rate “affecting” each train travelling along the railway line section, preceding the tunnel, can then be determined (and calculated) according to a fire rate expressed in terms of event/train-km.

The fire ignited is hence probabilistically characterized in terms of a HRR-time curve, according to the type of rolling stock (see the paragraph Hazard Analysis), while the probability to be detected by the system is determined according to the HRR value reached at the time of passage at the check point and to a threshold value.

The probability of a fire on board to be detected depends also on the ignition displacement with respect to the tunnel.

**Figure 3 – HRR curve in relation to the detection system displacement along the railway line**

Early stage fires potentially affecting passenger railcars could be also detected by devices installed on board or directly by the passengers if the ignition occurred at the interior of a coach. Fire principles occurring at the electrical equipment displaced under the railcar floor or above the coach ceiling (e.g. at the air conditioning system) can be better detected by wayside monitoring devices; nevertheless detection principle only based on the displacement of detection devices on board can imply relevant maintenance costs.

Fixed point detection system appropriately displaced along the railway line looks hence more reliable in order to ensure specified tunnel fire risk mitigation, which can be an advantage from the IM (Infrastructure Manager) point of view.

**Global risk assessment**

The consequences analysis above described is related to coherent initiator events, quantified through appropriate rate expressed in terms of events/year.

According to the hazard analysis results, specified operational scenarios determine values of fire-events/year.

The following operational scenarios have been considered:
The following table describes the results of the probabilistic risk assessment, where the possibility to implement a fire detection system displaced before tunnel portals has been taken into consideration.

Table 5 – Operational scenarios considered for the quantitative risk assessment

<table>
<thead>
<tr>
<th>Operational scenario</th>
<th>Type of train</th>
<th>Number of trains per day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(daytime – 18 h)</td>
</tr>
<tr>
<td><strong>A</strong></td>
<td>Intercity</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Freight</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>Tot</td>
<td>220</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>Intercity</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Freight</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Tot</td>
<td>120</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>High Speed/Intercity</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Freight</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>Tot</td>
<td>239</td>
</tr>
</tbody>
</table>

Table 6 – Risk analysis results

The detection system displacement, with respect to the tunnel portal, is then determined according to the maximum effectiveness:
- minimum brake distances related to each of the rolling stock belonging to the tunnel (line) operation;
- detection processing time;
- alarm time;

<table>
<thead>
<tr>
<th>Tunnel Length</th>
<th>Operational scenario</th>
<th>Collective Risk (fatalities/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without detection system</td>
</tr>
<tr>
<td>1'000 m</td>
<td>A</td>
<td>$4.207 \times 10^7$</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>$5.499 \times 10^7$</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>$1.185 \times 10^6$</td>
</tr>
<tr>
<td>4'000 m</td>
<td>A</td>
<td>$2.953 \times 10^6$</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>$3.800 \times 10^6$</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>$8.007 \times 10^6$</td>
</tr>
<tr>
<td>6'000 m</td>
<td>A</td>
<td>$4.225 \times 10^6$</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>$5.421 \times 10^6$</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>$1.128 \times 10^5$</td>
</tr>
<tr>
<td>16'000 m</td>
<td>A</td>
<td>$1.286 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>$1.645 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>$3.367 \times 10^5$</td>
</tr>
</tbody>
</table>
According to the risk analysis results we can identify a class of reference fire scenarios, having significant weight on the global risk level; reference fire scenarios can be characterized in terms of expected quantities (e.g. temperature, heat flux, gas species concentrations, etc.) values and gradients during an early stage.

The class of references scenarios defines the input data for further technological analysis addressing the determination of detection system requirements and performance criteria.

Cost-benefit considerations - Conclusions

Benefits to be accounted for in a CBA are the change in collective risk (i.e. FWI/year) for passengers, workers and public and must be expressed in monetary values:

- Value of Preventing Fatality (or serious injury) of one statistical death (or injured)
- Avoided damage or delays incurred by users of rail transport (passenger and freight train)
- Discounted values.

Benefits arising from the adoption of the safety measure must be considered within a specified period of time and the economic life of the measure must be considered as period of reference.

The following table gives an idea of the costs to be taken into account within a cost benefit analysis; the expected damage has been quantified in terms of number of days of operation interruption and monetary value, according to the fire HRR.

<table>
<thead>
<tr>
<th>HRR</th>
<th>10 MW</th>
<th>50 MW</th>
<th>150 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interruption duration (days)</td>
<td>7</td>
<td>60</td>
<td>180</td>
</tr>
<tr>
<td>Amount (k€)</td>
<td>200</td>
<td>1000</td>
<td>5000</td>
</tr>
</tbody>
</table>

Table 7 – Costs of operation interruption

According to the risk analysis results, applied to the Italian railway system, risk reduction after the application of a fire detection safety function as the one here described can be quantified within a range of $10^{-5} – 10^{-6}$ fatalities/year for very long tunnels (L>6 km), while for tunnel of length less than 6 km the benefits are quantified around $10^{-6}$ fatalities/year.

The benefits above quantified, only related to the fire detection safety function, can be regarded as negligible; in terms of cost-benefits the system realization and installation would be economically not convenient for the IM.

Nevertheless the same system concept can be adopted in order to implement a second safety function aimed at detecting loads exceeding the gauge, sharing the same physical device, HW platform and structure and further diagnostic and commercial functions.

Moreover the advanced character implied by the type of investigations and by the disciplines involved open to possibilities for future development and applications; the above mentioned considerations makes the project interesting beyond the cost-benefit evaluation.

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Risk-based evaluation of longitudinal ventilation with enhanced safety concept

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ABSTRACT
The longitudinal ventilation strategy is commonly used for road tunnels in urban environment in Sweden. This is partly due to how tunnels in urban environment was planned and designed before the EU Directive [1] (2004/54/EC) came in place. Even in new tunnels both to practical and economic reasons the use of longitudinal ventilation has been an outspoken demand from the Swedish road authority, SRA. Swedish law [2] requires that a risk analysis is carried out to demonstrate that an acceptable level of risk is achieved in the tunnels with longitudinal ventilation if there is a risk of queues. Otherwise transverse or semi-transverse ventilation strategy shall be used. During recent development, or a late awakening, it is clear that dense populated areas in Sweden will experience queues. This threatens the foundation of the Swedish modern tunnel safety concept which calls for enhancement.

This paper presents the risk-reducing effect of three alternative strategies, enhancements package, focusing on evacuation safety for road users. It is a combination of traffic management, fixed firefighting systems, reduced distance between escape routes and regulation of traffic with dangerous goods. In addition, it provides a comprehensive review of safety system details, combined with a longitudinal ventilation concept.

Keywords: longitudinal ventilation, queue, risk assessment, risk mitigation measures, safety concept.

INTRODUCTION
During the last twenty years, a tunnel practice for urban areas has been developed in Sweden, which to a great extent is based on the extensive investigations carried out related to the planning and design of the Ring project in Stockholm. The longitudinal ventilation concept was judged as appropriate during the prevailing conditions. Since then there has been an expressed desire from the SRA to apply the same or similar safety concepts in other tunnels in the urban environment in Sweden. This is due to both practical and economic reasons, e.g. the road users shall recognize the system and to keep design and production costs at a reasonable level.

The longitudinal ventilation concept is in many ways a robust solution that ensures that people are not exposed to hazardous smoke, given that two separate tunnel tubes are included in the design. Furthermore, an important condition is that queue is not allowed to occur in the tunnel [2]. In such case the tunnel has to be closed according to the safety concept. It has in recent years been shown to be difficult with few limited measures to prevent queues, which poses a potential major problem to the prevailing ventilation concept used.

To close a tunnel due to queues gives a major impact on the surrounding road network, e.g. wide spread traffic congestion, long travel time extensions and a hamstrung infrastructure, which has proven not to be accepted by the City Councils, e.g. in Stockholm. The reality is instead that the tunnels are taken in operation despite the queues, which means that important prerequisites for the safety concept are invalid. In practice, this course results in a poor design of a tunnel system in relation to how the system performs and then adds new problems e.g. increased risk in a traffic system.
The longitudinal ventilation strategy has a major dilemma that complicates the safety further, which is that in queue situations and in high traffic intensity the ventilation rate increases in the tunnel to meet the environmental limit values set to air quality. The ventilation rate can be as high as 8-10 m/s at the time of a queue. To detect accidents and slow down the large air masses are important for the safety strategy to work, but then takes long time. Combustion gases at the time of an accident resulting in a fire under these conditions give a very rapid smoke spread. In long tunnel systems there are also problems relating to the piston effect due to traffic movement which can make the decrease of the air flow even more problematic, even when it is forced [3]. Additional problems comes with the need to transport dangerous goods in tunnels with high traffic volumes in urban areas are added, which can cause serious and relatively very rapid accident sequence. These aspects are rarely addressed thoroughly.

Based on this problem profile WSP has been involved in evaluating and designing additional safety systems to enhance the traditional one. The additional systems in the safety concept with longitudinal ventilation strategy intends to meet the new safety requirements relating to the EU Directive (2004/54/EC) [1] TEN-road network based on the new conditions with the risk of queues. Swedish law [2], which is linked to the EU Directive (2004/54/EC) [1], requires that a risk analysis is carried out to demonstrate that an acceptable level of risk is achieved in the tunnels with risks of queues. Otherwise transverse or semi-transverse ventilation strategy shall be used. Risk analysis of this kind is complicated for several reasons. There is also little support in Swedish regulations regarding acceptance criteria and the available support is also often qualitative which provides considerable room for interpretation.

The aim of the paper is mainly to present and evaluate active traffic management and fixed firefighting systems as mitigation measures. The purpose of this paper is to explain how different mitigation measure affects the risk level in a tunnel.

LEGISLATION

Before 2004 when the EU Directive (2004/54/EC) [1] was in force safety design of tunnels was based on SRA handbook tunnel 99 [4] and later tunnel 04 [5] (EU Directive was first incorporated in to Swedish law in 2007.) The acceptable level of risk in tunnels according to tunnel 04 is formulated as a ambitions by politicians rather than as a well-founded design criterion:

“Tunnels shall be designed so that the risks associated with use of the road types containing crossing tunnels are no greater than for road types where no tunnels are included.” [5]

Tunnels risk level was therefore compared with open road and the comparison was made against the public road network at large, e.g. for roads with similar conditions like speed, urban areas etc. Under a few years, however, a change in the statistics regarding the number of traffic deaths has come and that the comparison with a general road network has been questioned. It seems reasonable that comparison should be made against a modern road of similar standard for example. Dangerous goods were earlier excluded from the analysis on weak basis etc.

This means that the risk level for an open road has reduced and that the space that previously existed for the additional risks in tunnels, due to fire and dangerous goods, has decreased. Moreover some statistics point towards that a tunnel cannot be said to be safer in pure traffic terms than the open road [6] and it is expected that risk due to fire and dangerous good is higher in tunnels. This and additional requirements (Swedish law) [2] concerning the ventilation strategy in the tunnels at the risk of queue has led to that the previous design of tunnels does not meet the new requirements.

Swedish regulations on safety in road tunnels (SFS 2006:418) [7] indicates that the safety measures to be taken in a tunnel shall be based on a systematic assessment of the system in all its aspects, i.e. infrastructure, operation, users and vehicles. The law further states a number of risk controlling factors (in the legislation referred to as parameters) to be included in such assessment. If a tunnel has a special design for this risk controlling factors, should a risk analysis be executed to determine if additional safety measures or additional equipment will be needed to ensure safety in the tunnel [2].
In a systematic assessment of a tunnel system in all its aspects in accordance with regulations on safety in road tunnels with Chapter 2. § 1 [2] can for example the following special characteristic, which need special consideration in the selection of safety measures, appear as specials:

- Tunnel Length (extremely long traffic tunnels)
- Complicated tunnel system containing the main and ramp tunnels, varying number of lanes and weaving sections.
- Traffic flow (extremely high traffic volume over 100 000 vehicles / day in total in both directions)
- High speed (80-100 km / h)
- Risk of traffic jams and queues
- Extensive traffic of hazardous materials (all classes allowed)
- Tunnel slope

In conclusion from a risk point of view these kind of tunnels are very complex and the level of risk, without special attention to extra safety measures, can be expected to be high.

**RISK ASSESSMENT MODEL**

In the current situation there is no simplified method for carrying out the safety design and planning for a tunnel in Sweden and the rules and legislations are varying between specific prescriptive measures to performance-based requirements. The available method for the design of the total safety is the systematic and scientific tool risk analysis.

This section presents the used risk assessment model briefly. The model is based on literature studies, empirical assessments, statistics, calculations and fault- and event tree methodology. The analysis is thus both qualitative and quantitative in nature. Event tree methodology is a tool to systematically develop and illustrate an accident possible course depending on what barriers and conditions there are and how they work. These barriers may consist of both technical and administrative measures. Active traffic management, fixed firefighting system (FFFS) and reduced distance between escape routes are examples of protective barriers. Event trees can be seen as an illustration of possible accident scenarios that may arise as a result of an initial event, in this case the fire in a vehicle due to vehicle defect or accident (resulting in fire or dangerous goods accident) [8, 9]. The event tree model in the analysis has been divided into a number of smaller event trees that are connected to a network of different event trees. The total number of end nodes in the model is over 1000. An important part of a risk analysis is to do sensitivity and uncertainty analysis to find the sensitivity in the model and to calculate the uncertain parts of the analysis, input data and assumptions. The analysis of sensitivity shows [10]e.g. that the number of hours a queue exist in a tunnel has a significant impact on the level of risk.

In practice, in order to achieve the requirement of the law, it’s necessary to carry out a risk analysis on the whole safety concept and then compare the level of risk to a reference tunnel with transverse or semi-transverse ventilation strategy. However, there are not any fixed stipulated requirements detailing how such reference tunnel shall be designed to be acceptable.

WSP has developed a quantitative risk assessment model that has been used in several major projects and analyzes the safety concept from a holistic perspective in which different risks and risk mitigation systems can be analyzed and compared with each other. The quantitative risk assessment model takes into account the following types of accidents presented in figure 1.

In the developed risk assessment model the benefits of active traffic management have been demonstrated effectively reducing the risk for queues and reduce the overall risk.

Focus of this paper is to describe active traffic management as risk-reducing measure and to describe a couple of other mitigation measures in combination with active traffic management. These are fixed firefighting systems, reduced distance between escape routes and traffic restrictions of dangerous goods, which are described briefly.
Figure 1  Accident risks addressed in the risk assessment model.

Figure 2  Basic safety systems

RISK LEVEL WITH PREVIOUS DESIGNS WITH LONGITUDINAL VENTILATION CONCEPT (TUNNEL A)
The overall design and level of risk for a tunnel with the traditional Swedish tunnel design is presented below and represents base-case used for comparison, from now on referred to as Tunnel A.

Tunnel A is designed with parallel tunnel tubes, providing the conditions to evacuate people between the tubes if an accident were to occur and for emergency services to make their way to the accident. The concept of longitudinal ventilation strategy is based on that the vehicle in front of the accident is to drive out of the tunnel and that the people behind the accident to evacuate to the other tunnel tube, in case of fire, which then acts as escape route.

The tunnel tubes are equipped with various safety systems including fire alarms, emergency lighting, information signs, fire extinguishers, longitudinal smoke control, radio breakthrough, traffic control, cameras, booms and more. Escape routes are equipped with firefighting equipment, help telephones and alarm, see figure 2.

The level of risk has been calculated per km. The proportion of heavy goods vehicles > 3,5 ton, HGV, is about 8% of the total traffic flow. The proportion of dangerous goods transports is 2,5% of the total traffic flow of HGV’s. The accidents have been analysis in different accident categories in the event tree model. The traffic flow in these calculations is 140 000 vehicles/day.

This design is based on free flowing traffic. Studies on traffic flow, however, demonstrate that the queues fervently can occur for about 6 hours per day without active traffic management for this kind of tunnel in urban areas [3]. Tunnel A below is calculated with 6 hours of queue. In comparison to this has the risk level for Tunnel A with 0 hour of queue been calculated.

<table>
<thead>
<tr>
<th>Table 1  The risk level of Tunnel A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accident category</td>
</tr>
<tr>
<td>Impact of collision (including fire in normal car)</td>
</tr>
<tr>
<td>Fire in HGV/bus without collision</td>
</tr>
<tr>
<td>Fire in HGV/bus as a result of collision</td>
</tr>
<tr>
<td>Accidents involving dangerous goods</td>
</tr>
<tr>
<td>Total accidents</td>
</tr>
</tbody>
</table>

In a tunnel system, tunnel A, without queue the risk difference against tunnel A with 6 hours of is 48
% on the total risk level and 79 % without traffic accidents. Queues make a significant difference on the risk level.

Figure 3 Expected number of deaths per year divided between accident categories, Tunnel A with 6 hours queue

The expected number of deaths due to normal traffic accident is estimated at 4.5E-02 deaths per year and km or for a 16 km long tunnel about 0.8 deaths per year. The risk picture indicates that the risk of deaths is dominated by accident relating to fire and dangerous goods accidents in the tunnel, which differs a bit form the general point of view.

RISK MITIGATION MEASURES

Traffic management

The introduction of traffic management is an attempt to achieve free-flowing traffic in the tunnel. Theoretically, an active traffic management that creates a free flowing traffic gives a low level of risk. This when road users down streams an accident can drive out and the people up streams are in a smoke free environment.

To be able to better understand how incidents and high traffic flow can generate queues and how they in turn can affect the flow of traffic within the tunnel system a traffic model should be used. WSP has in the last few tunnel projects mainly used a mesoscopic model but also a microscopic model should be used to study smaller networks.

Through the use of a mesoscopic model the whole tunnel system as well as much of the surrounding road network can be modeled. Output such as speed, traffic flow and the buildup of queues and the blocking of junction is result of the modeling. Different hours can be modeled and a number of incidents should be modeled to get an idea of how the queues will build up and what sections of the tunnel system or the surrounding road network is most likely to be affected, or is in fact affecting the buildup of queues within the tunnel.

Different scenarios of traffic disturbance have been modeled to investigate the impact within the system and on surrounding open roads. Studies show that small incidents are usually managed without the need to start major actions. The study also gives good indication on how the traffic system copes with disturbances of the available capacity.

The systems that we generally equip the road tunnels with are: A MCS (Motorway Control System) to help smoothen traffic in case of incidents, automatic barriers to quickly close parts of the tunnel system, a system of microwave and video detectors to detect incidents, queues and stopped vehicles, variable direction signs to direct drivers to alternative routes and to help drivers chose the best route to evacuate the tunnel in case of an incident. At last there is a system of VMS signs to inform drivers
about abnormal situations and to inform drivers in case of an emergency in the tunnels.

The traffic management toolbox consists of: 
*Ramp metering*, usually a basic traffic light together with a signal control that can regulate the flow of entering traffic to a main road. The flow can be set to current traffic conditions and can reduce congestion and prevent queues.

*Mainline metering*, is a control on mainline to a tunnel. It can be used to close the tunnel when the congestion is getting too high. It would also be possible to close the hole or some lanes of the main entrances of the tunnel for shorter periods of time earlier, too prevent congestion and massive queues. In order to make these decisions, however, the operators need some sort of decision making support tool.

*Access control*, can be used for surface ramps downstream from a tunnel exits that is not adding a lane, but rather is a weaving lane. It will in effect mean that the ramp is closed in the most extreme rush hour period. That could also be the case of some of the ramps leading directly into the tunnel if the congestion levels in the main tunnels would be too high. This option will most likely cause severe congestion on the surface network. It has to be remembered, however, that in case of a fire in the tunnels, all the tunnel entrances will be closed anyway. It is assessed better to let the tunnel control center to have access control than to close the mainline.

*Traffic signals*, many of the exits from the tunnels end up in a junction, either give way, signalized or a roundabout. In order to control the traffic going into the tunnels during ordinary traffic situations they would need to be signalized. This would be an alternative to access control where one could control the green times for the traffic flows going into the tunnels. It would also be a big advantage in case of a major incident in the tunnels when there’s a need to quickly evacuate the tunnels. One could then activate an emergency evacuation program in the traffic signals that would allow the exiting traffic to go out without being in conflict with other traffic flows, in a roundabout for instance.

*Hard shoulder running*, has proven effective when incidents have made it necessary to close an ordinary lane. It requires hard shoulders though, to lead the traffic from the area.

*Travel time information*, at a more distant point has been proved effective. The Danish road directory selected a system of travel information signs on the roads leading up to the road being refurbished and also gave the travelers the travel times on alternative routes. In order to ease congestion in road tunnels this solution could be used and it would most likely prove to be effective.

Although active traffic management manages to control traffic in a tunnel system so that free flowing traffic can be achieved under normal conditions, is the system not capable to prevent queues caused by incidents and accidents. For a 16 km long tunnel statistics and calculations shows that queues will occur somewhere in the system about 2 h/day and is therefore used in the calculation [3].

<table>
<thead>
<tr>
<th>Accident category</th>
<th>Expected number of deaths/year/km</th>
<th>Tunnel A Expected number of deaths/year/km</th>
<th>Risk compared to Tunnel A reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact of collision (including fire in normal car)</td>
<td>4,47E-02</td>
<td>4,47E-02</td>
<td>0</td>
</tr>
<tr>
<td>Fire in HGV/bus without collision</td>
<td>9,88E-03</td>
<td>3,05E-02</td>
<td>68</td>
</tr>
<tr>
<td>Fire in HGV/bus as a result of collision</td>
<td>3,31E-03</td>
<td>4,63E-03</td>
<td>29</td>
</tr>
<tr>
<td>Accidents involving dangerous goods</td>
<td>2,92E-02</td>
<td>3,49E-02</td>
<td>16</td>
</tr>
<tr>
<td><strong>Total accidents</strong></td>
<td><strong>8,70E-02</strong></td>
<td><strong>1,15E-01</strong></td>
<td><strong>24</strong></td>
</tr>
</tbody>
</table>

The result shows a significant difference between the tunnel with an active traffic management and Tunnel A. An explanation of some of the difference in the results: the result shows a difference
between “Fire in HGV/bus without traffic accident “. The accidents are due to vehicle defects and the decrease is calculated to 68 %. With decreased proportion of queue, 2h compared with 6h, the model takes account of the decreased traffic work and that risk reduces for serious accidents with many people in the tunnel. When traffic volume increases, the model also takes into account the number of vehicle defects increases. The proportion of serious accidents resulting in fire at queue situation, in dense traffic, due to traffic accident, has been evaluated leading to an increase in risk. Accidents that lead to severe collision and resulting fire has been assessed occur in situations with queues and overtaking accidents coming from traffic behind.

**Fixed firefighting system (FFFS)**

Expected effect of a fixed firefighting system, FFFS, in tunnels as those presented in this paper does not refer to a system in which all fires can be managed and extinguished.

The purpose of such system is to limit the fire to the start object and handle the fire when it is small and not allow it to become critical, i.e. of about 15 MW, corresponding to a fully developed fire in 2-3 medium-sized cars. The systems main purpose is to suppress fire. Performed CFD simulations clearly show that under the prevailing conditions, i.e., geometric and other conditions such as ventilation conditions, etc., arise critical conditions regarding visibility and toxicity of combustion gases at the time a fire becomes about 15 MW. Critical conditions of temperature occur mainly in the area around the fire under the evacuation phase.

The fixed fire firefighting system shall result in reducing the total number of fires to not grow above these levels. The completed risk assessment assumes that the system is activated early when the fire is likely to be small, and then control it, which means that the damage to the property will be limited and that life safety is assured. Since all types of vehicles are involved in the risk analysis the level of ambition that the FFFS must meet limit resulting fires from small cars to large trucks. There is no Swedish standard for fire suppression systems in tunnels. Therefore, the evaluation in order to achieve the above functional requirements is that the analysis is based on the standard used for the bus garage, High Hazard Production or design according to the guidelines for storage of separate goods as High Hazard Storage, according to EN 12845:2004. This is based on the storage height of a truck is between 2.5 m to 3.0 m. The system which has been the basis of the risk analysis has been a deluge system, which is a group release system with clusters of open sprinklers, nozzles. One section, which is controlled by a group of release valve when activated emits water from all sprinkler heads. Water releases always in two sections, i.e. normally in both upstream and downstream of the fire. For the risk analysis, it is assumed that water density is at least 10 mm/ min/m² [3]. The risk model results on the risk level are presented below.

**Table 3 Risk level of tunnel with FFFS and tunnel with FFFS and active traffic management.**

<table>
<thead>
<tr>
<th>Accident category</th>
<th>Expected number of deaths/year/km, with FFFS</th>
<th>Risk difference percentage reduction (%) against tunnel A</th>
<th>Expected number of deaths/year/km, with FFFS and FFFS and active traffic management</th>
<th>Risk reduction (%) compared to tunnel A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatalities due to:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact of collision (including fire in normal car)</td>
<td>4.47E-02</td>
<td>0</td>
<td>4.47E-02</td>
<td>0</td>
</tr>
<tr>
<td>Fire in HGV/bus without collision</td>
<td>2.75E-03</td>
<td>91</td>
<td>9.05E-04</td>
<td>97</td>
</tr>
<tr>
<td>Fire in HGV/bus as a result of collision</td>
<td>6.48E-04</td>
<td>86</td>
<td>4.63E-04</td>
<td>90</td>
</tr>
<tr>
<td>Accidents involving dangerous goods</td>
<td>3.09E-02</td>
<td>11</td>
<td>2.50E-02</td>
<td>28</td>
</tr>
<tr>
<td><strong>Total accidents</strong></td>
<td><strong>7.90E-02</strong></td>
<td><strong>31</strong></td>
<td><strong>7.11E-02</strong></td>
<td><strong>38</strong></td>
</tr>
</tbody>
</table>

The result shows a significant difference between the tunnel with a FFFS and active traffic management compared against Tunnel A.

The likelihood function / availability of the FFFS is assumed to be high to very high, this assumes that the system is well maintained. This is a normal assumption for fixed extinguishing systems in general. These assumptions are maid:
• The probability that the FFFS is activated as planned, given that the detection systems work as intended, is assumed to 0,99.
• The probability of the FFFS is activated as planned has been adopted to: 0.97
• The probability that the fire is not too large at the time of activation, given that the fire caused by vehicle defects: 0.95

For fire scenarios with traffic accidents and dangerous goods have similar assumptions been made.

Restrictions for dangerous goods traffic
The performed analysis is based on statistic of transport of dangerous goods. The analysis is based on no restrictions of dangerous goods, the tunnel class A is used in accordance with ADR-S framework [11]. Restrictions on transportation of dangerous goods can be varied in many different ways. Everything from that no transport of dangerous goods is allowed to that a reduced number of dangerous goods classes are not allowed during certain time periods to name but a few examples. Below presents the effect on the risk level when a restriction where no dangerous goods is allowed.

Table 4  Risk level of tunnel with restrictions of dangerous goods.

<table>
<thead>
<tr>
<th>Accident category</th>
<th>Restrictions of transports of DG Expected number of deaths/year/km</th>
<th>Risk reduction (%) compared to Tunnel A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact of collision (including fire in normal car)</td>
<td>4,47E-02</td>
<td>0</td>
</tr>
<tr>
<td>Fire in HGV/bus without collision</td>
<td>3,05E-02</td>
<td>0</td>
</tr>
<tr>
<td>Fire in HGV/bus as a result of collision</td>
<td>4,63E-03</td>
<td>0</td>
</tr>
<tr>
<td>Accidents involving dangerous goods</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Total accidents</td>
<td>7,98E-02</td>
<td>30</td>
</tr>
</tbody>
</table>

Restrictions of transports of dangerous goods will decreases the total level of risk with 30 % for a tunnel under these conditions.

Reduced distance between escape routes
In comparison object tunnel A the distance between escape routes is 150 m. The risk analysis compared this distance with a reduced distance that is 75 m. Reduced walking distance contributes to an improved evacuation situation by making the time to travel to the escape route less. A reduced distance between the escape routes also contributes making it easier to discover where to evacuate in an accident situation. I case of fire and a smoke filled environment the chance to find an escape route will be higher. To do a deep analysis of who a reduced distance affects the total risk level is a very hard to do. A estimation is adopted and the assessment is that it reduces the risk for evacuees with about 20 %. This when the closeness to an escape route raise awareness about where to find it and in the event of an evacuation in smoke filled environment increases the probability to find an escape route. The value was determined in an expert group and is presented in this paper as an example of qualitatively managed parts. It has in all parts of the analysis regarding the consequences of an accident taken into account if a reduced distance between escape routes makes a benefit or not [12].

Combination of risk mitigation measures
Three alternative combinations of risk mitigation measures are presented below. Enhancement pack 1 has FFFS, active traffic management and reduced distance between escape routes. Enhancement pack 2 has restriction of dangerous goods, active traffic management and reduced distance between escape routes. Enhancement pack 3, not in the table, is a combination of pack 1 and 2 i.e. has restriction of dangerous goods, FFFS, active traffic management and reduced distance between escape routes.
Table 5  Risk level of enhancement pack 1 and 2

<table>
<thead>
<tr>
<th>Accident category</th>
<th>Pack 1. Expected number of deaths/year/km, with FFFS, active traffic management and reduced distance between escape routes</th>
<th>Risk reduction (%) compared to tunnel A</th>
<th>Pack 2. Expected number of deaths/year/km, active traffic management, reduced distance between escape routes and restrictions of transports of DG</th>
<th>Risk reduction (%) compared to tunnel A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatalities due to:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact of collision (including fire in normal car)</td>
<td>4.47E-02</td>
<td>0</td>
<td>4.47E-02</td>
<td>0</td>
</tr>
<tr>
<td>Fire in HGV/bus without collision</td>
<td>7.24E-04</td>
<td>98</td>
<td>7.90E-04</td>
<td>74</td>
</tr>
<tr>
<td>Fire in HGV/bus as a result of collision</td>
<td>3.70E-04</td>
<td>92</td>
<td>2.65E-03</td>
<td>43</td>
</tr>
<tr>
<td>Accidents involving dangerous goods</td>
<td>2.00E-02</td>
<td>43</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td>5.69E-02</td>
<td>50</td>
<td>5.53E-02</td>
<td>52</td>
</tr>
</tbody>
</table>

The two different combinations, pack 1 and 2, of risk mitigation measures show nearly the same level of risk. The one with restriction of dangerous good, pack 2, shows a slightly better risk reduction. What this number is not showing is that the reduction of catastrophic accident is much bigger in pack 2.

Figure 4  Expected number of deaths per year divided between accident categories, enhancement pack 1

Further the FFFS in pack 1 reduces more of the severe fire scenarios. The combination of pack 1 and 2, pack 3 will give the tunnel with a risk level at 4.58E-02 death/year and km, which is only 2% over a risk level for an assumed open road/km and reduction of “Total Fire and Dangerous goods accidents” with 98 % in comparisons to Tunnel A (60 % reduction of the total risk).

Figure 5  Total risk level of Tunnel A compared against the different enhancement pack, expected number of deaths/year/km
CONCLUSIONS

The analysis shows that the contribution of risk in queue situations in the safety concept with longitudinal ventilation is significant. The analysis also shows that the entire contribution of risk due to queues cannot be dealt with active traffic management. The reason is that in tunnels with high traffic volumes, with up to 2000 vehicles per lane and per hour, will have regularly incidents (e.g. engine failure, fuel state, disease, punctures, etc.) and pure accidents in varying severity resulting in queues.

In a tunnel for example, with 140 000 vehicles per day, the analysis shows that about two hours a queue will occur due to the above contributions of incidents and accidents. This is despite active and roving road assistance with a response time of about 5 minutes. To reduce the risk associated with this type of situation and the overall level of risk, additional risk mitigation systems must be deployed. The additional systems consist of a fixed firefighting system, reduced distance between the escape routes or restriction on transportation of dangerous goods and reduced distance between the escape routes. The systems and the restriction are showing a significant reduction of the risk level in tunnel systems of this type. Transports of dangerous goods in tunnels make a big contribution on the risk level, regulations on dangerous good traffic under high traffic hour is judged to lower the risk level significant. The analysis also shows that huge demands are set on the mitigation systems that are deployed. Active traffic management is likely to affect the surrounding road network on daily basis to keep the tunnel without queues.

The legislation gives very little support for which ventilation strategy to use. In fact as long as tunnels have no acceptance criteria for tunnels, regardless of ventilation strategy, the risk level will be varied for different tunnels and the requirement to use transverse or semi-transverse ventilation strategy useless.

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Assessing Fire Development Risk in Rail Vehicles and the Impacts on Tunnel Infrastructure

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ABSTRACT

An essential factor in the design of tunnel emergency ventilation systems is the design fire. While a wide range of fires can occur within rail tunnels, a prominent hazard is an interior vehicle fire. How large a fire may become is dependent upon several factors including the initiation fire, vehicle interior lining materials and contents, vehicle configuration, and ventilation. Estimating the outcome of an initiation event is vital in developing appropriate design criteria for tunnel systems design. This paper presents an approach for characterizing initiation fires and predicting potential flame spread. It is demonstrated how quantities derived from small-scale test results can be used to quickly assess a material’s propensity to spread flames over a range of initiation fires. Risk assessment techniques can be used to rank initiation fire events and identify specific critical fire hazard scenarios, thereby establishing a risk register for a particular vehicle configuration. In considering the vehicles as integral components of an entire passenger rail system comprising tunnels, stations, and related emergency systems the proposed method can inform design and operational decisions in a holistic approach that accounts for the tunnel systems, vehicles and vehicle-based systems.

KEYWORDS: flame spread, fire growth, design fires, rolling stock, risk assessment

INTRODUCTION

One of the most important input parameters to life safety and emergency ventilation system designs to mitigate catastrophic events in rail tunnels and stations is the design fire. While there are a wide range of fire scenarios that can occur within these facilities, one of the more significant hazards is an interior passenger rail vehicle fire. How large the fire may become is dependent upon the initiation fire, vehicle interior linings and contents, vehicle configuration and ventilation.

Full scale tests can be used to evaluate fire hazards represented by different interior lining materials, contents and ventilation scenarios, when exposed to various initiation fire scenarios. However, full scale tests are costly, time-consuming, and not highly repeatable. Small-scale fire testing, combined with fire growth modeling can offer a cost- and time-effective solution. Through the application of a screening tool or criterion, it may be possible to quickly assess a material’s propensity to ignite and spread flames over a range of initiation fires. Additionally, small-scale test data can be used to estimate material pyrolysis and combustion properties for use as input in models with flame spread capabilities. Through careful model calibration and an in depth understating of a model’s limitations, such tools, which may include computational fluid dynamics (CFD) programs, provide means to predict flame spread and characterize overall fire development based on small-scale data alone.

This paper presents a method to use small scale testing to estimate fire hazards in passenger rail vehicles. The method combines: (1) characterization of postulated initiation fires in terms of thermal insult, (2) a simplified approach for predicting potential for flame spread based on small scale testing,
and (3) hazard-based fire and flame spread modeling to characterize design fire scenarios. The methodology lends itself to supporting threat, risk and vulnerability assessments of transit systems. A risk-based framework can also allow owners and operators to mitigate exposure through the vehicle design process by defining specific threats or initiating events to which the vehicle ought to be resistant. This paper intends to overview the process; details, implementation, or combining of the method with risk techniques are given elsewhere [1,2,3].

RISK-BASED APPROACHES

The Department of Homeland Security (DHS) outlines an approach which considers risk to be function of consequence, vulnerability, and threat [1]. Meacham [1] describes this for rail vehicles:

**Threats.** As used here the threat is fire, or more correctly an initiating fire. For purposes of characterizing the threat, fire in a passenger rail vehicle can be accidental or deliberate. Passenger rail systems experience accidental fires due to ignition from equipment failure within the train (e.g., locomotive power systems failure, equipment failure in the internal electrical systems, lighting systems, heating systems, brake systems, etc), from failure in the system infrastructure (e.g., power systems, station related hazards), and from external exposure fires (e.g., trash fires, brush fires). Deliberate actions such arson are also a significant threat to passenger rail systems.

**Vulnerability.** There are several dimensions of vulnerability. With respect to deliberate events, the vulnerability exists due to the generally open nature of the systems, particularly subways and commuter rail systems, with limited capacity to screen all passengers for security threats. Rail vehicles are also vulnerable in the sense that they use combustible materials, which can contribute to the size of the fire and the extent of resulting damage.

**Consequences.** Fires can remain small, contained to the initial item burning, or grow to encompass all vehicles in the train. The ultimate size of a fire will be influenced by the size of the initiation fire, the type, amount and characteristics of fuel available to burn within the vehicle, the size and location of ventilation openings, and the compartment (vehicle) configuration. Fire can result in significant damage to a passenger rail vehicle, its occupants, the occupants of a station, and to physical infrastructure such as rails, bridges, tunnels, catenary, cable and other services. The extent of damage in terms of life safety, physical infrastructure and operations can be catastrophic.

**Risk.** The overall fire risk should include characterization and assessment of potential accidental and deliberate initiation events, fire-related vulnerabilities, and the consequences of the fire events should they occur. Many risk assessment methods exist, and selection of a suitable approach should be based on the availability and reliability of the data and method.

THREATS

**Hazard Assessment**

Surveys conducted by the Rail Safety & Standards Board of rail transport systems in the U.K. [5] show that fire events make up 0.7 FWI/yr (fatalities weighted injuries per year). In 2008 the Federal Railroad Administration (FRA) Railroad Safety Statistics [6] estimates approximately 0.4% of all rail related accidents can be attributed to fire. A survey of all train and rail vehicle fires for an eight-year period (1992-2000) in the U.K. [7] shows the cause of 44% of the total fire incidents were attributed to arson. Looking just at passenger trains, the incidents of fire due to arson were 56% of the total. This is consistent with data collected since 2006 from U.K. and Europe [8] rail systems where 73% of interior passenger train fires are attributed to arson (Figure 1).
Initiating Fires

Different initiating fires may produce a range of different outcomes. For example, a small trash fire may only spread along a seat, up the adjacent wall, and then self-extinguish. Alternatively, a gasoline fire could be large enough to cause full vehicle involvement. The ultimate fire size associated with these fuels is an important factor in determining if the initiating fire will lead to involvement of interior lining materials. Scenarios of interest in a passenger rail vehicle setting may include trash bags, suitcases, vehicle seats, and flammable liquids [9]. Initiating fires depicted in Figure 2 are representative of a range of probable events that may be used in a risk-based approach.

After identifying the nature and size of potential initiating fires, it is important to then characterize the fires and assess the likelihood that the fire would ignite vehicle contents and result in flame spread. In general, the issue of concern is the potential thermal exposure from the initiating fire, a function of the intensity and duration of the fire to the materials which may next become ignited. For example, a match can easily ignite a thin piece of paper, but will not be able to ignite a thick block of wood.

BENCH-SCALE TESTING

US Federal Regulations and NFPA 130 [10], as examples, specify fire tests each material must pass to achieve compliance, hence the term “compliance tests”. These tests provide limited data for use in an engineering analysis. The cone calorimeter [11,12], on the other hand, can provide more detailed output to support an engineering analysis. The cone calorimeter is a standardized testing apparatus [11,12] that uses oxygen consumption calorimetry to measure the heat release rate of a small-scale material specimen. By measuring the concentration of oxygen, carbon monoxide, and carbon dioxide within the apparatus flue gases, it is possible to estimate the heat release rate of the burning specimen [13,14]. This involves exposing a specimen measuring 0.1 m by 0.1 m to a constant external radiant flux. This surface heat flux can be varied up to 100 kW/m² allowing for fire performance and burning characteristics, such as heat release rate per unit area, smoke and species production, and time to ignition to be evaluated under different heat flux conditions [9].
Cone calorimeter data can be used both for material screening and as a basis for estimating material combustion and pyrolysis properties. Representative rail vehicle interior lining materials (walls, flooring, ceilings, seating, glazing, etc.) would be tested at heat fluxes, ranging between 15 kW/m² and 75 kW/m², representative of the thermal environments of pre- and post-flashover compartment fires. In addition to quantities normally measured in cone tests, additional measurements of surface and back-face temperatures can be utilized in material property estimation routines [15,16,17,18].

![Seat padding specimen; Cone Calorimeter test apparatus and specimen holder](image)

**Figure 3** (a) Seat padding specimen; (b) Cone Calorimeter test apparatus and specimen holder

**Vulnerability**

**Ignition**

By measuring the time to ignition at varying heat fluxes, it is possible to estimate the material’s critical heat flux, the minimum heat flux at which ignition of the material may occur, by plotting the inverse of time to ignition raised to an appropriate power versus cone calorimeter heat flux. The point at which the curve crosses the external flux axis (x-axis) is the critical heat flux. The thermal exposure generated within the cone calorimeter can then be defined as the product of the time to ignition and the incident flux less the material’s critical heat flux as follows:

\[
(\dot{q}^n - CHF) \times t_{ig}
\]  

(1)

With knowledge of the critical heat flux and thermal exposure experienced during testing, one can then compare against the thermal exposure generated by a given initiation fire to assess whether the initiation fire is an adequate ignition source to ignite the material of interest – an initiation fire that burns sufficiently long, with enough energy can ignite the second material. If the thermal exposure from an initiation fire exceeds that developed during a cone calorimeter test, ignition and subsequent involvement of the material could be expected. If the thermal exposure is less than that generated during the cone calorimeter test, then material ignition would not be expected.

**Flame Spread**

While susceptibility to ignition of a material by a given initiation fire is a key indicator of risk, it does not fully define the vulnerability of a material to a particular hazard. Depending on the material and the strength of the initiation fire, the ensuing fire could either decelerate or accelerate. For a decelerating fire, the burn-out rate exceeds the flame spread rate and the amount of material actively involved in combustion decreases with time, often leading to (self) extinguishment. In such a fire, the amount of material that becomes involved and the extent of damage can be limited. For accelerating fires, the spread rate is faster than the burnout rate resulting in more and more material becoming actively involved in combustion. The resulting fire can become very large and potentially lead to a critical event (flashover) in which most/all contents of the vehicle are actively burning. Determining which materials under certain exposure conditions would result in accelerating flame spread is important in evaluating material use in rolling stock. A first order screening approach can
be conducted based on Quintiere’s [19] flame spread parameter to identify which materials are likely
to support flame spread at various heat fluxes. The equation utilizes fire parameters, observed,
measured or derived from cone calorimeter results. The b-parameter is given as:

\[ b = 0.01 \dot{E}^* - 1 - \frac{t_{ig}}{t_{end}} \]

where: \( \dot{E}^* \) is the average heat release rate per unit area (kW/m²); \( t_{ig} \) = time to ignition; \( t_{end} \) = is the
end measured test time (e.g., time to burnout). Flame spread can be considered to accelerate if “b” is
greater than zero and decelerate is “b” is less than zero. Figure 4 demonstrates the dependence “b”
on incident flux for some typical lining materials. It can be seen that “b” is directly proportional to
flux indicating that materials will support accelerating flame spread at higher incident fluxes.

The b-parameter can be used in at least two ways: (1) as a screening tool to inform decisions about
material selections, and (2) as a first-order hazard assessment. For the former, consider two wall
lining materials in Figure 4(a) – the fiber reinforced plastic (FRP) and the painted phenolic FRP. At
incident fluxes less than 35 kW/m², decelerating flame spread would be predicted for both materials.
At incident fluxes greater than 50 kW/m², the b-parameter for the FRP gelcoat is positive, suggesting
the material will support accelerating flame spread. At similar incident heat fluxes, the painted
phenolic consistently has lower b-parameter values; at 50 kW/m² it is still negative. This means that
under similar thermal exposure conditions the painted phenolic is less likely to support accelerating
flame spread than the FRP. As such, material selections could be made based on relative values of
“b”. As a first-order hazard assessment tool, “b” can crudely predict material response to certain
initiating fire events by comparing the incident heat flux from an initiating fire event to that utilized in
the cone calorimeter experiments. In this way, the b-parameter can be used to evaluate if decelerating
or accelerating flame spread can be expected in response to a certain initiating fire.

**CONSEQUENCE**

**Initial Flame Spread**

A simplified upward flame spread model, based on the work of Mowrer and Williamson [20], has
been developed to represent the initial flame spread that might occur in passenger rail vehicles [1].
Upward flame spread is a complex phenomenon which involves thermal exposure from an initiation
fire to a surface (e.g., a wall), sufficient heating of the wall material to release combustible gases
(pyrolysis) and ignite them, and the ability of the material to continue to burn in the absence of an
initiation fire by creating a sufficiently large and hot flame to sustain the pyrolysis process. Figure 5
illustrates the characteristics of upward flame spread as adapted from Mowrer and Williamson [20].
The model uses parameters measured in small-scale tests and includes expressions to demonstrate
how flame height, pyrolysis height, and burnout height relate to one another and change over time.
The model assumes one-dimensional concurrent flow flame spread along the wall. The overall flame
height, \( x_f \), consists of the flame created on the wall by the external source fire and the flame extension
up the wall. The pyrolysis height is represented by $x_p$. When fuel is consumed or used up, it no longer supports flaming and a burnout front, $x_b$, develops. The initiation fire imposes a heat flux on the vertical wall. After the first exposed material is ignited, the flame extends up the wall, emitting a flux to the unburned fuel above. The flame spread model essentially uses “b” to assess whether sufficient burning will occur for the pyrolysis zone to accelerate faster than the burnout zone. Details of the flame spread model are presented elsewhere [1,2,3].

Exemplar output from the simplified model is provided in Figure 6, which shows the results for a material exposed to two different initiation fires: (a) a 40 kW trash fire and (b) a 400 kW flammable liquid fire. For the trash fire exposure, “b” is negative; for the flammable liquids fire, “b” is positive for the given material. Figure 6 (i-a) shows that the distance between the pyrolysis height and the burnout height, $x_p-x_b$, decreases over time, indicative of decelerating flame spread. Figure 6 (i-b) shows the distance between the pyrolysis height and the burnout height increasing over time, indicative of accelerating flame spread. Figure 6 (ii-a) and (ii-b) show estimates of the heat release rates resulting from the predicted flame spread. This example demonstrates the use of the model for assessing one material under multiple exposures; it can also be used to assess different materials under similar exposures.

Fire Spread and Fire Growth Modeling

While “b” and the simplified upward spread model are suitable for first order analysis of individual materials and their vulnerability to defined fires, neither can address multiple materials, actual vehicle configurations, or compartment effects. These tools address ignition and “early” fire development. However, for system design it is essential to understand the ultimate outcome of a scenario to define a
design basis fire. This requires the ability to predict involvement and interaction of multiple factors in fire development including vehicle material contents and ventilation conditions. Methods that have been used for estimating rail vehicle fires include: (1) the summation of fuel loads divided by an assumed burn time; (2) area-scaling of cone calorimeter test results; and (3) post-flashover, single-zone models. The underlying assumption in each is that all materials burn simultaneously, ignoring characteristics of the initiating event, incipient burning, and variations of heat flux. In contrast, flame spread modeling using computational fluid dynamics (CFD) models such as Fire Dynamics Simulator (FDS) [21, 22] can resolve complex geometries and account for multiple materials.

Material Property Estimation

While FDS contains the basic physics necessary for fire growth modeling, the determination of the material properties required for pyrolysis modeling remains a challenge. Due to the numerous input quantities required, and the difficulty in directly measuring these from tests, a commonly used approach involves working backward from bench-scale tests utilizing numerical optimization methods such as genetic algorithms (GA) [15,16] or shuffled complex evolution (SCE) [17,18] to determine effective properties. In these methods, hundreds of combinations of model input parameters are generated and passed to the (FDS5) pyrolysis model to simulate mass loss and front and back surface temperatures. The fitness of each parameter set is found by quantifying how well the model results match experimental data from cone calorimeter tests. Convergence is achieved when there is no further improvement in the fitness from one generation or evolution to the next.

Mockup Testing and Model Calibration

Pyrolysis modeling is a burgeoning field and model capabilities are not yet extensively validated with respect to flame spread and fire growth. Therefore, testing and model calibration are important steps in the process. Real-scale mockup fire tests have been conducted in a standard ISO room [23]. The mock-up is designed to represent a portion of the rail vehicle including representative contents and lining materials. Such a test set-up and corresponding fire model is shown in Figure 8. Effective material properties determined in the property estimation process are applied to the model.

Figure 7  Comparison of measured and modeled mass loss rate at 50 kW/m² for (a) painted phenolic FRP and (b) seating fabric

Figure 8  Mockup fire test configuration, (a) burn test compartment; (b) replica fire model
Figure 9 compares measured and predicted HRR and compartment heat fluxes. The overall shapes of the curves are well represented, but the peak heat release rate was over-predicted. The results also show a slight bias toward under-prediction of peak temperatures (not shown) and heat fluxes.

**Figure 9** Experimental and model comparison a) heat release rate b) heat flux

**Model Setup and Baseline Assumptions**

With a calibrated fire model, predictions of fire spread can be made to inform the severity of a particular initiating scenario and to examine the effects of design selections and/or mitigation measures. The modeling discussed here is a case study to illustrate how this approach can form part of the vehicle and system design process. The model consists of a representative rail car layout with a fire located in the corner beneath a seat. Materials used in the model are: Phenolic FRP for ceilings and walls; carpet/pad assembly for floors; foam/fabric assembly for seats; and FRP for seat backing.

**Effect of Material Selection**

Different wall linings, depending on composition, will behave differently when exposed to the same initiating fire. This example compares the FRP and the painted phenolic FRP panels in the same configuration. Figure 11 shows the HRR curves and corresponding fire spread when exposed to a baggage fire. The results show that the phenolic FRP panel is a better performer at limiting fire spread. Fire spread for the FRP panel has spread to the adjacent seat and has involved part of the wall; the phenolic FRP is limited to the back seat and the lower part of the wall.

**Figure 10** Fire model a) isometric exterior b) isometric plan view inside the car

**Figure 11** Predicted a) HRR curves and fire spread over b) phenolic and c) FRP panels
Mitigating hazards in the vehicle design process not only addresses life safety risks but can also yield system-wide benefits. For this case study two options are considered: 1) no mist system, and 2) an on-board mist system. The example only considers equipment installation costs of the mist system and corresponding improvements to the ventilation system. Assumptions common to both options are: single bore, twin track tunnel 9 m high and 13 m wide, ventilation fans with 118 m³/s capacity @ $1.34 M USD (fully loaded costs), life expectancy of fans = 30 years, 1000 vehicles in the system. For Option 1, the following is assumed: design fire HRR = 25 MW, critical flow of 244 m³/s, 3 fans per plant, and 10 fan plants necessary. For Option 2, the following is assumed: mist installation cost = $18,700 USD/car, weight=200-400kg/car, mist system life = 30 years, design fire HRR = 2 MW, critical flow of 112 m³/s, 1 fan per plant, and 8 fan plants required. Considering these parameters, Table 1 illustrates the potential system-wide savings for tunnel emergency ventilation systems. This is a hypothetical case, in which the impacts of vehicle material selection and on-board suppression on system-wide design criteria, e.g. the design fire, were evaluated and quantified. Other costs not considered in the analysis are: track wear and increased maintenance due to increased vehicle weight, mist system maintenance, property acquisition costs, station/tunnel structural damage, vehicle replacement cost, and indirect design benefits due to reduced ventilation equipment, etc. An exhaustive cost benefit analysis should be conducted that considers all design aspects.

Table 1  Installation cost comparison of no on board suppression vs. on board water mist system

<table>
<thead>
<tr>
<th>Option</th>
<th>Fire Size (MW)</th>
<th>Mist Cost ($M USD)</th>
<th>Fan Plant ($M USD)</th>
<th>Total Cost ($M USD)</th>
<th>Annual Cost ($M USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – No mist</td>
<td>25</td>
<td>-</td>
<td>40.28</td>
<td>40.28</td>
<td>1.34</td>
</tr>
<tr>
<td>2 – Mist</td>
<td>2</td>
<td>18.76</td>
<td>10.74</td>
<td>29.50</td>
<td>0.98</td>
</tr>
</tbody>
</table>

**SUMMARY**

The use of analytical tools within a risk assessment framework to screen materials, estimate material vulnerability to ignition and flame spread, assess fire growth, and to determine order-of-magnitude fire sizes given an initiation fire has been highlighted. With respect to rolling stock and infrastructure design, such tools have a range of potential applications [1], including in the hazard assessment of new and existing rolling stock, threat assessment of critical infrastructure by better quantifying design basis fires, improved assessment of fire mitigation alternatives, establishing and understanding risk thresholds, as well as regulatory support.

Through the use of appropriate derived quantities, small-scale material testing results can be coupled with real fire data to cost-effectively assess a wide range of scenarios and material combinations for existing and proposed vehicle designs. This could be used as part of a threat, vulnerability and risk assessment (TVRA) of vehicles and emergency systems in coping with those estimated fires. At the vehicle design stage, the methodology can be applied to assess the performance of different interior lining materials with respect to resistance to ignition and contribution to overall fire size. The tools allow informed judgments about material use in vehicles as well as overall system vulnerabilities.
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8. Arup, Real Fire Data. Understand the Risk
Optimization of Measures Directed on the People Safety at Tunnel Fire by Means of Computational Methods

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ABSTRACT

The increase of intensity of transport streams in large cities results in the necessity of construction of such complex and frequently unique constructions as transport tunnels. One of the most actual aspects for the design and operation of tunnels is the maintenance of their fire safety. Large-scale fire experiments in tunnels are rather expensive and laborious, besides that their results can not be directly extrapolated on any tunnel. Therefore mathematical modelling is very perspective for a decision of fire safety problems. In this paper the mathematical model is developed which allows assessing the maintenance of the safe people evacuation from the road tunnel with taking into account some of its peculiarities. The example of such assessment for road tunnel is presented.

KEYWORDS: road tunnel, fire modelling, safety evacuation

INTRODUCTION

The increase of intensity of transport streams in large cities results in the necessity of construction of such complex and frequently unique constructions as transport tunnels. The experience of exploitation of transport tunnels, especially located in cities, shows high probability of wrecks and accidents accompanied with fires. The raised fire danger of transport tunnels is caused with:
- high intensity of vehicles movement with a significant amount of combustible materials;
- a plenty of people who can be involved in an emergency;
- the limited opportunities of evacuation and rescue of people from an underground construction;
- difficulty of expansion of forces and means of fire suppression in conditions of a probable jam of motor vehicles and a lot of other reasons.

The fires which occurred in European tunnels were often accompanied with victims and large destructions and losses [1]. So for such unique objects as road tunnels the fire safety system is of very importance. This system can include both active protection systems (fire extinguishing system, smoke extraction system) and passive protection system (division of a tunnel into sections, creation of service and evacuation corridors, safety zones etc). The main goal of fire protection system is the maintenance of people safety during a fire.

Due to peculiarities of tunnel fires several countries create national and international programs of tunnel fire experimental studying. The most famous of them are EUREKA, «Memorial Tunnel», Runehamar tunnel, UPTUN, SOLIT etc. All Russian Research Institute for Fire Protection has also constructed the experimental facility for full-scale fire experiments in the tunnel [2]. But the realisation of large-scale fire experiments in tunnels is rather expensive and laborious, besides that their results can not be directly extrapolated on any tunnel. Therefore mathematical modelling is very perspective for a decision of fire safety problems. Such models approved on experimental data, could
become a basis of the maintenance of fire safety of an object with taking into account its specific features.

**ALGORITHM OF COMPUTATIONAL ASSESSMENT OF PEOPLE SAFETY**

Fig. 1 shows the scheme of algorithm of computational assessment of people safety. We can see that this algorithm includes three key points. They are the prediction of fire development, the modelling of people movement and the analysis of the received results (formulation of the criterion of people safety and checking whether it is valid).

![Algorithm of computational assessment of people safety](image)

**FIRE SCENARIOS (DESIGN FIRES)**

The detailed analysis of the designed fires being used in the world was made in [3]. In Russia there is no any official document which gives recommendations on the choice of design fire in road tunnel. But the following values of maximum heat release rates (HRR) are commonly used: 100MW for tunnels without transport restrictions, 50 MW for tunnels where lorry movement is prohibited or allowed with special measures, 30 MW for tunnels with cars and vans only.

But for the assessment of people safety the rate of HRR growth is even more important than maximum HRR. So it’s necessary to describe the dependence of HRR in time. The dependence being
used in All-Russian Research Institute for Fire Protection formally differs from all recommendations presented in [3]. It consists of two stages. The stage of linear growth from 2 MW at t=0 (imitate small leakage of gasoline) to maximum HRR at 900 s and the stage of constant HRR after 900 s. The decay stage is not considered because people evacuation has finished before it occurs. But quantitatively this dependence doesn’t significantly differ from European recommendations.

Usually the scenario with the fire origin at the part of tunnel with maximum slope is considered. Sometimes in tunnels, where the slope is big and have different directions the fires at extremum points are also simulated. Firstly the fire scenarios without of smoke extraction system are modelled and if people safety evacuation is not provided the calculations are repeated with smoke extraction system taking into account and the necessary smoke extraction rate is determined.

**ASSESSMENT OF PEOPLE SAFETY IN ROAD TUNNEL**

Below the example of people safety assessment in one of the real tunnels is presented.

The mathematical model of fire implemented by means of the code SOFIE [4] included the following governing equations: continuity equation, full equations of Navier-Stokes, enthalpy equation, $k-\varepsilon$ turbulence model with buoyancy correction and species equations. For combustion simulation eddy break-up model was used. The radiation heat transfer was modeled by means of the discrete radiation transfer model (DTRM).

This model predictions were compared with experimental data on tunnel fires in [4-6].

For estimation of the time of evacuation ways blocking the following hazardous factors were taken into account: loss of visibility, rise in temperature up to critical value 70°C (343 K), increase of heat flux up to 1.4 kW/m², increase of carbon monoxide concentration up to critical value of $1.16 \times 10^{-3}$ kg/m³, increase of carbon dioxide concentration up to 0.11 kg/m³.

As the critical distance for an estimation of blocking time as a result of a visibility loss in a smoke the value of 20 m was chosen, that approximately corresponds to the width of a tunnel. According to [8] this value of visibility distance under the standard conditions of a light exposure corresponds to the value of optical density of 0.12 Np/m.

The results of simulations shows that the most critical hazardous factor in this case is loss of visibility (except the small region just near the fire where the heat flux is the most dangerous).

The dynamics of optical density in tunnel at absence of smoke extraction system presented in fig. 2. The figure shows that by the moment 60 s optical density at the height 1.7 m exceeds the critical value at the distance 35 m from the centre of fire origin. Then the smoke continues its spread along the tunnel and by the moment 300 s the evacuation ways upside the tunnel slope are blocked.

In fig. 3 the optical density dynamics is presented for the case of working smoke extraction system. Three smoke extraction zones were turned on with length of 100 m. Each zone included two lines of valves placed with 10 m interval. The flow rate of each smoke extraction zone was 250000 m³/hour. The activation of smoke extraction system was made at the time moment of 60 s.

The figure shows that the use of smoke extraction system delays both the smoke descending and the smoke spread along the trunk of the tunnel. By the time moment 60 s at presence of smoke extraction system the smoke doesn’t descend below the height of 1.7 m and by the moment 300 s the smoke spreads only to the mark of 85 m (fig 3c).
Figure 2. Optical density of smoke (Np/m) in the central vertical cross-section of the tunnel at the time moments 60 s (a), 180 s (b), 300 s (c) at absence of smoke extraction
Figure 3. Optical density of smoke (Np/m) in the central vertical cross-section of the tunnel at the time moments 60 s (a), 180 s (b), 300 s (c) at presence of smoke extraction.
Necessary to note, that the formulation of the people safety criterion is as important as people movement and fire development modelling. Traditionally the assessment of people safety is carried out by the comparison of the blocking time of the evacuation exits and the time of complete evacuation of people to the safe zone. In tunnels due to big length of the evacuation ways such approach has a dramatic limitation because the situation is possible when the people are covered with smoke in the middle of evacuation way and, if the evacuation exit is located far from the fire source, they can reach the fresh air zone and leave the tunnel before the exit is blocked (see fig. 4). The modified formulation of the criterion is proposed which consist in the comparison of the distributions of blocking time and time of evacuation along the length of the tunnel.

\[ t = t_1 \]
\[ L_1 \]
\[ t = t_2 \]
\[ L_2 \]
\[ t = t_3 \]
\[ L_3 \]

Time of people egress

Time of blocking

Distance from fire source, m

Figure 4. Limitation of the traditional criterion
Simulation of people evacuation was made on the base of the mathematical model of individual - stream movement of people from a building [7].

The following variants of evacuation were considered:
-variant-1. Evacuation exits with 1.2 m width are situated at the distance 120 m from each other. The fire is near one of the exits. The scheme of evacuation is shown below.

-variant-2 Evacuation exits with 1.5 m width are situated at the distance 150 m from each other. The fire is near one of the exits. The scheme of evacuation is shown below.

-variant-3 Evacuation exits with 1.2 m width are situated at the distance 120 m from each other. The fire is in the middle of distance between the exits. The scheme of evacuation is shown below.

- variant-4 Evacuation exits with 1.2 m width are situated at the distance 120 m from each other. The fire is in the middle of distance between the exits. The scheme of evacuation is shown below.
variant-5 Evacuation exits with 1.2 m width are situated at the distance 120 m from each other. The fire is at the distance of 40 m from the exit. The scheme of evacuation is shown below.

variant-6 Evacuation exits with 1.2 m width are situated at the distance 120 m from each other. The fire is at the distance of 40 m from the exit. The scheme of evacuation is shown below.

According to the accepted criterion of people safety the following condition must be valid for each site of evacuation ways

\[ t_{p} + t_{n,3} \leq t_{n} \]

where \( t_{p} \) – calculated time of people evacuation (time of movement);
\( t_{n,3} \) – time from the fire beginning to evacuation beginning;
\( t_{n} = 0.8 \ t_{b3} \) – necessary time of evacuation.
\( t_{b3} \) - time of evacuation way being blocked.

In fig 5 the distributions of necessary and calculated evacuation times along the tunnel are presented. The time \( t_{n,3} \) was taken equal to 30 s according to [9]. So the criterion is valid if the difference between necessary and calculated time is more or equal to 30 s.

The figure shows that for the scenario without smoke extraction the criterion is not valid for all variants of evacuation.

For the scenario with smoke extraction for variants where the fire occur near the evacuation exit (variants 1,2) the criterion is valid when people go to the nearest exit. But for variants where fire occur between the exits (variants 3, 5) the safety criterion is not fulfilled when people go to the nearest exit. And besides the design decisions the special algorithm of evacuation control for the provision of safe evacuation (variants 4, 6).

So the calculations allowed to determine acceptable width of evacuation exits and distance between them, the flow rate of smoke extraction system and shows the necessary algorithm of evacuation control.

From the above analysis we can also conclude the fire near the evacuation exit which is often supposed the most dangerous for people in public buildings can be less dangerous in tunnels.
FIGURE 5. Necessary and calculated evacuation times along the tunnel
CONCLUSIONS

The mathematical model is developed which allows assessing the maintenance of the safe people evacuation from the road tunnel with taking into account some of its peculiarities. The example of such assessment for road tunnel is presented. This model was successfully used in designing of fire protection systems for several tunnels in Moscow and other cities.

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8. Procedure of the determination of calculation values of fire risk in buildings works and constructions of different classes of functional fire hazard, VNIIP, 2009, - 71 p
Decision Support System for Emergencies in Road Tunnels

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ABSTRACT

The tunnel operator is the first person handling an emergency situation in a road tunnel. When an accident occurs, the operator is required to make right decisions mainly based on the contingency plan. The current tunnel safety is focused on prevention through the tunnel design and facilities, risk analysis and contingency plans, however this does not solve the problem once the accident has occurred. This paper presents a Decision Support System (DSS). This System provides the decisions in real time to deal with the detected emergency. Furthermore, the System enables to estimate the severity of the accident and the total evacuation time if necessary. The DSS is integrated by the following models: 1) Incidents Model, 2) Evacuation Models and 3) Decision Model by using and Object Oriented Programming C#. An application case is presented for a hypothetical emergency for a double bored unidirectional road tunnel. The results showed: 1) DSS provides decisions in real time minimizing the response time of the operator 2) the additional information offers an overview of the severity of the accident, 3) the evacuation model calculate the evacuation times if necessary.

KEYWORDS: decision support system, emergency management, road tunnels, real-time.

INTRODUCTION

Recent history has shown that tunnels constitute dangerous environments in case of emergency. In last few decades, only in Europe, accidents in road tunnels have caused over 400 deaths [1]. Disasters such as the Mont Blanc Tunnel fire (Italy-France, 1999) and the St Gotthard Tunnel fire (Swiss Alps, 2001) have caused many deaths and serious injuries to several people. These tragedies have shown the need for an effective emergency response [2]. The tunnel safety is dependent on three main factors: 1) tunnel design, 2) tunnel management and 3) emergency response. However, current road tunnel safety is limited by the traditional approach focused on the tunnel design and facilities, risk analysis and contingency plans. Prevention is a key factor but emergencies can happen. A proper emergency management is a main factor to minimize the risk for people by maximizing the speed and effectiveness of the actions. The tunnel operator is the first person dealing with the emergency and informing the tunnel users, supervisor and emergency services regarding the situations [3]. The operator will be required to choose the right decisions in a short time under several initial uncertainties. The lack of information and the stress of the situation can lead to delays and fails in the decision making.

Nowadays technology can be a key tool to improve the effectiveness of the emergency management and the human safety in road tunnels. In this sense, GIDAI Group (University of Cantabria, Spain) has finished a research project - funded by Spanish Ministry of Development – whose aim is to obtain a Decision Support System (DSS) for emergency situations in road tunnels. The DSS has the capability to propose the course of actions to deal with the emergency situation [4, 5]. The System is integrated by three models: 1) Incidents Model, 2) Evacuation Model and 3) Decision Model. The DSS can be applied to any tunnel by introducing a file with the own tunnel characteristics. This paper is divided in two parts. In the first part the Decision Support System (DSS) is described. The second part shows application cases for different hypothetical emergencies in a double bored unidirectional road tunnel.
DECISION SUPPORT SYSTEM (DSS) OVERVIEW

Figure 1 shows the Decision Support System (DSS) schema and the different interfaces that integrate the System.

![Decision Support System (DSS) Schema](image)

Figure 1  Decision Support System (DSS) Schema.
The DSS can be applied to any tunnel by introducing the tunnel parameters file (*.ds1), this file is developed by using the auxiliary software (*paramSI.exe*). When an accident occurs, the tunnel operator detects the emergency mainly through the Automatic Incident Detection (AID) and/or CCTV, or by other tunnel facilities such as SOS or fire detection system. The operator set up the inputs (windows *Inputs*) into the Decision Support System DSS (see table 1).

<table>
<thead>
<tr>
<th>Boolean variables</th>
<th>Numerical variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is there an accident?</td>
<td>Number of lanes blocked</td>
</tr>
<tr>
<td>Is there a fire?</td>
<td>Nº of Surveillance-camera</td>
</tr>
<tr>
<td>Is there a spillage?</td>
<td>Nº of vehicles involved</td>
</tr>
<tr>
<td>Is there any injured person?</td>
<td>Nº of heavy vehicles involved</td>
</tr>
<tr>
<td>Is there a serious incident?</td>
<td>Nº of buses involved</td>
</tr>
</tbody>
</table>

Table 1 Inputs used in the DSS

The System provides in real time a proposal of decisions (window *decisions*). Furthermore the DSS estimates the accident severity (total number of people involved, number of fatalities and/or injured people and location of the accident), the results are shown in the window *Additional Information*; this will be useful to give additional information to the emergency services. The System also calculates the total evacuation times (self-rescue and rescue processes) if this is necessary (windows *Results for Area 1* and *Results for Area 2*).

The System works faster than real time and permits the feedback of the changing information. This means that the operator may obtain new results at the same time as the accident characteristics change.

**INCIDENTS MODEL**

In the ISTSS 2010 (Frankfurt am Main) the first stage of the study was presented [4] – Infrequent Events (Incident) Model. The model considers the information (see Table 1) introduced into the System and it estimates the severity of the incident (number of people with normal mobility, reduced mobility and assisted mobility who are involved in the accident).

The Incidents Model is based on Boole algebra, probability theory and a Black Box Model. The inputs and outputs were defined in order to develop the Model. Data about international tunnel accidents [6] were collected in order to define the inputs of the Incident Models. A statistical analysis of the data enabled to identify and classify those variables.

The tunnel geometry is divided into two zones (see figure 1):

Area 1 - the area directly affected by the accident. This area includes 1) vehicles and people directly involved, 2) vehicles and people are in danger due to fire or hazardous spillages and 3) the emergency exits near the accident.

Area 2 - adjacent area to Area 1. When the tunnel is closed a bottleneck is formed. The people trapped inside the tunnel (in their vehicles) who are not directly affected by the accident have to be evacuated for their safety. The available space is wider in Area 2 than in Area 1 and thus it is easier for people to evacuate here.
The conceptual and mathematical models establish the relationships between inputs and outputs. The outputs of the Incident Models can be divided in two groups:

1) Location of the Incident.
   - Distance from the tunnel entrance to the beginning of the Area 1.
   - Distance from the tunnel entrance to the end of the Area 1.
   - Distance from the tunnel entrance to the end of the Area 2.

2) Estimation of the accident severity
   - The number of people to evacuate from Area 1 ($n'_{IT}$). It depends on the type and number of vehicles directly involved in the accident and the occupancy of each vehicle.
     \[ n'_{IT} = k_{VL} \cdot n_{VL_{DI}} + k_{VP} \cdot n_{VP_{DI}} + k_{VA} \cdot n_{VA_{DI}} \]  
   - Number of people affected by the accident – normal mobility $n'_{INM}$, reduced mobility $n'_{IRM}$ and assisted mobility $n'_{IAM}$. This depends on the number and type of vehicles involved. It is calculated in terms of the probabilities of occurrence considering a serious accident ($P(NM|A_{GG}), P(RM|A_{GG}), P(AM|A_{GG})$). Probabilities are obtained from the statistical analysis.
     \[ n'_{INM} = P(NM|A_{GG}) \cdot n'_{IT} \]
     \[ n'_{IRM} = P(RM|A_{GG}) \cdot n'_{IT} \]
     \[ n'_{IAM} = P(AM|A_{GG}) \cdot n'_{IT} \]  
   - Number of persons trapped in the Area 2. It depends on the number of vehicles trapped into the tunnel.

The outputs of the Incident Model are part of the inputs in the Evacuation Model.

**EVACUATION MODEL**

If it is necessary to evacuate the tunnel, the System will provide results in real time of total evacuation times – considering self rescue and rescue processes. There are two types of inputs in the Evacuation Model: 1) outputs of Incident Model and 2) Behavioural Variables considering the different mobilities after the accident (normal, reduced and assisted).

The Model combines a course network considering two nodes [7]: Area 1 and Area 2 (see Figure 2) and a microscopic approach for modelling the individual behaviors. It should be noted that differences between two Areas lead to consider two different Evacuation Models: Evacuation Model of Area 1(Rescue and Self-rescue) and Evacuation Model of Area 2 (Rescue).

During the first stages of the emergency there is a high level of uncertainty such as the number, individual characteristics and the initial location of people involved in the accident and people trapped into the tunnel. To address this, a stochastic approach is necessary by considering multiple situations and their potential outcomes (sample of results).

Based on Monte Carlo methods, the model has the capability to perform multiple simulations by changing random inputs of tunnel users such as pre-movement times, walking speeds and initial location. Furthermore, the proposed model considers the configuration and characteristics of evacuation scenarios as random variables too.
The presented model permits to perform several simulations within a few seconds obtaining a sample of total evacuation times. The model statistically treats the sample of total evacuation times and fit it to a known distribution (if possible). Otherwise, density estimation is given using histogram. The main output parameter is a percentile of evacuation times (0.90, 0.95 and 0.99). The model also provides other statistical characteristics: mean, variance, maximum and minimum values.

**Evacuation Model of Area 1**

The evacuation time of each tunnel user depends on his/her pre-movement time, his/her unrestricted walking speed and the distance through the escape routes. These are considered as random variables in the model. It should be noticed that the model assumes default values (statistical parameters) for each behavioural variable that can be changed by the user at any time. Therefore, the evacuation time is given by:

$$t_{E_{1i}} = t_{pm_{i}} + \frac{d_{mov_{i}}}{v_{mov_{i}}}$$

Where:

- $t_{E_{1i}}$ - Evacuation time for the $i$th person.
- $t_{pm_{i}}$ - Pre-movement time for the $i$th person.
- $d_{mov_{i}}$ - Distance to the exit of Area 1 for the $i$th person.
- $v_{mov_{i}}$ - Walking speed for the $i$th person.

The total evacuation time is defined as the time when the last person leaves the tunnel by the expression:

$$t_{E_{1j}} = \max \left\{ t_{E_{1ij}(NM)}^{(NM)}, t_{E_{1ij}(RM)}^{(RM)}, t_{E_{1ij}(AM)}^{(AM)} \right\}$$

Where:

- $t_{E_{1j}}$ - Total evacuation time for $j$th simulation.
- $t_{E_{1ij}^{(NM)(RM)(AM)}}$ - Evacuation time for $i$th person (normal, reduced or assisted) in $j$th simulation.

For people with normal and reduced mobilities, the pre-evacuation time is the time required for each tunnel user to understand what is going on (recognition) and the time to leave the vehicle and start the evacuation movement (response). A normal distribution is assumed. The statistical parameters are different for normal (mean 103 s and standard deviation 20 s) and reduced mobilities (mean 137 s and standard deviation 37 s). For assisted mobility, the pre-movement times are dependent on the arrival time of the emergency services. It is assumed a normal distribution with a default values: mean 1399 s and standard deviation 243.7 s.

The travel distances are independent on the type of mobility. It is not possible to know the initial location of the people involved in the accident, so the travel distances fit to a uniform distribution between the longest and the shortest distances (Fig.3). These values are calculated from the geometry of the tunnel, the distances to the accident (output of the incident model) and the number and type of vehicles involved.

Walking speed distributions are assumed as normal distribution and they are based on the values from SFPE Handbook [8] multiply by a random factor. The default parameters are: 1) mean 1.21 m/s and standard deviation 0.28 m/s for normal mobility, 2) mean 0.88 m/s and standard deviation 0.28 m/s for reduced mobility and 3) mean 1.12 m/s and standard deviation 0.30 m/s for assisted mobility.
Evacuation Model of Area 2

In Area 2 the evacuation time is the sum of a pre-movement time and the travel time expressed in equation (3). In each simulation, the model registers the evacuation time for all users trapped in Area 2 and considers the time when the last tunnel user leaves the tunnel or access to a safe place (i.e. cross passage) as the total evacuation time. In this first version of the model, the user should introduce an estimation of the number of vehicles in Area 2. Otherwise, this information can be obtained from the traffic counters in the tunnel. The model considers the number of people inside the vehicles as a random variable between a maximum and minimum value that can be predefined by the user (i.e. 1-5 occupants/car, 1-2 occupants/truck and 20-40 occupants/bus). Therefore, in each simulation the occupation load is different.

In Area 2, the vehicles are in queue inside the tunnel. The model considers that tunnel users are distributed uniformly inside the tunnel. The pre-movement time for each tunnel user can be divided into recognition time \( t_{pm}^{(1)} \) and response time \( t_{pm}^{(2)} \). In case of an accident in tunnels, the users have to understand what is going on. However, during the first stages of the emergency, they may only have the information from what they see around them [9] (i.e. a vehicle in front). The lack of information can lead to behaviours such as vehicle affiliation (people remain seated inside their vehicles) [8, 10, 11]. People involved in or nearby the accident are more likely to have direct perception and interpretation of the danger. On the other hand, different studies about human behaviour during evacuation process in tunnels have shown that tunnel users are strongly influenced by the actions of others (i.e. to decide to get out of the vehicle or choose an exit) [12, 13]. The model implements the pre-movement time by considering that \( t_{pm}^{(1)} \) is linearly dependent with the distance of the tunnel user \( d'_{I1} \) respect to the accident zone \( d_{mov} \).

\[
t_{pm}^{(1)} = t_{pm}^{(0)} + \frac{d'_{I1} - d_{mov}}{v_{mov}}
\]

The model calculates the \( t_{pm}^{(1)} \) considering the time needed by the persons next to the accident area to reach different locations during their movement towards the exit with a speed of 1.55 m/s \( v_{mov} \) and pre-movement time of 30s \( t_{pm}^{(0)} \). The \( t_{pm}^{(2)} \) is assumed as a normal distribution with a mean of 67.5 s and a standard deviation of 17.5 s. The unimpeded walking speed fits to a normal distribution with a mean of 1.25 m/s and a standard deviation of 0.32 m/s. These values can be changed by the user (SFPE).

Comparison with other models

All models require verification and validation process. A comparative analysis of the Evacuation Model of Area 2 was performed with the results of three evacuation models: GridFlow [14], STEPS[15] and PathFinder [16]. The application case is the Lantueno Tunnel (Cantabria – La Meseta Highway A-67, Spain).
Lantueno Tunnel is a two-bore road tunnel. Each bore has two lanes with sidewalk. Its length is about 670m. The evacuation scenarios consider an accident (light vehicle and heavy vehicle) in the centre of the tunnel. A total of 54 vehicles were trapped in the tunnel (49 light vehicles and 5 heavy vehicles). The comparison is divided into two tests. In Test 1, no behaviour is performed in order to check that the simulation of movement is working satisfactorily. No pre-movement is considered and a fixed unimpeded walking speed of 1m/s is assigned to all of the tunnel users. In Test 2 a behaviour comparison is performed. In this test the scenario has been run 100 times by the evacuation models to capture stochastic variations in the results. The pre-movement times have been assigned using normal distribution laws (different areas are considered in the validated models to implement the pre-movement times). The same unimpeded walking speed distribution has been assigned for all tunnel users in all models. This is a normal distribution with a mean value of 1.20 m/s and a standard deviation of 0.20 m/s.

<table>
<thead>
<tr>
<th>MODELS</th>
<th>Evacuation time (s)</th>
<th>M (s)</th>
<th>SD (s)</th>
<th>Max.(s)</th>
<th>Min.(s)</th>
<th>95th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathfinder</td>
<td>260</td>
<td>497</td>
<td>31</td>
<td>624</td>
<td>429</td>
<td>554</td>
</tr>
<tr>
<td>STEPS</td>
<td>257</td>
<td>496</td>
<td>50</td>
<td>742</td>
<td>434</td>
<td>580</td>
</tr>
<tr>
<td>GridFlow</td>
<td>258</td>
<td>495</td>
<td>42</td>
<td>670</td>
<td>419</td>
<td>434</td>
</tr>
<tr>
<td>EvacTunnel®</td>
<td>262</td>
<td>491</td>
<td>44</td>
<td>671</td>
<td>434</td>
<td>587</td>
</tr>
</tbody>
</table>

Table 1. Comparative Results for Test 1 and Test 2.

Table 1 (Test 1) shows that the basic movement components of the proposed model work adequately. A small difference is found due to the random distribution of the tunnel users who are further from the tunnel portal (their start position). Table 2 shows the results for Test 2. These are essentially coincident in all models. On the other hand the 95th percentile in the proposed model is higher than the other models. The aim of the model is to be implemented in the DSS. The System will improve the emergency management by providing confidence results in real time.

**DECISION MODEL**

Based on the Decision Theory and Expert Systems, the Decision Model considers the outputs of Incident and Evacuation Models and it provides in real-time the course of actions to deal with the emergency, such as:

- Inform the Tunnel Staff.
- Deploy the Emergency Services.
- Deploy the Emergency Services.
- Close the Tunnel.
- Maximum Lighting.
- Inform the Tunnel users.

The Decision Model determinates the decision trees representing the decisions nodes (square) and chance nodes (circles), i.e. the Figure 4 shows the decision tree for the evacuation:

![Decision tree for Tunnel Evacuation](image-url)
APPLICATION OF THE DECISION SUPPORT SYSTEM (DSS)

Considering the Lantueno Tunnel, it was assumed an accident near the exit of the tunnel. A large number of vehicles were trapped in the tunnel (120 light vehicles and 16 heavy vehicles). This is between 136 and 632 persons to evacuate. Different possible cases were considered (Table 2).

<table>
<thead>
<tr>
<th>Case</th>
<th>Fire</th>
<th>Spillage</th>
<th>Light vehicles</th>
<th>Heavy Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>x</td>
<td></td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>1.2</td>
<td>x</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.3</td>
<td>x</td>
<td></td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2.1</td>
<td>x</td>
<td>x</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>x</td>
<td>x</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.3</td>
<td>x</td>
<td>x</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>3.1</td>
<td></td>
<td></td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3.2</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3.3</td>
<td></td>
<td></td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>4.1</td>
<td>x</td>
<td>x</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4.2</td>
<td>x</td>
<td>x</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>4.3</td>
<td>x</td>
<td>x</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

*Table 2. Application cases for the Decision Support System.*

The results are divided into three groups: Decisions, Additional Information and Evacuation Results.

**Decisions**

The Decision Support System provides the course of action to deal with the emergency. In all the cases the decisions are similar due to the severity of the accident (Fire with/without spillage and spillage):

- Inform the Tunnel Staff.
- Deploy the Emergency Services.
- Close the Tunnel.
- Maximum Lighting.
- Inform the Tunnel users.

The decisions match with the contingency plans for the tunnel operator.

**Additional Information**

Regarding the estimation of the emergency estimation, Table 3 shows the results for each analyzed case:

<table>
<thead>
<tr>
<th>Mobility</th>
<th>CASES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.1</td>
</tr>
<tr>
<td>normal</td>
<td>1</td>
</tr>
<tr>
<td>reduced</td>
<td>2</td>
</tr>
<tr>
<td>assisted</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
</tr>
</tbody>
</table>

*Table 3. Comparative Results for Test 1.*

The number of people involved in each case is different due to this is a random variable. It depends on the number and types of vehicles involved in the accident. For this reason, Cases 4.1, 4.2 and 4.3 have the highest levels of people involved.
Evacuation Results

Figures 4 and 5 show the total evacuation times for Area 1 and Area 2. In Area 1, the 95th percentile is not less than 38 min. On the other hand, the mean times are around 30 min. The figure 4 shows that the maximum time is in case 4.1 (40.61 min) where three light vehicles and a heavy vehicle are involved. The evacuation of assisted people is determinant in evacuation times as we expected.

In Area 2, the maximum evacuation time is in case 3.1 (58.75 min). This means that in 95% of the cases the evacuation time was less than 58.75 min. The number of people trapped inside the tunnel is determinant in evacuation times.

CONCLUSIONS

A Decision Support System for road tunnel has been presented in this paper. The aim of the System is to provide possible decisions in order to deal with an emergency. Furthermore, the System gives estimation about the severity of the accident and the total evacuation time.

This System is integrated by the following models: 1) Incidents Model, 2) Evacuation Model and 3) Decision Model. The Incidents Model gives the following outcomes: 1) estimations about the number of fatalities and injured people (input for the Evacuation Model) and 2) possible decisions (inputs for the Decision Model). Based on the outputs from the Incidents Model, the Decision Model provides in real-time the course of actions to deal with the emergency such as close the tunnel, active the emergency services, illumination and ventilation strategies, declare evacuation, etc.
In case of evacuation, the Evacuation Model, based on Monte Carlo Methods, run multiple simulations considering the tunnel and emergency characteristics and the human behaviour. It provides results in real-time, with a given confidence level, about the required self-rescue and rescue times.

The System can analyze the changing conditions during the emergency (feedback). This tool enables the operator to know the potential outcomes and proposes the appropriate strategies:

- To minimize the risk for people (achieving a quick and effective evacuation).
- To maximize the speed and effectiveness of the emergency management.
- To achieve a suitable use of the available resources.

The System can be easily implemented in any Control Centre. It is flexible, easy to use and its modular structure permits more developments and improvements.

REFERENCES

Brisbane’s Busway Network – Twelve Years of Designing and Operating Safe Tunnels

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1Stacey Agnew Pty Ltd, Australia, 2Parsons Brinckerhoff, Australia
3Donato Consultancy, Australia (consulting to the Department of Transport and Main Roads)

ABSTRACT

With a population of just over two million people, the city of Brisbane, Queensland, is one of Australia’s fastest growing cities. Brisbane’s world class Busway (or Bus Rapid Transit) network has become an example of best practice for public transport since the South East Busway opened in 2001. Buses travel in dedicated and congestion-free corridors separated from general traffic to provide a fast, frequent and reliable public transport system. The current operating Busway network includes two underground bus stations, a number of trenched stations, and 16 bi-directional tunnels, with the longest currently operating tunnel being 630 m in length. The system also includes a number of underground bus turn-arounds. More Busway tunnels in the order of several kilometers are planned for Brisbane’s immediate future.

Much of the underground Busway infrastructure includes systems and facilities that would be considered to be best-practice for major urban road tunnels, such as pollution monitoring, longitudinal and semi-transverse ventilation, vehicle and thermal incident detection, protected egress paths, passive fire protection, and fixed fire suppression. Tunnel security, fire safety and air quality along the Busway has been continuously evolving with respect to:

- Design approach.
- Underground infrastructure and systems.
- Busway operations and control.
- Emergency response, fire brigade intervention, and planning.

This paper discusses the evolution of Brisbane’s Busways over a 12 year period, with a focus on tunnel fire safety.

KEYWORDS: fire life safety, tunnel, ventilation, busway, bus rapid transit, bus station

INTRODUCTION

A Busway is a dedicated road corridor, separated from general traffic, for buses being used for public transport [1]. Busways offer a congestion-free trip for commuters and they are particularly suited to cities with low populations covering a large area, where it is not economically practical to provide a comprehensive rail transport service.

One of the features of Brisbane’s network is the use of tunnels and underground stations. Busways are of course not unique to Brisbane. The Northern Busway in Auckland is a surface roadway and was largely based on the Brisbane Busway concept. It includes two tunnels. Other bus networks in the world with dedicated tunnels and underground bus stations include the Kamppi Centre in Helsinki (the world’s largest) and the 22-platform Denver Union Bus Station (currently under construction).

The Brisbane Busway infrastructure is owned by the Queensland Department of Transport and Main Roads (TMR), and operated by Translink, a state agency that coordinates and delivers bus, train and ferry services across South East Queensland. Translink manages more road-type tunnels, than any other private or government road agency in Australasia. Over the past 12 years, approaches to tunnel
fire safety have changed in line with evolution of local and international best practice and also the varying needs of the projects commissioned in Brisbane.

The surface and underground operations of the Busway are monitored and managed 24 hours a day, seven days a week through a state of the art Busway Operations Centre (BOC). Buses are managed through a Network Control Centre (NCC) collocated with the BOC. There are now over 600 CCTV cameras along the network. To ensure timely and effective response to incidents, Translink maintains a program of operator and driver training and continuous improvement of procedures and response plans.

**BUSWAYS – A SUCCESS STORY**

Over 60 million trips [2] are made each year along 25 kilometres of Busway (including the new Eastern Busway) that now cross the city through 21 Busway stations. The Busway system has been built in stages, with the first stage opened to carry patrons to the 2000 Olympic Games soccer events held in Brisbane, and the latest stage opened in August 2011. The Queensland State Government funded construction of the entire network.

Busways have been constructed in Brisbane to allow buses to carry commuters at about double the speed of cars during peak times. A Busway can carry over 18,000 people per hour. A general traffic lane will carry about 1400 people per hour. Currently the Busway network is servicing over 200,000 passengers each day. The Busways provide an accessible, attractive, flexible, and efficient transport system which provides access to the CBD and also across the city. To allow for future development and expansion of the city, the Busway system is generally light rail compliant and could be used to provide a joint bus and light rail corridor. Brisbane Transport, a business unit of Brisbane City Council, operates a fleet of 1166 buses, many of which use the Busway network. Approximately 28% of Brisbane’s bus fleet runs on compressed natural gas (CNG).

**UNDERGROUND INFRASTRUCTURE AND SAFETY PROVISIONS**

Over the past 12 years, the safety provisions made in Brisbane’s Busway tunnels and underground stations have been evolving. The tunnel design features considered best, good and mandatory practice have evolved over the years of implementation. It is generally the case that no two tunnels are the same. Each tunnel’s design features are influenced by the unique requirements of that tunnel and the project it was part of.

Table 1 lists the major fire life safety features of Brisbane’s Busway tunnels in chronological order. In particular, pressurized longitudinal egress passages (Figure 1) are now common. Tunnel occupants enter the fire separated passages through doors at the side of the roadway. These offer several advantages, among them simplicity of operation and the ability to have closely spaced exits. They are substantially cheaper than smoke extraction systems to provide the same level of risk reduction. Deluge suppression is becoming the norm especially in longer tunnels. Hydrants and hose reels are now standard (Figure 1). Linear heat detection, video incident detection, and low-level wayfinding lighting are becoming the norm. It is apparent from Table 1 that there has been an evolution driven by the objective of rationally enhancing public safety. However, this aim of advancing community benefit has resulted in additional design/construction effort, operational complexity, and operator responsibility.

In terms of the focus on operations, driver training, and safety awareness of the asset owner, the modern Busway network is similar to a rail network. In addition to changes in the physical systems installed, the last twelve years has also seen an evolution in project delivery and safety management systems, with fundamental principles adopted from the aviation industry.
Table 1. Summary of Brisbane’s operating Busway tunnels and safety features.

<table>
<thead>
<tr>
<th>Facility and Tunnel Details&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Smoke&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Egress&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Water&lt;sup&gt;d&lt;/sup&gt;</th>
<th>Other features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Queen Street Bus Station, 1987</td>
<td>N + L</td>
<td>P + OT</td>
<td>S + Hoses</td>
<td>Underground station, on site control room</td>
</tr>
<tr>
<td>South East Busway (SEB), 2000</td>
<td>N</td>
<td>PL</td>
<td>H</td>
<td>First major tunnels</td>
</tr>
<tr>
<td>Cultural Centre underpass, 130 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEB, Vulture Street tunnel, 511 m</td>
<td>L</td>
<td>OT</td>
<td>H</td>
<td>Mid-point egress elevator + stairs</td>
</tr>
<tr>
<td>SEB, Mater Hill tunnel, 175 m</td>
<td>L</td>
<td>PL</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>SEB, Buranda tunnel, 190 m</td>
<td>L</td>
<td>PL</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>SEB, Buranda tunnel, 60 m</td>
<td>N</td>
<td>PL</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>SEB, 2001, Garden City tunnel, 280 m</td>
<td>L</td>
<td>PL</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>Inner Northern Busway Stage 3 to 5</td>
<td>N</td>
<td>PL</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(INB3-5), CBD to Royal Brisbane Hospital, 2003, QR Underpass, 130 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INB3-5, 2001, Normanby Underpass, 75 m</td>
<td>N</td>
<td>PL</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>INB3-5, 2001, Victoria Park Tunnel, 290 m</td>
<td>L</td>
<td>PP (60 m)</td>
<td>H</td>
<td>Egress passage for first and last third of tunnel length</td>
</tr>
<tr>
<td>INB3-5, 2003, Fairways Tunnel, 100 m</td>
<td>N</td>
<td>PL</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>INB1, King George Square Bus Station, 2008, 550 m</td>
<td>L + E</td>
<td>OT + P + PP (80 m)</td>
<td>H + D (bus stops) 10 mm/min</td>
<td>Underground station, on site control room</td>
</tr>
<tr>
<td>Eastern Busway Stage 1 (EB1), Boggo Road Busway (BRB), 2009 QR Underpass, 95 m</td>
<td>N</td>
<td>PL</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>EB1, Boggo Road, 630 m</td>
<td>L</td>
<td>PP (40 m)</td>
<td>H + D 6.5 mm/min</td>
<td>Currently longest tunnel</td>
</tr>
<tr>
<td>EB1, Harrogate, 180 m</td>
<td>L</td>
<td>PP (40 m)</td>
<td>H + D 6.5 mm/min</td>
<td>Uses jet fans during egress</td>
</tr>
<tr>
<td>Eastern Busway Stage 2 (EB2), 2011 Logan Tunnel, 218 m</td>
<td>L</td>
<td>PP (40 m)</td>
<td>H</td>
<td>Uses jet fans during egress</td>
</tr>
<tr>
<td>EB2, Laura Underpass, 110 m</td>
<td>N</td>
<td>PL</td>
<td>H</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> All tunnels have bi-directional bus traffic.
<sup>b</sup> Smoke management features: N = natural, L = longitudinal (jet fans), E = exhaust
<sup>c</sup> Egress features: PL=portals, PP=pressurised passage (exit spacing), OT=protected path, P=via platform
<sup>d</sup> Water: X = none, H = hydrants and hose reels, S = fusible sprinklers, D = deluge (application density)
<sup>e</sup> Tunnel lengths are from project information or approximate from Google Earth measurements.

Table 1. Summary of Brisbane’s operating Busway tunnels and safety features.

STANDARDS AND DESIGN CONSIDERATIONS

The inaugural Australian standard for tunnel fire safety design (AS4825) was published in March 2011 [3]. In addition to addressing road and rail tunnels, this document makes specific mention of Busways. The standard leans towards a process-based approach, with commentary on safety items typically provided. Features of the standard relevant to the design approach for bus tunnels include:

- Classification. Tunnels (>80 m) are divided into long (>120 m) and short tunnels, uni- or bi-directional traffic, and tunnels with and without an intersection.
- A bus tunnel is defined as a “tunnel defined for principal use by commuter buses driven by drivers with training in emergency response procedures, excluding coaches or other vehicles driven by drivers without training”.
- Fundamental objectives for fire safety include occupant safety, emergency services intervention and protection of adjoining property.
• General design advice is provided in a number of topics including traffic characteristics, preventative measures, incident mitigation, asset protection, business interruption, structural damage, emergency services intervention, incident management, tunnel configuration, constructability, maintainability, reliability and redundancy, and operation (e.g. operator on-site or off-site).

• In general, the standard tends to note the decisions required rather than being dogmatic on specific provisions. Guidance is provided on matters such as stakeholder definition and inclusion, design stages (from concept to operation), method of design analysis and acceptance, tunnel-specific guidance (e.g. development of a functional description for the tunnel safety system), and operation and maintenance guidelines.

Figure 1. Boggo Road Busway tunnel, Boggo Road pressurized egress passage, and Logan Tunnel emergency equipment cabinet (roller door, hose reel, hydrants, call point, brigade phone).

The Australian standard AS4825 does not mandate specific design requirements in many areas. In many senses it is more like a high level guideline. It is a very new document and whether or not it brings about change to the current Busway tunnel design and construction practices remains to be seen. Since 1999, TMR has maintained a prescriptive draft Busway Planning and Design Manual [4]. It is intended to deliver standardisation in design approach and provisions across the Busway network. Busway designers have also referenced other international standards for underground transportation facilitates, particularly NFPA130 and NFPA502, as well as applying design from first principles. Historically, particular focus has been placed in Australian projects on the Fire Engineering Brief (FEB) as a means to describe the design and approach to stakeholders and record a basis for the detailed design. Topics include fire safety objectives, occupant characteristics, trial concept design, preliminary technical assessment, acceptance criteria and assessment methods. The FEB process for performance-based design is an artefact of the so called International Fire Engineering Guidelines (IFEG) [5].

Other design criteria and considerations unique to bus tunnels and safety are noted below.

• A design fire size in the range of 30 MW to 50 MW is generally applied. The fire growth rate typically gets considerable attention. Soot yield and estimates of toxicity of smoke are also starting to have increased focus [3].

• The use of compressed natural gas (CNG) as a bus fuel has led to questions about the risk of explosion. However, the cylinders are designed to appropriate Australian standards [6], which means that they will relieve pressure (i.e. controlled CNG discharge) automatically above a given temperature or pressure. They can withstand significant impact without failure.

• Tenability criteria typically considered for egress include temperature, radiative heat transfer and carbon monoxide (used as an indicator of toxicity). Visibility is also applied as a criterion even though it is not loss of visibility alone which determines the onset of non-tenable conditions. The increased emphasis on visibility has seen the provision of low-level tunnel wayfinding lighting.

• Equitable access for persons with disabilities (i.e. ‘access with independence and dignity’) is often
confused with requirements for reasonable egress under life threatening circumstances. Persons with disabilities are always considered and standards and disability consultants give guidance to achieve the greatest degree of ‘equitable egress’ as can be reasonably justified [7, 8].

- The Busway network is a highly controlled road environment, with full time remote management and trained vehicle drivers. That is a major point of difference when considering risks normally associated with road tunnels.
- The Building Code of Australia (BCA) is generally not applicable to bus tunnels, however, it is applicable to the occupant areas of stations. In the design of a new facility, care needs to be taken with the interface between the tunnel and building, to be sure that prescriptive code approaches in the building do not compromise the design of the overall facility.
- Air quality is a very important criterion for bus stations, even those not underground. In a tunnel environment, the design criterion is generally the same as for road tunnels. PIARC guidelines [9] are generally applied. In all the underground stations, the platform waiting areas are aerodynamically separated via walls and platform screen doors, and the tunnel ventilation system.

EXAMPLES OF DESIGN APPROACHES DEMONSTRATING EVOLUTION

Queen Street Bus Station (QSBS)

Opened as a standalone station in 1987 ahead of World Expo '88 in Brisbane, QSBS is a single level underground bus station located in the Brisbane central business district (CBD) beneath a shopping centre and the Queen Street Mall. In 2008, QSBS was integrated into the Busway network via the Inner Northern Busway (Stage 1 and 2), discussed below.

The station, which has 17 stops, incorporates fusible head ordinary hazard sprinklers, smoke detection, and various evacuation measures that are common to buildings, such as signage, public address systems, and alarm systems. Evacuation from the QSBS tunnels is via the platforms. QSBS is connected aerodynamically and operationally with adjacent facilities including a shopping centre and atrium, hotel, and King George Square Bus Station (KGSBS/INB1). With a capacity of 164 m³/s, the normal ventilation system extracts contaminated air via pavement level registers and currently shuts down on a fire alarm. Up until the completion of INB1 (below), the QSBS had no dedicated mechanical smoke management system. When the adjacent and connected KGSBS was constructed in 2008, two new jet fans were installed in QSBS to provide limited longitudinal ventilation through the connected stations and tunnels. KGSBS can also supply to, or exhaust from, QSBS, thereby providing other opportunities for smoke management.

At the time of station design, performance-based fire safety engineering was an emerging field and smoke modelling techniques were not commonplace. Prescriptive fire engineering based on the BCA was normal. As a result, the platform areas of the station and the bus tunnels were essentially treated as typical building compartments and the QSBS fire safety systems were not “performance-engineered” in the way that modern underground transit facilities are. TMR will be updating the fire safety features of QSBS in a staged upgrade (to a practical level, acknowledging the constraints posed by an existing facility).

South-East Busway (SE) / Inner Northern Busway (INB) Stage 4/5

These projects were delivered at a time when analysis and performance-based approaches were in their infancy in terms of practical application. From discussions with TMR, it is understood that risk-based approaches and zone models were applied, along with some prescriptive fire brigade requirements.

Inner Northern Busway Stage 1/2 (Queen Street to Upper Roma Street) (INB1)

INB1 is located in the CBD of Brisbane. Stage 1 of the project includes an approximately 500 metre
long tunnel section. This is comprised of an underground bus station with 10 stops, two underground platforms, two concourses (one underground), a tunnel connecting to an existing underground bus station (QSBS described above), and tunnels connecting to surface streets and a surface bus station. The project was delivered by the INB Hub Alliance (design and construction) for TMR [10].

The design and analysis were required to demonstrate that occupants could evacuate during a ‘worst credible’ fire scenario. The deterministic approach, taking conservative values of all inputs simultaneously, results in scenarios with probabilities so low that they should perhaps not be design cases. Acceptance was based on the criterion of available safe egress time (ASET) exceeding the required safe egress time (RSET). The major safety feature to achieve this was a large capacity (300 m³/s) smoke exhaust system. The system was designed to limit smoke spread for a 30 MW fire [10]. A deluge system was also provided above the station areas, but not relied on in analysis of the level of safety. The smoke exhaust and deluge systems were both new additions to Brisbane’s Busway network tunnels.

The inclusion of deluge and smoke exhaust introduced several further steps in the design process for Busways:

- The use of computational fluid dynamics (CFD) was arguably more significant on this project than previous ones. For the very complex exhaust duct geometry, the pressure loss estimate and hence the fan sizing to achieve the required exhaust capacity relied on CFD models [10].
- Optimal smoke management during a real emergency relies on the operator selecting the correct fire location in order for the exhaust dampers local to the fire to activate. Deluge operation is based on a manual request from the operator to activate a given zone [10]. These features placed a much greater burden on the operator than did previous facilities.
- CFD was used to demonstrate that the ASET>RSET acceptance criterion was met. The results of the analysis were documented in a dedicated fire engineering report which was reviewed by local fire authorities and an independent peer reviewer.
- The station areas (platforms and concourses) connected to the Busway tunnels were covered legislatively by the Building Code of Australia (BCA). The tunnel-building interface provided some unique challenges since the BCA made very prescriptive FLS requirements (e.g. sprinklers, occupant numbers, exit spacing, smoke exhaust) while the tunnel side had no prescriptive standard and relied on engineering design [10].

The smoke exhaust system resulted in an increased level of operational complexity which was managed with a mode table describing the ventilation and safety system operation. The mode table covered the following:

- Exhaust fan operating point.
- Dampers to operate and percentage open for a given fire location.
- Jet fans to operate and percentage of full speed for a given fire location.
- Operation of platform screen doors.
- Operation of traffic control measures.
- Operation of egress provisions such as pressurisation systems and PA announcements.
- Alarms to neighbouring facilities (QSBS and INB2).
- Detection methods.

Although the mode table was very detailed and described operation of many systems, it was unambiguous to system programmers, installers and operators alike. Each mode was tied back to fire engineering analysis undertaken at concept design. This allowed a correct implementation and a clear carriage of requirements from concept through to commissioning.

During testing and commissioning, smoke testing using a method equivalent to the Australian standard [11] was undertaken. A gas burner was used which could be easily moved around and
stopped/started (Figure 2). The alliance delivery model enabled designers and constructors to work collaboratively. This delivery model allowed the tunnel control system programmer to be present on site and work directly with the designer. Based on results of tests, adjustments were made to the control system operation and then tests re-run almost immediately. The result was that a significant degree of system tuning and optimisation took place.

Figure 2 Hot smoke test burner apparatus.

The INB1 project connected Brisbane’s northern and southern Busways via a major interchange station in the CBD. It greatly expanded the functionality of the Busway. In terms of fire safety design provisions, the inclusion of a smoke duct in this facility did not result in a universal adoption of smoke ducts in future facilities, however, deluge systems became a much more common requirement in future Busway tunnels (Table 1). The project also elevated the level of operator involvement, and focused system integration via functional mode tables, which are common in rail installations.

Eastern Busway (EB)

EB Stage 1 was opened in 2010 and included the 630 m long Boggo Road Busway (BRB) Tunnel (Figure 1) and an underground bus turn-around. Many of the fire life safety facilities employed at BRB have been carried through to subsequent Busway tunnels. The BRB tunnel includes a deluge fire suppression system capable of a discharge density of 6.5 mm/min applied over a total roadway length of 60 m. Prior to BRB, 10 mm/min was the standard application rate for Busway tunnels on the basis of the Australian “norm” for long road tunnels at that time. Busway tunnels built after BRB have adopted the lower rate of 6.5 mm/min. Given that the literature suggests that a rate of between 2 and 5 mm/min may be satisfactory for controlling (not extinguishing) heavy goods fires [12], an application rate lower than 6.5 mm/min could be considered for future Busway infrastructure. The BRB/EB projects also introduced camera-based incident detection technology to the Busways.

The latest operational infrastructure in the Busways network is EB Stage 2, which opened in July 2011. Like INB 1 and 2, this project was successfully completed through an alliance delivery model that allowed the owner, operator, designers and constructors to be co-located as an integrated project team. EB Stage 2 includes the 210 metre long Logan Tunnel, and the 110 metre long Laura Underpass. One interesting aspect of the Logan Tunnel is the use of jet fans to proactively manage smoke during the self-egress phase. Upon automatic detection of a stopped vehicle, the ventilation system starts to gently push the smoke towards the closest portal thereby minimising risk to non-incident tunnel occupants located upstream. A differential portal pressure sensor is installed to modulate the ventilation to accommodate local wind effects. The EB Alliance used Computational Fluid Dynamics (CFD) and hot smoke testing (using methylated spirit pans) to prove the ventilation design of the tunnel (Figure 3). The smoke testing identified an interesting local backlayering phenomenon on the inside wall, caused by the tight curvature of the tunnel. That effect was not identified during design simulation.
Other features of this project included the following:

- The Logan Tunnel PA system has recently been upgraded with consideration of best practice for road tunnels for engineering an appropriate level of PA system intelligibility [13].
- The Logan Tunnel has a novel fire fan control panel for fire brigade use. It consists of a single “All Fans” button that causes a 100% tunnel purge in a direction that is automatically chosen so as not to reverse the prior automatic ventilation response.

**BUSWAY OPERATIONS**

The Busway Operations Centre (BOC) was designed to manage the safe orderly and expeditious movement of buses along the Busway. There is extensive CCTV coverage along the Busway, and at stations, and the Busway Safety Officers (BSO) are trained to manage the vision and react to any incident or emergency along the Busway. All buses operating on the Busway have radio communication with the BOC. BSOs have extensive training to operate the various fans and deluge systems that make up the FLS equipment in the tunnels. The first BOC was opened in 2000 and eventually moved to be within the Brisbane Metropolitan Transport Management Centre (BMTMC), to enable more efficient integration with the city and the state traffic management centres.

The BOC manages the longest network of tunnels in Australia. As the system has expanded and the number of tunnels increased, there has been an increase in the sophistication of the training and the tools available to the BSOs. They are issued with Handbooks and are provided with one-on-one training, on site, on the Busway before practical completion. Bus drivers are trained in the operation of the Busway and particular attention is given to ensuring that they know what to do in a range of potential incidents and emergencies along the Busway. They are trained to manage their passengers in a fire emergency in all of the tunnels, and they have a working knowledge of what to expect from fans and deluge systems.

The drivers are provided with driver training movies (Figure 4) and their individual copy of the Busway Authorised Driver Training Manual (BADTM). The BADTM provides a description of the Busway and its facilities and also lays out the procedures for drivers involved in incidents and emergencies. The BSOs patrol the Busway during part of their shift and thus stay familiar with the infrastructure while gaining relief from the pressure of managing the CCTV vision. This creates a very good situational awareness and enhances their skills when the CCTV vision has to be used to manage incidents or emergencies.
FIRE BRIGADE INTERVENTION

The local fire brigade for the Busways is the Queensland Fire and Rescue Service (QFRS). The QFRS is mandated under the Queensland Fire and Rescue Act of 1990 to protect persons from fire, protect persons who are trapped, and to act in an advisory role to promote fire prevention and control and related safety matters. Despite this fundamental mandate, the practical role of QFRS on Busway projects has changed over the last 12 years. In the last three years, an Intra-governmental Agreement (IGA) has been established at the start of new Busway projects as an instrument for providing clarity over roles and responsibilities of the main parties including the QFRS. The following are a number of observations highlighting how fire brigade intervention considerations have changed for the better in recent times:

• The QFRS are being engaged by the asset owner and designers at a much earlier stage in the projects.
• There is greater recognition of the key role the QFRS plays in protecting assets and reducing business continuity risk and so more importance is placed on providing QFRS with facilities that are fit for purpose and ensuring a smoke free path to the seat of the fire.
• Much more work is now undertaken during design on QFRS tactical plans and Local Area Plans (LAPs), with a focus on QFRS arrival to site, and providing tailored incident control and staging points. On recent projects, having designers involved with the development of the Busway tactical plans has laid the foundation for further standardisation of response requirements across the network.
• QFRS site controls for systems such as deluge and ventilation have been greatly simplified. The QFRS now accept that the BSOs are the best people to operate tunnel plant during an incident. That is in contrast to past years where a traditional “buildings” approach was taken, and the brigade would be provided with a fire fan control panel which allowed them to operate individual ventilation equipment. Coupled with the need for the BOC to operate tunnel equipment at the request of the QFRS, there has been more attention placed on provision of reliable communication hardware and effective communication protocols.
• There is a greater understanding by QFRS of the use of probabilistic methods in design.

CONCLUSIONS

• The Brisbane Busways network is a success story in function, capacity, sustainable transport, and, public safety. Looking over the progression of the Busway infrastructure over the last 12 years, there has been an obvious evolution in the design for safety, particularly with respect to fire, that will positively influence future transport infrastructure in Australia and elsewhere.
• The approach to design for Busway safety is likely to see more standardisation of safety provisions and of the approach taken for justifying those provisions. In the future, TMR, as the asset owners, will need to be prepared to weigh up the immediate cost benefits of standardisation against the potential long terms benefits of on-going innovation in design. The Australian standard AS4825 recognises risk-based approaches and it may be the case that these are used to
deliver more cost effective designs in the future.

- One of the contributing factors to the success of recent Busway projects has been the holistic owner and operator-focused approach to design. Recent project experiences in Brisbane suggest that the alliance delivery model is well suited to encouraging a collaborative design effort involving the owner, operator, designer, constructor and emergency services from design through to construction and commissioning.

- Emergency services are end-users of tunnel safety infrastructure. Designers need to liaise with emergency services at the outset of projects to understand their needs. Responder interfaces need to be simple and communication pathways to the tunnel operator, robust and effective.

- There is scope for both the Australian Standard AS4825 and the current draft TMR Busway Planning and Design Manual to be updated to reflect actual design practices in Busways.

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The use of traffic flow predictions to enhance tunnel safety

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ABSTRACT
This paper shows the benefit of using the new “Three-phase traffic theory” that has been developed by Boris Kerner [1] in the recent years. By focusing on the transitions between phases in the physics of traffic, a pattern – typical for each highway or arterial – could be identified and used in real time applications. Combining the new traffic theory with well-detected highway network makes it possible to make short-term predictions on minute-by-minute basis. In Stockholm a warning system for extreme congested traffic situations in the 3,5 km long highway tunnel Södra länken (Southern Link) has been develop. The system gives a warning to the operators in the traffic management centre up to 5-10 minutes in advance. This allows for an accurate traffic information and well-prepared launch of the tunnel closing procedure.

BACKGROUND
The increasing problem with congestion in urban highway environment creates large variation in travel time for the road users. In several countries highway are built in tunnels to reduce the local environmental problems in residential areas. However, congested traffic in tunnels is a major safety problem in case of fire, as well as a health problem with high levels of NOx-emissions.

The Southern Link is a 4 km long urban motorway in a tunnel. The construction of the large highway tunnel in the southern suburbs of the City of Stockholm was finalised in late 2004. It is one quarter of the ring road around Stockholm. It was planned for a daily traffic of around 60.000 vehicles, but since the opening in 2004 the traffic has steadily increased.

The design speed was 70 km/h but the standard is very high and corresponds to normal highway speed levels in the range of 90-100km/h. The ventilation and safety measures were based on the assumption of normal speed.

The lowest speed during peak hours was forecasted using standard static traffic models to be in the range of 40 km/h with daily traffic volumes around 60-70.000 vehicles. However, the year after the opening the traffic volumes reach nearly 100.000 veh/day and the speeds dropped close to 10 km/h during morning peak hours. Due to safety reasons the tunnel has to close at these low speeds.

The safety concept for the Southern Link calls for no queues with very low speeds in the tunnel. This is of course because that in case of a vehicle on fire, the cars upstream must be able to evacuate the tunnel to avoid the toxic fumes that will be exhausted upstream with the aid of jet-fans. The cars downstream should stop, the passengers should leave their cars and go to the safe emergency shelters and evacuate to the adjacent tunnel tube that has been closed off for traffic.

So how do you balance the need for safety with the need to keep the tunnel open for the daily commuters? The traffic managers that handle the tunnel needs to close entrances to the tunnel when there is a risk of very slow moving traffic in the tunnel. This is most dangerous in the easterly direction when the Southern Link feeds the Essingeleden during the morning rush hour. The traffic managers have ITV-cameras that show them the traffic and the AID-signals that alert them to slow traffic, but is the traffic volume increasing or decreasing?
To help the traffic-managers to decide when they should close the tunnel entrances we have developed an algorithm what predict traffic speed 5-10 minutes into the future. The data is one minute average speeds from the microwave detectors mounted above each lane at about 100 m intervals in the tunnel. The main use for this is the MCS-system used to alert motorist with signs above the lanes that give recommended speed in case of queuing. The data is fed in to our algorithm that is implemented at PL-SQL scripts in our database. The algorithms send out a prediction each minute how the traffic will be in 2 sections in the tunnel for the next 5 minutes, either green, orange or red. This has been in place since 2010 and the success of the trials have made that we will implement the same algorithms in other places.

Fig 1: Overview of the monitoring system where MCS-detectors are used for local queue alarms as well as predictions algorithms

In order to manage tunnel closing the operators at Stockholm traffic management centre asked for a warning system to provide accurate information on the traffic situation, i.e. a prediction or probability for extremely low speeds in the tunnel.

THREE-PHASE TRAFFIC THEORY
In the last years a new traffic theory has been introduced by a research group in Germany (Boris Kerner et al) [1], [2], [3],[4]. In principle, the traffic flow could be divided into three main phases – free flow, synchronised flow and moving jams. Especial the transition between these phases is of high interest with modelling traffic in highway environment.

In particular, the progression of a moving jam is under special concern in understanding extreme congestion. One of the characteristics of the moving jam from a road-user point of view is the “stop-and-go” driving, where the vehicle temporary comes to a complete stop with zero velocity in motorway environment.
The intense and comprehensive installation of sensors on highly congested highways in urban environment gives the opportunity to fully explore the new theory. Not only in the analysis of historical data but also for real time applications.

Each congested highway section (typical 3-10 km) has its own fundamental traffic pattern or speed contour. This representation has been used for decades by traffic engineers and researcher (A D May) [5]. The three-phase traffic theory offers a new understanding of the speed contours.

**PREDICTION PROTOTYPE**

An off-line prototype of the prediction system has been used to tune the algorithms with data from several months. As the traffic patterns change during high and low traffic months – typical May-June is a period with high traffic demand in Sweden, whereas Dec-Feb has low traffic demand – a rolling update of the patterns has to be performed. There is also a long-term shift towards more and more congested that has to be considered.

The off-line prototype also provides a unique platform to tune the prediction algorithm. The first version was based on pattern recognition combined with simple rules. A new version works with probabilities and filtering techniques.

The fundamental idea behind the prediction technique is to identify moving jams upstream the main tunnel exit and follow its progression through the highway network. If the width and progression speed of the moving jam is above certain thresholds the first level if the warning system is triggered. In the next level of the warning system the expansion of the moving jam is under consideration, i.e. the duration of very low speed at a specific detection point in the network. Often the moving jam is shrinking as it approaches the exit of the tunnel, therefore the probability of tunnel blocking is less likely.
Fig 3: The tracking of moving jams during rush hours (6-10 am) in different days. The speed counters in the upper diagrams and the identification of moving jams on the corresponding days below.
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**Fig 4: Method based on regression analysis and/or rulebased**

**IMPLEMENTATION**

As the major bottleneck is situated nearly 5 km from the tunnel exit - and with a typical progression speed of the moving jam in the range of 5-10km/h - a warning could theoretical be given 30-60 min in advance. However, the forecasting method is performing less accurate and there is also a need to avoid false alarm, which allows for a warning 10-20 minutes in advance. When the alarm is set the operators are able to activate VMS with queue warning and use other traffic information channels to warn drivers of a coming tunnel closing.

By introducing a state vector of speeds and flows for each section (detections point) a spatial correlation between the sections can be recognized using data from several months. Regression analysis is used to find the coefficients in the travel time prediction algorithm (5, 10 and 15 minute horizon). More interesting from a traffic management point of view is to warn the Södra länken tunnel operators when low speed in the tunnel is predicted.

Two alarms are set based on the method outlined is the paper. The most important is the “exit blocking” alarm that indicates the coming presence of a downstream moving jam that reduces the saturation flow at the tunnel exit. The second alarm is the “full tunnel” alarm that predicts extensive queuing in the tunnel in the near future (5-10min).

The first tests indicate computer and database performance problems as the method is running a rolling horizon with a one-minute resolution. The calculation has to be done in less than one minute and in the full scale implementation at Trafik Stockholm is takes less than one seconds to perform the prediction calculation.
Fig 5: An incident at 7.20 creates a moving jam. The “exit blocking” alarm is set at 7.28 and the “full tunnel” alarm is set at 7.32 (section 16 is down giving a black line in the diagram).

This is displayed for the operators in a web page, where each minute a new prediction appears as colored bars on the page.

Fig 6: Implementation on operator screen in Trafik Stockholm
OPERATIONAL EXPERIENCE

After an initial trial period the prediction system has been fully operating for over one year. The operators where given an introduction to the system and how to interpret the alarms. As the number of closing procedures are rather low, typical 1-2 times a month, it is difficult to make a statistical analysis. However, the number of tunnel closings has dropped after the implementation of the system. Interviews with tunnel operators indicate that some closing decisions has been cancelled because the system indicates less congestion within 5-10 minutes.

More important is the impact of traffic information that is now based on more reliable traffic data and prediction. The external VMS-based queue warning system is place appr 5-10 km from the tunnel entrances. These VMS are only giving tunnel queue warning when the prediction alarms indicate a severe condition in the near future. The same traffic information is given over the radio stations.

In the figure below a couple of interesting situations with prediction alarms are outlined.

![Fig 7: Implementation on operator screen in Trafik Stockholm](image)

In above example for 31st of August 2010, you can see how the predictions helped the traffic-managers handle the queues in the tunnel and could with high confidence close the some of the tunnel entrances.

In the example below from 8 Dec 2010 the impact from early warning is shown. The queue blocking the exit from the main tunnel is predicted some 10 minutes in advance and allows the operator to activate the VMS queue warning system at diversion points upstream the tunnel entrance.

The full tunnel alarm is then delayed due to reduced traffic demand. In this case the exit alarm predicts a less severe situation at the same time the full tunnel alarm becomes active. Hence, the closing of the tunnel entrances could be avoided.
8 dec 2010

Sudden shift in the exit alarm @ 7.50

Stable exit alarm during 8.00-8.40 => VMS queue warning

Exit alarm temporary at level 2 during kl 8.40-9.15 = continue VMS queue warning

Fig 8: Implementation on operator screen in Trafik Stockholm

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Safety in Swedish railway tunnels

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KEYWORDS: Railway, tunnel safety, rescue services, risk level, guideline, Sweden.

INTRODUCTION
Safety in tunnels is complex, and policy making has to account of several factors, including; the standpoints of different stakeholders, technical system and solution, costs and benefits and risks [1].

During the last 20 years the demand for heavier freight and higher speeds for passenger traffic has led to straighter tracks with less incline. As a consequence the number of tunnels has increased and become longer, see figure 1. A result of this development is guidelines on tunnel safety. The first guideline was published in 1993 and was latest revised in 2007.

The Swedish Transport Administration (STA) operates 160 railway tunnels. STA is responsible for the long-term planning of the transport system for road, rail, shipping and aviation and also responsible for building, operating, and maintaining state roads and railways. STA was founded 2010 mainly by a fusion of the Swedish Road Administration and the Swedish Rail Administration. In the coming years several long tunnels, including underground stations, will be built beneath the major cities of Sweden.

Figure 1. Railway tunnels operated by Swedish Transport Administration and publication of guidelines on tunnel safety in railway tunnels.
Swedish railway tunnels are mostly constructed in hard rock by the so called drill and blast method. In recent years the number of cut and cover tunnels have increased, mostly in the major cities.

The majority of the tunnels are rural indicating that the external assistance, in case of an accident, is far away. Therefore the most important aspect of safety is to enable self-rescue.

The trend observed is that safety measures is a function of the number of vehicle and passengers. The municipality and the local fire brigade have been involved from an early stage in all projects, and it is clear that these bodies often have a large impact on the final design of the respective tunnel facility. The infrastructure manager has to maintain these measures during the lifetime of the facility to ensure the safety in the tunnel. This aspect of tunnel safety is often overlooked in the design stage which causes problems in the operational phase, [2]

GUIDELINES ON SAFETY IN RAILWAY TUNNELS

The first guidelines for safety in railway tunnels were published by the Swedish rail administration in 1993. In the beginning of the 1990’s there were plans to expand the railway network and allow higher speeds. This generated a need for straighter tracks and therefore more and longer tunnels. At the time of publication of the first guidelines STA operated approximately 25 km of railway tunnels. Within five years the total length was almost doubled.

In the first guidelines a set of measures were defined. Tunnels where split into three categories by length, Table 1. Inspiration to this classification came from Italy, [3]. The exact classifications of length were made by the Swedish rail administration.

<table>
<thead>
<tr>
<th>Tunnel class</th>
<th>Length</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>&lt; 500 m</td>
</tr>
<tr>
<td>B</td>
<td>500 - 2000 m</td>
</tr>
<tr>
<td>C</td>
<td>&gt; 2000 m</td>
</tr>
</tbody>
</table>

Table 1. Tunnel classes [4]

For each class A and B a set of basic safety measures were defined. For class C tunnels additional safety measures could be applied. However, the guideline did not describe any method for how to evaluate the need and the benefit of the additional measures applied.

In 1997 the second edition of the guidelines were published. The railway network has in comparison with other means of transportation a high level of safety [5]. Contributing factors are regulation and control of traffic movements, and technical requirements on infrastructure and rolling stock. Because of these regulations and requirements a probabilistic approach can be used to evaluate tunnel safety. This was realized in the second edition, and a safety level for tunnels were defined:

“Train traffic per kilometre in tunnels shall have the same safety level as railway traffic per kilometre track on open track, excluded level crossings” [6]

Accidents in level crossings make a great contribution to the total number of accidents and were excluded by obvious reasons. In the new guidelines tunnels were no longer classified by length. Instead all subsystems were taken into account when evaluating the risk for a accident happening in a specific tunnel. The most important step in the safety evaluation process, figure 2, is to define the entire traffic system. By doing this relevant statistic data can be used in the evaluation and possible accidents can be identified. Basic safety measures are always included in this step.
Figure 2. Safety evaluation process. [5]
The identification of accidents is followed by the risk evaluation. This is made in a traditional way using event-tree and fault-tree analysis. In this process personal from regular operation and external assistance are involved. When the risk evaluation is done the result is compared to the stated safety level. If the result shows that the safety is greater than open track the work is done. If the result however shows a level of safety in accordance with open track additional safety measures should be evaluated with regard to benefit. In the case the results show that there is an unacceptable risk additional safety measures, table 2, must be applied and the risk evaluation re-done.

<table>
<thead>
<tr>
<th>Basic safety measures</th>
<th>Additional safety measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency brake override</td>
<td>Anemometers (to guide rescue services)</td>
</tr>
<tr>
<td>Emergency communication</td>
<td>Detectors hot wheel detectors</td>
</tr>
<tr>
<td>Emergency exits</td>
<td>ITV/CCTV (train or tunnel)</td>
</tr>
<tr>
<td>Emergency lighting</td>
<td>Mobile fans for rescue services</td>
</tr>
<tr>
<td>Emergency plans</td>
<td>Parallel service and rescue tunnel.</td>
</tr>
<tr>
<td>Escape walkways and signage</td>
<td>Regular exercises</td>
</tr>
<tr>
<td>Fire fighting water supply</td>
<td>Separation of freight and passenger traffic</td>
</tr>
<tr>
<td>Fire protection requirements for structures</td>
<td>Shorter distance between emergency exits</td>
</tr>
<tr>
<td>Fire safety requirements for building material</td>
<td>Smoke detection</td>
</tr>
<tr>
<td>Safety installations on rolling stock</td>
<td>Smoke ventilation</td>
</tr>
<tr>
<td>Tunnel specific competence of train crew</td>
<td>Wider walkways and emergency exits</td>
</tr>
</tbody>
</table>

Table 2. Examples of basic and additional safety measures

The current guideline, the third edition, was published in 2007 and the safety level is the same as before. The major change since 1997 is that the technical specification for safety in railway tunnels [7] has been incorporated. This document is a compulsory regulation for all EU member states and includes detailed technical requirements as well as functional requirements. All these are in the third edition of the guideline the basic safety measures.

In the second edition a risk matrix was used to evaluate if the safety level was achieved. In the third edition this matrix was replaced with a F-N diagram making it possible to evaluate the result in greater detail and to evaluate the benefit of measures on accidents with low probability and great consequence, [6].

Although the STA have guidelines of how safety in tunnels can be achieved, a common view together with other actors in society is hard to reach. Several documents are needed to design a safe railway tunnel, figure 3. A study in 2003 made in cooperation with several authorities draw the conclusion that all laws have to be fulfilled even if they contradict one another. This often results in conflicts between different actors.

Figure 3. Pieces needed to design a safe railway tunnel,[8].
DESIGN PROCESS
The municipality and the local fire brigade have been involved from an early stage in all projects, and it is clear that these bodies often have a large impact on the final design of the respective tunnel facility.

Disagreements regarding tunnel safety were discussed in length between the client, and the municipality and fire brigade, [2], [9]. The most governing issue in all projects seems to be generic, namely the distance between the escape routes, and the design and capacity of the fire fighting water supply. Discussions regarding details of other safety-related installations have also taken place frequently.

The local rescue services doesn’t fully approve of the probabilistic approach used. Even if the STA:s safety level is reached local rescue services often demand additional measures. This is because the rescue services want a design based on a worst case scenario. Additional safety measures demanded by other actors are to subject to a cost benefit analysis according to the STA guidelines before they are introduced.

MAINTENANCE AND AVAILABILITY
The measures taken to increase the safety level directly lead to increased maintenance. If a correct maintenance plan isn’t applied the installations will fail. In recent projects a separate document has been developed, SITS, Safety in technical systems [10]. This document is used in the design phase to make functional demands on all technical systems related to the safety in the tunnel. In practice the SITS describe the limitation of how long certain systems can be out of order before traffic movements are no longer accepted.

The assumption is that, if an accident happens, all measures will function. Regular inspections in elder tunnels show that safety related installations often are out of order. Today the regulation telling the maintenance crew how long it has to take to put these right, is unclear.

Looking at the different types of measures the conclusion from inspections is that installations that are used regularly in the maintenance of the track and tunnel are the most reliable. That is installations which have multiple purposes other than strictly safety in case of an accident. Also robust installations with low complexity are reliable. These measures are e.g. lighting, walkways and signage.

The most errors today are observed in fire fighting water supply systems, emergency doors and smoke ventilation. That is complex systems and installations that seldom are used other in the case of an accident.

DISCUSSION
The STA must continue its work to reach a common view on safety in railway tunnels with other actors in order to enable processes and installations to be standardized to a larger extent. Consequently, the maintenance become easier and cheaper and focus in tomorrow’s projects can be upon the truly unique moments. Improvement by learning from earlier experience demands that there exist repeatable activities. From a project perspective many activities are experienced as new and unique, from a national perspective the bulk of activities are repeatable from one project to another.

There is a need for more distinct regulations on maintenance and a limitation for failure. A information process is needed to all actors involved. The focus of this information should be to make everyone realize, that even if it is very unlikely that a accident will occur in a tunnel today, the consequence could be great. It is essential that the safety measures implemented will function at the time of an accident.
The train crew plays an important role in the case an accident. Fast decision making greatly reduce the evacuation time in the case of a fire. Periodic exercises would help the train crew to handle and identify a dangerous event. Exercises would also help to show the rescue services how best to contribute in different types of accidents.

A new safety evaluation should be made for each tunnel with certain intervals to determine the need for changes in the safety measures. An evaluation of the tunnels should also include a compilation of the most common errors in the safety measures. In this way the most reliable measures can be identified and improvements made in less reliable measures.

CONCLUSION
Demand for heavier freight and higher speeds for passenger traffic has led to straighter tracks with less incline. As a consequence the number of tunnels has increased and become longer demanding a more efficient process for the safety in tunnels.

It is obvious that safety in tunnels is a complex issue and has to account for both political aspects as well as the standpoints of different stakeholders. These standpoints vary due to different interpretation and contradictions of governing regulations and consequently it have resulted in time consuming and unsuccessful discussions in several projects. The most governing issue in all projects seems to be generic, namely the distance between the escape routes, and the design and capacity of the fire fighting water supply. The municipality and the local fire brigade have been involved from an early stage in all projects, and it is clear that these bodies often have a large impact on the final design of the tunnels.

Installations with the purpose to increase the safety level leads to increased maintenance costs. It is not unusual that it takes a long time to repair installations that is out of order. A contributing factor is wrong cost estimations for the tunnel maintenance. Meaning that in practice it is a low probability for the installations to function in case of an accident. This phenomenon is also observed from regular inspections in elder tunnels indicating that safety related installations often are out of order. If one look into the different types of installations can be concluded that installations used regularly in the maintenance of the track and tunnel are the most reliable. These installations have to work to make it possible to maintain other parts of tunnel/track e.g. lightning, walkways and emergency exits. Other types of installations that aren’t used regularly often fail.

REFERENCES


On the Power of Simulation and the Need for Experimental Validation

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Amberg Engineering Ltd., CH-8105 Regensdorf-Watt
VSH Hagerbach Test Gallery Ltd., CH-8893 Flums

ABSTRACT
An appropriate combination of simulation and experimental work is essential for both scientific advancement and enhanced design. The Amberg Group has the quite unique privilege of in-house extensive experimental and simulation capabilities. A critical review of the current state of simulation and experimental work in the field of tunnel safety is provided in this paper, with emphasis on the synergies and interactions between the two fields. From the point of view of practical application in design and design-verification, simulation tools have reached a mature stage and can be readily used for most tasks at hand. Nevertheless significant uncertainties still need to be solved based on new experimental data. Such issues include design fires for train and metro as well as the use of new technologies such as FFFS (Fixed Fire Fighting Systems). The different issues related to simulation and full-scale testing are approached based on practical design and design-verification experience as well as based on the findings resulting from recent and ongoing research efforts.

KEYWORDS: Tunnel safety & security, FFFS, simulation, validation, large-scale testing

1 INTRODUCTION AND OBJECTIVES
Recent enhancements of simulation techniques, coupled with increasing low-cost computational power, allow for a very extensive use of numerical simulation techniques also in the field of underground safety. The cost of simulation is dropping very rapidly and its power is increasing. Large-scale experiments show radically different trends. While new sensors and data-acquisition techniques slowly improve the quality of experimental data, their cost stagnates or increases, because of increasing labor cost and new energetic and environmental constraints. Can we design and validate safety concepts for complex underground infrastructures based on simulation alone? Can we replace time-consuming, expensive real-size test campaigns with quick, cheap and accurate numerical experiments?

This paper focuses on design-related needs, rather than on academic research issues. It presents considerations based on two different points of view, arising from two professionals with different backgrounds and playing different roles, but acting within the same company and with the same broad goal, improving the safety of underground infrastructures. They represent on one side the perspective of the consulting engineer “at the front”, needing tools and knowledge for carrying out his daily design-related work. On the other side there is the entirely different perspective arising from full-scale testing and applied research on materials and components carried out at VSH. Two different but complementary perspectives, which help identifying interdisciplinary needs.

2 THE ROLE AND NEEDS OF SIMULATION
From a consultant engineer point of view, 1D or 3D simulation techniques can be applied at different levels and for different purposes:

- Design or design verification, e.g. performance verification of the ventilation system for a complex underground metro or train station.
• Safety verification in rail and road tunnels, where real-life fire scenarios are analyzed for assessing the user’s self-rescue conditions and chances.
• Passive and active fire protection.
• Detailed design, e.g. optimization of FFFS configurations.
• Support to component development and verification, e.g. FFFS or fire detection systems.
• Assessment of damages on structure and life due to explosion.

The specific requirements on simulation’s quality can be extremely heterogeneous, depending on the specific application. For the design tasks they can be formulated as follows:

• Accurate and reliable 1D or 3D solver.
• Comprehensive validation and fair knowledge of the limits of applicability.
• Fire characterization, in terms of heat-release rate, pollutant and smoke production.
• Modeling of specific components (jet fans, smoke-extraction dampers, nozzles for FFFS).

“Standard” simulation for design or for verifying tunnel safety concepts is well established and does generally not need much experimental support. Several 1D and 3D tools are very well validated and can be used with confidence. Such applications include e.g. the simulation of fire scenarios in road and rail tunnels for verifying the performance of smoke-management concepts as well as for optimizing the prescriptions for emergency management and ventilation control. Another key field of application is ventilation design for underground metro and rail stations or other large level or underground buildings. Simulation allows for a rapid comparison of different concepts, determination of the smoke-extraction rates needed and detail optimization of ventilation concepts.

The role of simulation for safety verification is quite different and more delicate. Some minimum safety requirements are explicitly formulated in national and international regulations (prescriptive approach). A typical example is represented by the maximum distance between emergency exits in tunnels, which typically ranges from 500 to 1’000 m for single or double-track tunnels in Europe (decision 2008/163/EC concerning the technical specification of interoperability relating to “safety in railway tunnels” in the trans-European conventional and high-speed rail system) and 244 m (800 ft) to 762 m (2500 ft) in the USA (NFPA 130). However, the distance between cross passages is in the range of 300 – 350 m for most recent long Alpine tunnels [3]. Similarly, NFPA 130 prescribes a maximum allowable platform evacuation time of 4 minutes or less. Clearly these minimum prescriptions are not generally applicable and performance-based safety verifications are needed. The Swiss Federal Office of Transport did an excellent effort, based on the Swiss Directive against major risks (“Störfallverordnung”), for establishing criteria for such efforts for railways, tramways, cableways, boats, buses and trolley buses [29]:

• “We adopt the most effective safety measures at the lowest possible cost.”
• “Public transport operations come with risks. We accept residual risk only when, to the best of our knowledge, such risk is justifiable and cannot be entirely eliminated through reasonable measures. Where there are conflicting interests (e.g. safety vs. profitability), we attribute great importance to safety.”
• “Whenever incidents occur, the persons affected must have a fair chance of survival.”

For a given project these principles can be verified basically by two means:

• Quantitative Risk Analysis (QRA), for comparing the safety level of different tunnel on the same line (e.g. the Zimmerberg, Ceneri and Gotthard Base Tunnel on the new Gotthard line) as well as for comparing the general risk level with acceptability curves.
• Scenario analysis, which allows for a fairly straightforward assessment of situations, which can be managed by means of a given safety system.
Establishing a level of safety means accepting residual risks. While QRA provides reasonably objective but abstract results, scenario analysis allows for a direct appreciation of the consequences of possible accidents. This is in our opinion by far the best approach towards infrastructural safety. The practical application of scenario analysis for design verification is based on the following steps:

- Selection of the relevant scenarios, which shall cover “reasonable worst-case situations”, which could be very infrequent but must be accounted for by the safety system.
- Detailed simulation of fire development and smoke propagation.
- Detailed simulation of the evacuation process, accounting for fire effects, particularly for the presence of smoke.

The requirements in terms of simulation are in principle quite similar for QRA and scenario analysis, with some differences. QRA is a statistical approach and accounts for all scenarios in a weighted manner, thus the details from the individual scenarios tend to “disappear” in the analysis. Simulations for scenario analysis must be carried out in a more detailed manner because the safety concept must provide a “fair chance of survival” for all selected scenarios. Relevant simulation issues include therefore visibility, thermal and radiant load as well as concentration of the major pollutants. This is particularly challenging because it involves a detailed analysis of physically complex effects, such as the fire source and the specific combustion conditions on one side and smoke stratification on the other.

Important differences, specific needs and special issues arise from different “families” of applications:

- Road tunnels
- Rail or metro tunnels
- Rail or metro stations
- Large caverns for different applications.

The issues relevant for caverns and other kinds of underground structures are similar as for underground stations, but the widely different exploitations and configurations pose extremely heterogeneous issues, e.g. with respect to potential fires and escape configuration. They shall not be discussed in more detail herein. A comparative discussion of road, rail and metro was provided by Brousse [9][14]. The issues most relevant for the present discussion are summarized in the following table.

<table>
<thead>
<tr>
<th></th>
<th>Metro</th>
<th>Rail</th>
<th>Road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>500-600 m</td>
<td>up to 50-60 km</td>
<td>up to 15-20 km</td>
</tr>
<tr>
<td>Emergency exits</td>
<td>200-400</td>
<td>500-1'000 m</td>
<td>300-500 m</td>
</tr>
<tr>
<td>Cross section</td>
<td>small</td>
<td>small</td>
<td>large</td>
</tr>
<tr>
<td>Fire frequency</td>
<td>low</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Fire HRR</td>
<td>7-30 MW</td>
<td>10-200 MW</td>
<td>2-200 MW</td>
</tr>
<tr>
<td>Emergency ventilation</td>
<td>simple or none</td>
<td>stations only</td>
<td>longit. – transverse</td>
</tr>
<tr>
<td>Number of persons</td>
<td>100-250/wagon</td>
<td>up to 1’500-2’000</td>
<td>1-100</td>
</tr>
<tr>
<td>Self-rescue time</td>
<td>5-20 min</td>
<td>10-30 min</td>
<td>3-5 min</td>
</tr>
<tr>
<td>Intervention time</td>
<td>5-10 min</td>
<td>10-60 min</td>
<td>5-60 min</td>
</tr>
</tbody>
</table>

Table 1  Comparison of different transport systems.

Compared to road systems, rail and metro are therefore characterized by very large person concentrations on narrow escape paths, which lead to long or very long self-rescue times. In case of train stops in the tunnel the technical possibilities for smoke management are in most cases limited to very limited. The safety concept is frequently based on smoke stratification. The picture is further complicated by the high uncertainty level with respect to heat-release rate and its time development.
3 FROM LARGE-SCALE EXPERIMENTS TO DESIGN TOOLS

A number of pioneering large-scale test provided invaluable insight in many aspects of tunnel fires. Among the most important early experiments, carried out before the fire in the Mont Blanc tunnel of 24 March 1999, one shall mention:

- Ofenegg (1965) [15][13] – These pioneering tests, carried out in Switzerland using several petrol pool fires (6.6 to 95 m²), focused on the influence of the fire source size and ventilation (longitudinal and semi-transversal) on temperature distribution and smoke behavior. Some test of sprinkler systems contributed establishing PIARC’s long standing position on FFFS.
- Eureka 499 “FIRETUN” (1990-1992) [12] – The experiments, carried out in Norway, investigated the combustion characteristics of a wide range of road and rail vehicles, as well as a number of calibrated fires. Some results are reviewed in [27].
- Memorial Tunnel fire test program (1993-1995) [23] – This test series, carried out in the USA, focused on the smoke behavior from a large number of diesel oil pool fires, ranging from 10 to 100 MW, using a wide spectrum of ventilation systems.

These and many other large-scale experimental efforts have provided most of the current knowledge on tunnel fire development and smoke propagation in tunnels, with invaluable and lasting benefits in terms of both design and modeling. From the point of view of simulation these include:

- Understanding of general tunnel-fire characteristics.
- Quantification of fire sources for road, rail and metro fires, in terms of heat-release rate and smoke development.
- Detailed knowledge on smoke behavior, particularly on smoke stratification and critical velocity.
- Temperatures distributions, air velocity and pollutant concentration.
- Detailed databases for validation of simulation tools for air velocity and smoke propagation.

Nevertheless it shall be pointed out that these groundbreaking investigations partly suffered from the lack of a fully controlled and equipped test environment. More recent, comprehensive test series were:

- Fire Tests in the Second Benelux Tunnel (2000-2001) [24] – The tests were carried out in a new road tunnel to assess the tenability conditions for escaping motorists in the case of a fire in a Dutch road tunnel and to study the effect of mitigating measures on these conditions. The heat-release rate was up to 20 MW.
- Runehamar Tunnel fire test series (2003) [8] – The tests focused at providing detailed information on the influence of ventilation on the peak heat release rate and fire growth rate, the production of smoke and toxic gasses from various goods and the possibility for rescue services to fight heavy-good vehicle large fires (70 to 200 MW).

The available fire tests were recently reviewed by several authors, including [6][10][11][13][17][19]-[27]. Based on the data available, several simulation tools have been carefully validated and are readily applicable to a wide spectrum of problems. Based on our experience, the following approaches for fire analysis can be recommended:

- Road tunnels: 1D two-layer zonal model, e.g. [4][5].
- Rail and metro tunnels: CFD, e.g. FDS (Fire Dynamic Simulator)
- Stations and caverns: CFD, e.g. FDS (Fire Dynamic Simulator).

Among the remaining issues, the most critical is probably represented by the design fire. New-generation trains are much more difficult to ignite but are at times characterized by substantially more combustible materials than older systems, such as those tested in the Eureka 499 program [12]. There-
fore substantial ignition energies, such as those originated by arsonist attacks (e.g. Daegu 2003) or unusual sources (e.g. Kaprun 2000) are usually required for full fire development [7]. Standard design fires might therefore be applicable or not, depending on the specific application at hand. Engineering approaches and data are discussed by [10][11][13][17][19][26]. The initial growth phase is frequently modeled by a quadratic curve with variable coefficients, representing different development speeds. Ingason [18] presented a compact fire curve, which can represent the entire fire in a consistent manner. Simulations for road-tunnels fires are frequently based on very simple fire curves, with a linear growth to a fixed maximum value, typically in the range of 5 to 100-150 MW [11][18]. This issue is frequently not relevant for analyzing the self-rescue phase, since this will in most cases be completed long before the peak heat-release rate is achieved. The conditions for rail and metro vehicles are much more difficult. As shown in Table 1 the self-rescue phase is much longer in rail and metro tunnels than in road tunnels. Depending on the specific design fire, the self-rescue process could not be completed at the time, where the peak heat-release rate is reached. Figure 1 shows representative experimental data and the corresponding design curves from Germany. Additionally, a particular project-specific design fire with a peak heat-release rate of 54 MW, reached within only 15 minutes, is shown as an illustration. This very rapid development and high peak intensity represents an extremely challenging problem, particularly in case of train stop in a tunnel. As an example at the opposite end of the spectrum, the design fires for New York City Transit’s newer trains were recently reduced from 14 to 5 MW [28]. For comparison the design fires for passenger trains used for the new Alpine tunnels in Switzerland reach 10 MW after 20 min (one coach) and 20 MW after 70 min (two coaches) [7]. Two further points of uncertainty shall be pointed out:

- The ignition source represents a key parameter for fire development. Only substantial fire sources (typically a few liter of liquid fuel due to arsonists, as e.g. in Daegu 2003) can generate the largest heat-release rates in modern, fire resistant (e.g. compliant to DIN 5510) rail and metro vehicles [7]. The question frequently arises in design, whether such fire sources shall be accounted for or not.
- It must furthermore be pointed out that the fire data presented accounts for only one burning passenger carriage at the time. Depending on the time scales of fire development and intervention, it is questionable, whether the fire-fighting teams could intervene in time for preventing fire propagation the further carriages.

The data show a very large scatter and many questions marks. From the point of view of the engineer “at the front” this uncertainty is enormous and must be tackled by an appropriate combination of experimental, computational and theoretical work.
A viable alternative to extremely expensive large-scale experiment is small-scale testing. The similarity laws are presented in [6][26][27]. Practical applications were recently presented e.g. in [11][21]. Small-scale experiments allow for relatively rapid and inexpensive parametric studies and investigations of physical effects under well-controlled conditions. Geometric similarity can in most cases be enforced, but not all dimensionless similarity parameters can be correct in the experiment. Further uncertainties include the source model, near field convection and radiative heat transfer rates, so that extrapolation of results to full scale is not obvious. This concerns particularly heat-release rate, a most fundamental parameter in fire testing [11][27]. Thus small-scale experiments are certainly not a full replacement for full-scale testing.

4 RECENT RESEARCH EFFORTS

Tunnel safety and security has been identified being important by many stakeholders, leading to funds available for a number of research projects carried out in the frame of the European funded R&D Framework Programmes FP5 through FP7. Especially FP5 and FP6 covered a wide range of underground safety and security projects, dealing with innovation, upgrade, safety improvement as well as networking to support the underground infrastructure safety community. Apart from those topics, a design study for a large scale underground research facility on safety and security was funded by the EC. This design study specifically dealt with the need for testing as means of validation of simulations or lab scale experiments. The following list shows a brief overview of FP5 / FP6 /FP7 projects contributing to a higher level of underground safety [10][20][26]:

- Durable and Reliable Tunnel Structures (DART 2001-2004)
- Upgrading Methods for Fire Safety in Existing Tunnels (UPTUN 2001-2004)
- Innovative systems and frameworks for enhancing of traffic safety in road tunnels (SAFE TUNNEL 2001-2004)
- Safety Improvement in Road & rail Tunnels using Advanced ICT and Knowledge Intensive DSS (SIRTAKI 2001-2004)
- European thematic network on fire in tunnels (FIT 2001-2005)
- Thematic Network on development of European guidelines for upgrading tunnel safety (Safe-T 2003-2006)
- Large Scale Underground Research Facility (LSURF 2005-2008) [1][2]
- International Road Tunnel Fire Detection Research Project (2007-2008) [25].

Figure 2 Layout and fire testing in the VSH (A86 Paris).

In Europe there are three major European large-scale test facilities with very different characteristics and a very wide spectrum of activities. They also cooperate within the L-surF effort [1][2]:
- Runehamar Test Tunnel (Norway)
- TST Tunnel Safety Testing (Spain)
- VSH Hagerbach Test Gallery (Switzerland).

The Hagerbach Test Gallery VSH provides a (steadily growing) underground network of test galleries with a total length of over 5 km, of which 250 m are reserved for fire testing, with a cross section of 55 m$^2$. The VSH consists of broad variety of galleries excavated in limestone with a fire protection layer of sprayed concrete. It is equipped with a versatile ventilation system. The VSH has an own concrete / rock laboratory.

5 DESIGN APPLICATIONS

A typical “end-user” application of simulation is design verification based on scenario analysis. Smoke propagation and self-rescue must be analyzed in detail for a number of representative scenarios. The time available for evacuation depends mainly on fire characteristics and smoke propagation. Safety is achieved if, for every selected scenario, the conditions along the whole escape path are satisfying during the whole self-rescue process. This provides to every person involved a fair chance of safe escape.

Tenability conditions are reviewed e.g. in [7][22][26][27]. The conditions along the escape path (thermal and radiant load, concentration of asphyxiant and irritant gases, visibility [22]) are evaluated using the results of three-dimensional simulations (CFD). Typical relevant toxic substances are CO, CO$_2$ and HCN. The maximum allowable concentration for these substances is presented in Table 1. A further threat results from radiant and thermal load. It is generally accepted that the radiant heat flux should be lower than 2.5 kW. The tolerance time to high air temperatures depends on air humidity. Air temperatures above 80°C are critical. Loss of capacity to act must be expected for temperatures of 100°C after 10 to 20 minutes [27].

<table>
<thead>
<tr>
<th>Smoke concentration</th>
<th>Exposure time [min]</th>
<th>Visibility range [m]</th>
<th>CO concentration [ppm]</th>
<th>CO$_2$ concentration [Vol %]</th>
<th>HCN [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>30</td>
<td>&gt;20</td>
<td>100</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Medium</td>
<td>15</td>
<td>10-20</td>
<td>200</td>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>High</td>
<td>5</td>
<td>&lt;10</td>
<td>500</td>
<td>3</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 2  Limiting values for safety of life when exposed to smoke [7].

Based on our experience and taking into account the large uncertainties while determining the concentration of noxious gases (which depends very strongly on the composition of the burning materials and
on the specific, local combustion conditions), in the authors’ opinion this issue is best evaluated based on visibility and temperature alone. Since a certain level of thermal and optical stratification is always observed, the evacuation conditions are typically evaluated at a height of 2 m.

A few illustrative results are presented in Figure 3, in terms of visibility length. Note that the simulation is based on the German 25 MW fire curve presented in Figure 1. The results show that the time available for escape is of the order of 15 minutes. Later on, the visibility downstream of the train drops rapidly and the conditions on the walkway are not anymore suited for self rescue. The results clearly depend very strongly on the design fire and on the train’s stopping times. The level of uncertainty is very large, particularly with respect to the time scales of fire development.

Figure 4 Challenging recent design issues. Left: Deep stations Barcelona, metro line 9. The metro station, located about 80 m below the surface and built on two levels, is visible on the lower right-hand side of the picture. Right: The innovative solutions adopted for the A86 in Paris required new technical solutions for ensuring the tunnel’s safety.

6 OPEN ISSUES AND THE NEED FOR FURTHER RESEARCH

Simulation has achieved, from the point of view of the ventilation and safety engineer “on the field”, a very mature stage. Software is well validated and (partly) inexpensive, hardware is increasingly powerful and inexpensive. Can we design and validate safety concepts for complex underground infrastructures based on simulation alone? Can we replace time-consuming, expensive real-size test campaigns with quick, cheap and accurate numerical “experiments”? The answer is obviously negative. Practical experience shows that simulation can be used with confidence only within or reasonably close to the bounds of known experimental experience. Input data, boundary conditions and some physical models must be established and validated based on solid experimental data. Among the practical, design-relevant issues requiring further experimental attention, the following appear paramount:

- Design fires - Simple standard design fires proved to be useful for a large spectrum of applications but are not universally applicable. The fire characterization for new-generation rail and metro material shows a very large scattering both in peak heat-release rate and time to peak. This introduces significant uncertainties in design.
- Fire details - Advanced applications, e.g. in the field of quantitative risk analysis or detailed scenario analysis, require quite detailed data on thermal and radiant load, pollutant release rate and optical smoke density. Such data depend heavily on the burning materials and on the combustion conditions, first of all on the fire’s stoichiometric conditions, as well as on smoke stratification. Current models are not yet sufficiently mature for delivering such information in a reliable manner.
- Passive fire protection – The large body of information available on passive fire protection is
only partly integrated in simulation tools. In future the design of infrastructure components shall be based more on specific simulations of the material’s thermal load and ignition characteristics than on predefined thermal curves.

- **Active fire protection** - The physics of comparatively new technologies, such as FFFS using very fine droplets and/or additives, is not reliably accounted for in existing models, particularly if the interaction between several systems (e.g. ventilation and FFFS) is of primary interest.
- **New technologies** – New concepts, e.g. involving the use of flexible barriers in tunnels for preventing uncontrolled smoke propagation in case of fire, can be developed largely based on simulation, but need a careful experimental verification before implementation.
- **New applications of existing technologies** – As in the case of Paris’ A86, external constraints lead to the development of radically new safety concepts, which require proper experimental validation.
- **Component development and testing** - New safety-relevant components, such as new fire-detection devices, need a full-scale validation.

In the author’s opinion an even more strict interaction between simulations and physical experiments is needed, for reducing the cost of large-scale experiments and improving the overall process effectiveness. As practiced in other fields of engineering, such as airplane or gas-turbine design, a typical interaction could be structured as follows:

- **Experiment preparation**: Detailed simulation of the experimental setup during the test-design phase. The intended experimental setup is investigated using CFD with focus on detailed experiment design (e.g. sensor characteristics and emplacement, thermal protection etc.).
- **Calibration**: Preliminary experimental investigations for calibrating the simulation. In this phase measurement and CFD results are compared in detail for one or a few relevant configurations. All calibrations needed for obtaining best agreement for the specific problems and configurations at hand are carried out.
- **Exploration and optimization through simulation**: Starting from the configurations used for calibration, optimization is carried out using CFD. This typically involves a large number of simulations, where the effect of all relevant parameters is investigated.
- **Verification**: Experimental verification of the results from the previous step, further optimization where required and final assessment.

7 REFERENCES


New Concept for Design Fires in Tunnels

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ABSTRACT

A new concept for design fires in tunnels is presented. The concept is based on a simple engineering approach including important geometrical and physical variables of the tunnel and the fuel. The engineering equations originate from the calculation of critical conditions inside the tunnel such as visibility, velocity and maximum ceiling temperature. The concept leads to a range of design fires given in megawatts (MW) for a specific tunnel. This will make it easier for designers to choose an appropriate design fire for the ventilation system and the tunnel construction. The main advantage is that it is not dependent on the choice of vehicle and it gives a meaningful range of design fires to work with for a specific tunnel. The effects of ventilation on the maximum heat release rate become inherently ruled out by this method. The range of design fires for tunnels that are 2.5 m to 7 m high is between 2 MW and 130 MW. The method shows that the tunnel height becomes the single most important parameter influencing the choice of a design fire.

KEYWORDS: tunnel, design fire, heat release rate, critical velocity, temperature

INTRODUCTION

A small fire in a passenger vehicle in an urban road tunnel can be likened to a “friendly fire”, as it is seldom hazardous to the tunnel users. Such a fire results in minor interruptions in the traffic and the damage to the infrastructure itself is scarcely noticeable. On the other hand, a single or multiple Heavy Goods Vehicle (HGV) trailers or a petrol tanker on fire can be likened to an “elephant fire” in terms of danger and potential to wreak havoc on the tunnel itself and its occupants. Every step in the fire development becomes dangerous for users, nearby vehicles or the construction itself. This type of fires have for example been observed in the Mont Blanc fire [1], the Tauern fire [2] and the Frejus tunnel fire [3] where multiple HGVs were burned.

One can ask whether it is realistic to regard these “elephant fires” as design fires, and if not, why not? The design fires found in guidelines and standards internationally [4-5] can vary considerably, from 2.5 MW up to 300 MW. They are usually given as tabulated data from different types of vehicles. A relevant question when selecting an appropriate design fire is whether it possible to establish a limit for when it is no longer meaningful to investigate or consider a design fire larger than a given critical size? In the same way, one can ask whether it is possible that a typical “friendly fire” is too small for it to be worthwhile for it to be considered in the design process?

The selection of a design fire provides the basis for numerous fire protection aspects in the tunnel. Further, design fires can be determined in different ways. For egress analysis, a fire growth rate up to a given constant heat release rate (MW) value is often used. For the ventilation system, the design fire is given in MW and represents a single vehicle and not a combination of different vehicles. For the construction, the design is based on standardized time-temperature fire curves (ISO, HC, RWS, HCM, RABT) without any direct relation to the fire load in the tunnel. The choice of other technical systems is often related to the tunnel length and/or the traffic density.

The hypothesis for the work presented in this paper is that there exists a meaningful range of design fires that needs to be considered in the design of evacuation, ventilation and tunnel construction. The consideration of design fires outside this range is irrelevant. Any influences of mitigation systems are
not considered here. In order to investigate where the boundaries for this range of design fire sizes lies, simple mathematical expressions for visibility, critical velocities, maximum ceiling temperatures and geometries of fuels and tunnels have been used. The first step was to identify parameters and variables in the design that are important or even critical. The second step was to develop or establish useful correlations to identify these design fire limits. The approach presented here focus on the minimum design fire for different technical systems and tunnel geometries rather than what the traffic conditions may generate for a design fire. In an engineering fire safety design it is important to consider both these parts of the design.

**THE BOUNDARY CONDITIONS**

Important geometrical parameters identified include the tunnel height and the tunnel width. The fuel geometry, height above the road surface and projected area of the fuel, are also important. For evacuation, the visibility is the first parameter to become critical. Other important parameters relating to ventilation and construction include the critical velocity and maximum temperature beneath the ceiling. With these parameters in mind, an investigation was carried out to identify the range of critical design fire sizes in MWs. In this analysis, only a constant heat release rate was considered. In order to identify the limits for the range of design fires it was decided to use the following critical conditions:

1) **Visibility in the tunnel.** It is possible to identify a heat release rate for a given critical visibility, assuming that tunnel users cannot find their way out or the escape path is too long and therefore they will be exposed to a toxic environment for a long time. As we know that the visibility becomes critical more rapidly than the toxic environment [6], we can use visibility to find a minimum design fire related to evacuation. The fire growth rate is a critical parameter when calculating evacuation, but for the purpose of this study it has been excluded.

2) **Critical velocity.** The critical velocity is defined as the minimum longitudinal ventilation velocity to prevent reverse flow of smoke from a fire (backlayering) in the tunnel. There exists correlations which show that above a certain longitudinal velocity, the critical velocity will not change, independent of the heat release rate [7]. This approach has been used to find a minimum heat release rate related to a critical velocity. This means that the longitudinal velocity does not need to increase to prevent backlayering even if the heat release rate increases. There exist also one to third power equations that do not reach a constant critical velocity independent of the heat release rate [8-9]. For the purpose of the concept developed here these one to third power equations are not applicable, although we will discuss the use of these equations later.

3) **Maximum ceiling temperature.** Above a certain heat release rate from a single vehicle burning, the maximum temperature beneath the ceiling will not change [10]. In the present study an excess temperature of 1350 °C was used as the highest constant ceiling temperature. This approach yields the minimum design fire related to temperature exposure to the ceiling from a single burning vehicle.

In conclusion, in order to find a range of design fires given in MW, we use engineering correlations to extract the heat release rates when we attain certain critical conditions or when we know there will be no change even if the heat release rate is increased. The level becomes dependent on the design objective (evacuation, critical velocity or construction) and tunnel geometry. Any type of influence of a deluge water spray systems is not considered here.

**THEORETICAL APPROACH**

In the following, a set of equations are presented for each of the three critical conditions given earlier. These equations will be used to develop correlations calculating the range of design fires in MWs.
Visibility

The three parameters: heat release rate \( Q \), air velocity \( V \), and cross-sectional area \( A \), can be combined into one single non-dimensional parameter, \( Q^* \):

\[
Q^* = \left( \frac{Q}{m_o c_p T_o} \right)
\]

where \( Q \) is the total heat release rate (kW), \( m_o = \rho_o V A \) is the ambient air mass flow rate (kg/s), \( c_p \) is the specific heat of air at constant pressure (kJ/kg K), \( T_o \) is the ambient temperature (K), \( \rho_o \) is the ambient density (kg/m\(^3\)) and \( A = W H \) is the cross-sectional area (m\(^2\)) \((H \) is tunnel height (m) and \( W \) is tunnel width (m)). Equation (1) shows that increased \( Q \) for the same air velocity increases \( Q^* \) and thereby the expected hazard downstream the fire. By examine different hazards we can find different \( Q^* \) which can be identified with different indices. A fixed value of \( Q \) and increased air velocity \( V \) leads to lower \( Q^* \) and thereby lower expected hazard. If we assume no effect of the air velocity on the heat release rate, \( Q \) we will lower the hazard if the air velocity is increased.

In order to explain the parameter \( Q^* \) we can try to relate it to some critical conditions obtained in a tunnel fire. Let us investigate the critical \( Q^* \) for visibility, i.e. \( Q^*_{\text{vis}} \), where the subscript \( \text{vis} \) means visibility. Similar methods can be developed for toxicity, but this is outside the scope of this paper.

The smoke concentration \( C_s \) (kg/m\(^3\)) in a duct flow can be expressed as [10]:

\[
C_s = \frac{Y_s m_f}{V_T}
\]

where \( Y_s \) is the smoke yield of the fuel (kg/kg), \( V_T \) is the volume flow (m\(^3\)/s) and \( C_s \) is the smoke concentration (kg/m\(^3\)). Using equation (2) and assuming that mass flow of mixed combustion gases and fresh air \( m_g = m_0 = \rho_o V A \), and \( Q = m_f H_c \) and using equation (1) we find that:

\[
Q^*_{\text{vis}} = \frac{C_s H_c}{Y_s \rho_o c_p T_o}
\]

Here \( m_f \) is the mass loss rate of fuel (kg/s) and \( H_c \) is the effective heat of combustion (kJ/kg). The visibility \( V \) (m) can be related to the \( C_s \) using the following equation [11]:

\[
C_s = \frac{2}{V \xi \ln 10}
\]

The specific extinction coefficient of smoke is \( \xi \) (m\(^2\)/kg). Tewarson [12] has tabulated data on the so-called mass optical density, which is defined as \( D_{\text{mass}} = \xi Y_s \) (m\(^2\)/kg), for numerous materials. Using equations (3) and (4) and using this relation for \( D_{\text{mass}} \) we obtain:
\[
Q_{\text{vis}}^* = \frac{2}{V_{\text{vis}}} \ln 10D_{\text{mass}} \frac{H_c}{\rho_o c_p T_o} \tag{5}
\]

Thus, we can calculate the critical \(Q_{\text{vis}}^*\) for visibility in smoke inside a tunnel. By defining the design fire \(Q = Q_{\text{vis}}\) (kW) we can obtain the design fire related to visibility as:

\[
Q_{\text{vis}} = Q_{\text{vis}}^* \rho_o c_p T_o VWH \tag{6}
\]

The obtained \(Q_{\text{vis}}\) will be a conservative value, as no transportation time or stratification of smoke is considered along the entire tunnel length (steady state one dimensional bulk flow).

**Critical velocity**

The governing parameters are the heat release rate \((Q)\), air density \((\rho_o)\), ambient temperature \((T_o)\), thermal capacity of air \((c_p)\), gravitational acceleration \((g=9.81 \text{ m/s}^2)\) and tunnel geometry \((H)\). The non-dimensional \(Q^*\) can be expressed as [13]:

\[
Q^* = \frac{Q}{\rho_o c_p T_o g^{1/2} H^{3/2}} \tag{7}
\]

and the critical velocity \(V_c^*(\text{m/s})\) is obtained from

\[
V_c^* = \frac{V_c}{\sqrt{gH}} \tag{8}
\]

where

\[
V_c^* = \begin{cases} 
0.81Q^{*1/3} & Q^* \leq 0.15 \\
0.43 & Q^* > 0.15 
\end{cases} \tag{9}
\]

When \(Q^*\) becomes larger than 0.15, the critical velocity \(V_c\) will become a constant value. This can be seen in Figure 1 as a constant horizontal line (plateau) where \(V_c^* = 0.43\). The tunnel width \(W\) was not included in the study by Li et al. [11].

![Figure 1](image)

**Figure 1** Estimation of the minimum heat release rate considering critical velocity [13].
The design fire $Q_{cv}$ (kW) can then be expressed as:

$$Q_{cv} = Q^* \cdot \rho_o c_p T_o g^{1/2} H^{5/2}$$

(10)

A well known one to third power equation for critical velocity is given in NFPA 502 [5] which is based on [9]:

$$V_c = \frac{K_1}{K_2} \left( \frac{g Q H}{\rho_o c_p T_f A} \right)^{1/3}$$

(11)

where

$$T_f = \frac{Q}{\rho_o c_p A V_e} + T_o$$

and where $T_f$ is the average temperature at fire site in Kelvin. The constant $K_1$ is 0.606 and $K_2$ is 1.0 when no slope is present. As this equation is used in NFPA 502 it becomes very important for design fires and will therefore be evaluated in relation to the new concept presented here.

**Maximum ceiling temperature**

Li et al. [14] and Li and Ingason [10] have developed an engineering correlation which can be used to calculate the maximum excess ceiling temperature in tunnels as a function of the heat release rate, ventilation rate, effective tunnel height and fuel geometry:

$$\Delta T_{\text{max}} = \begin{cases} 17.5 \frac{Q^{2/3}}{H_{\text{ef}}^{5/3}}, & V' \leq 0.19 \\ \frac{Q}{V b_{fo}^{1/3} H_{\text{ef}}^{5/3}}, & V' > 0.19 \end{cases}$$

(12)

where

$$V' = V \cdot \left( \frac{gQ}{b_{fo} \rho_o c_p T_o} \right)^{1/3}$$

(13)

The effective tunnel height, $H_{\text{ef}}$, is defined as the height from the bottom of the fuel source to the ceiling, i.e. $H_{\text{ef}} = H - h_{fo}$, where $h_{fo}$ is the height from tunnel floor to bottom of the fuel. For a HGV trailer, $h_{fo}$ can be set to 1.2 m. The effective radius of the fire source, $b_{fo}$ (m), can be obtained by estimating the projected area of the fuel, $A_p$ (m$^2$). For a HGV trailer this can be the length of the trailer times the width of the trailer. The effective radius of the fuel then becomes:

$$b_{fo} = \sqrt{\frac{A_p}{\pi}}$$

(14)

In equation (12) the maximum excess gas temperature is independent of the tunnel width, $W$. This phenomenon was observed by Lönnermark and Ingason [15]. They used a wide range of tunnel widths in a model scale test series and were not able to see any effects of the tunnel width on the maximum ceiling temperature. Therefore, the width was not used by Li and Ingason [10]. In Figure 2 the experimental results given by Li and Ingason [10] are presented. It can be seen that the excess ceiling temperature will not change when the value on the horizontal axis (equation (12)) exceeds 1350. This knowledge will be used to determine the heat release rate required to reach to the plateau of 1350 °C.
The maximum excess temperatures given for two ventilation regions. Region I \( V' \leq 0.19 \) is the graph to the left and Region II \( V' > 0.19 \) is the graph to the right [10].

Equation (12) can be rearranged in order to obtain the design fire \( Q_T \) (kW), which relates to the maximum excess temperature depending on which ventilation region is obtained:

\[
Q_T = \begin{cases} 
\frac{\Delta T_{max}}{17.5} \cdot H_{ef}^{5/2}, & V' \leq 0.19 \\
\Delta T_{max} Vb_{ef} H_{ef}^{5/3}, & V' > 0.19 
\end{cases}
\tag{15}
\]

The value of each parameter in equation (15) can be adjusted based on the tunnel and the fuel type.

APPLICATION

Now we have three different equations to determine the range of design fires: equation (6), (10) and (15), respectively. The highest design fire is expected to be obtained from the maximum excess ceiling temperature, equation (15). The lower design fires are expected to be obtained based on the visibility, equation (6) and on the critical velocity, equation (10). In the following we will systematically go through and discuss each of these equations.

Visibility

The visibility in environment having structural elements such as walls, floors and doors in an underground arcade or long corridor according to Jin and Yamada [16] can have a minimum value of 2 (-). The average value of \( D_{mass} \) for all the materials listed in Table 1-13.7 (76 different materials) in Tewarson [12] is 245 m²/kg. Ingason [11] gave some \( D_{mass} \) values from vehicles measured in the EUREKA test series. These values corresponds to a burning school bus. The average heat of combustion, \( H_c \), for same number of materials is \( H_c = 31100 \text{ kJ/kg} \). If we assume that the critical visibility is 1 m \( (Vis = 1\text{m}) \) and \( D_{mass} = 245 \text{ m²/kg} \) we obtain \( Q_{vis}^* = 0.31 \). Assuming that the critical conditions are obtained when the velocity \( V_c \) in equation (6) corresponds to the critical velocity \( V_c \), we can put \( V_c = V_c^* \sqrt{gH} \) into equation (6), \( (g=9.81 \text{ m/s}^2) \) where \( V_c^* \) is equal to 0.43. Further, the aspect ratio of tunnel width \( (W) \) to tunnel height \( (H) \), \( \zeta = W / H \), can vary from 1 to 3 for most tunnels. In most cases the parameter \( \rho_a c_p T_a \) is equal to 352. Thus, we obtain a new equation for \( Q_{vis} \) (MW):

\[
Q_{vis} = 0.15 \cdot \zeta H^{5/2}
\tag{16}
\]

Critical Velocity

The value of \( Q^* = Q_{vis}^* \) can be chosen as 0.15 (the lowest value to get up to the plateau in Figure 1). It is, however, known that the ventilation system needs to be compensated for extra pressure losses in longitudinal flow with large fires [17]. The experience from Memorial fire tests suggests a reduction
of the ventilation flow of 11 – 62 % [17] for fires from 10 – 100 MW using three jet fans. With six jet fans the corresponding reduction is 1 – 50 %. The reduction of the velocity in the Runehamar tests was about 20 – 25 % [18]. For an exhaust ventilation system the heating up of the exhaust ducts will influence the pressure losses and thereby the ventilation flow. The question is whether we need to compensate for these pressure losses and thereby increase the size of the design fire?

We have to keep in mind that the effect of thermal expansion doesn’t affect the critical velocity but rather the performance of the ventilation system and its interaction with the tunnel. The pressure loss over the fire place, temperature reduction due to different heat losses and the slope of the tunnel, all influence the final velocity. Thus the reduction in the velocity has to be dealt with in the design of the specific ventilation system. Therefore the choice of $Q_{cv}'$ is set here to the minimum value of 0.15.

This gives the minimum design fire to control the backlayering for a given tunnel. In order to maintain a positive control of the backlayering, the tunnel longitudinal air velocity corresponding to the reduced airflow must be maintained above the critical air velocity for the design fire heat release rate [17]. One way to obtain a value of $Q_{cv}'$ that compensates for the reduced airflow, and thereby obtains higher design fire, is to consider the average temperature downstream a given tunnel. It is outside the scope of this paper to do so. Assuming $\rho_o c_p T_o$ is equal to 352 (kJ/m$^3$), $g=9.81$ m/s$^2$ and $Q_{cv}' = 0.15$ we obtain a new equation for $Q_{cv}$ (MW):

$$Q_{cv} = 0.165 \cdot H^{5/2}$$  \hspace{1cm} (17)

As mentioned earlier, equation (11) is a one to third power equations and does not yield a clear braking point where we can obtain a given minimum heat release rate. Equation (11) will be discussed later in relation to the results obtained by equation (17).

Maximum ceiling temperature
As we are interested in obtaining the higher design fire $Q_T$ from equation (15) we assume that the we have a velocity $V'$ corresponding to the critical velocity $V_c$. Thus, we are only interested in using the equation corresponding to $V' > 0.19$ in equation (15). Thus, we can put $V_c = V_c' \sqrt{gH}$ into equation (15), $V' > 0.19$, ($g=9.81$ m/s$^2$) where $V_c'$ is equal to 0.43 we obtain a design fire $Q_T$ (MW):

$$Q_T = 11.3 \cdot 10^{-4} \cdot \Delta T_{\text{max}}^{1/6} A_p^{1/6} \sqrt{H \left( H - h_{fo} \right)}^{5/3}$$  \hspace{1cm} (18)

RESULTS AND DISCUSSION

Now we have developed three different equations which all yield the minimum design fire for three different applications. All the equations show a significant influence of the tunnel ceiling height, $H$. Therefore, this parameter should be defined as the single most important parameter for the fire safety design of a tunnel. Other parameters of importance are the tunnel aspect ratio, $\zeta = W / H$ which is important for the visibility but $W$ has much less influence on critical velocity and ceiling temperature. The geometrical parameters of the fuel, $A_p$ and $h_{fo}$, are found to be important for the excess ceiling temperature, $\Delta T_{\text{max}}$. In general the aspect ratio is a parameter that needs to be considered, but the influence of it varies.

In figure 3, the results of using equations (16) – (18) are shown for a range of tunnel heights varying between 2.5 m and 7 m, covering most practical tunnel heights. The design fires in MWs are plotted as a function of the tunnel height $H$. The input parameters are $A_p=25$ m$^2$ (corresponds to 10 m long trailer which is 2.5 m wide), $h_{fo}=1.2$ m, which is a typical height of the loading area for a HGV trailer and two aspects ratios, $\zeta = 1 - 3$. The excess ceiling temperature is 1350 °C.
Figure 3  Plot of different design fires for different tunnel heights between 2.5 m to 7 m.

The lowest heat release rates needed to obtain critical conditions in 2.5 m high tunnels is in the range of 2 MW to 5 MW and the minimum heat release rates to obtain critical conditions in 7 m tunnels varies from 20 MW to 130 MW. In all cases the longitudinal velocity in the tunnel corresponds to the critical velocity. This is a very interesting result, as most designers determine their design fires without any type of relation to the geometry of the tunnel or the fuel. The type of vehicle decides the design fire and that can be compared to these results.

Analysis of equation (11), the NFPA 502 equation, indicates that for heat release rates above the highest obtained design fire $Q_T = 130$ MW the increase in critical velocity using 130 MW instead of 200 MW for heights varying from 2.5 m to 7 m, is in the range of 1 – 8 %, respectively. If the same comparison is made for an increase from 130 MW to 300 MW, the change in calculated critical velocity with equation (11) is 2 – 13 %. This shows that even for equation (11) used in the NFPA502 standard, the increase in calculated critical velocity is moderate above the value of 130 MW as a design fire. Consequently, the choice of a design fire higher than 130 MW will not significantly change the results. In the calculations, an aspect ratio $\zeta = 2$ was used.

The concept presented here can be used to determine the minimum conditions to work from, and to give a reasonable indication of which design fires should be considered. That the tunnel height is such a dominating parameter is very important information for designers. The higher the tunnel height become, larger design fires are needed to obtain critical conditions. This does not mean that tunnels with a higher ceiling height are more hazardous than those with a lower ceiling height. On the contrary, lower tunnel heights require lower heat release rates to obtain the same conditions as in higher tunnels.

The aim of this study was to explore the range of design fires that are meaningful to work with, assuming that the fire load corresponds to a single vehicle. The heat release rate values found in the literature are definitely in the range found here. In a large fire, such as a tanker fire, most of the fuel is spilled on the surface and $h_p$ can be assumed to be 0. This gives us a minimum design fire of 180 MW. Design fires for tanker are given in NFPA 502 as a range of 200 – 300 MW [5]. This show that the lower value is quite close to the one obtained here.

The most surprising result is the low design fire for $Q_{cv} = 0.15$. The ceiling temperature at the critical
condition is not very high, about 250 °C. This can be easily calculated by using the heat release rate obtained for the critical velocity in equation (18). Another interesting way to use equation (18), is to use the standardized time-temperature curves such as ISO, HC and RWS, see figure 4, and calculate the corresponding heat release rate for a specific tunnel.

![Image](https://via.placeholder.com/150)

**Figure 4** Plot of calculated heat release rate for some standardized time-temperature curves at the critical velocity.

Of the three different equations derived, equation (18) yields the highest heat release rates. This is reasonable and should be considered in the design process for the construction. The equation is also very useful in showing the connection between the heat release rate and the standardized time-temperatures. As shown in figure 4, the design fire \( Q_T \) can be obtained by assuming a given standardized time-temperature curve.

The equations (16) – (18) are very useful tools to estimate the range of design fires for a given tunnel. The minimum values obtained should be put in relation to the actual fire load for a given tunnel. In other words an analysis of the potential fire load that will travel through the tunnel should also be carried out. If the tunnel height is relatively low, there is no reason to choose a design fire that is far above the one obtained by the concept given here. On the other hand if the tunnel height is large, there is no reason to choose a design fire that is much lower than the calculated here, especially if the fire load analysis indicates that the potential for such a fire exists for the tunnel. All together the process has to be put into a context based on the purpose of the design.

**CONCLUSIONS**

The design fire range obtained with equations (16) – (18), derive the minimum values required to obtain critical conditions for a single vehicle fire in a given tunnel. The highest design fires are obtained by equation (18). The range of design fires for tunnels that are 2.5 m to 7 m high is between 2 MW and 130 MW, assuming that the bottom of the fire source is 1.2 m from the road surface of a HGV trailer. This is well in line what is found in the literature. Assuming that the highest tunnel height investigated (7 m) is decisive for the value of the design fire we obtain a range of 20 MW to 130 MW depending on the criteria for the design.

The tunnel height becomes the single most important parameter influencing the choice of a design fire. This is important to consider in the design of tunnel fire protection. This does not mean that higher tunnel height is more hazardous than lower tunnel height. On the contrary, low tunnel heights require lower heat release rates to obtain the same conditions as in tunnels with higher tunnel heights.
The method presented is a very useful tool to estimate the range of design fires for a given tunnel and really show the relevant range of “friendly fires” and “elephant fires”. Further, it is possible to use the obtained equations to calculate what heat release rates are necessary to obtain a given standardized time-temperature curve for ISO, HC, RWS, RABT or HCM. This provides the key to a clear discussion between designers of ventilation systems and the tunnel construction.

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Fine Water Spray Tunnel Fire Protection from Fixed Installed Systems

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INTRODUCTION

VID Fire-Kill and SINTEF NBL did in May 2009 conduct a series of full scale tunnel fire tests in the Runehammar 1.6km long test tunnel. The purpose of the tests was to test the fire fighting and smoke handling abilities of the fine water spray delivered from a VID Fire-Kill Tunprotec system installed in the ceiling centerline of the 9m wide and 6m high infrastructure tunnel.

THE TUNPROTEC FINE WATER SPRAY SYSTEM

Three 20m Tunprotec tunnel protection Zones were installed in ceiling centerline in the centre of the 1.6km long and 9m wide road tunnel. In the event of a fire in a fire protected tunnel, the Tunprotec Fine Water Spray System is designed to simultaneous deliver Fine Water Spray in three twenty meters long tunnel fire protection zones. The tunnel fire protection zone the fire is located to, and a zone on each of it’s side. The Fine Water Spray the Tunprotec System supplies in each active tunnel fire protection Zone is 30m³/h at 10 bar water pressure. The Fine Water Spray are evenly distributed in the whole Tunnel fire protection zone as water droplets with Dv90 < 250µm and an average water density of 2,8mm/min.

THE TUNNEL TEST FIRES.

The Tunprotec Fine Water Spray was tested in three different fire test scenarios:

Test A: diesel pool fire, 3m³ diesel oil was evenly spread in 6 x 2m² 0,6m high fire trays. Estimated heat release rate: 22MW

Test B: wood fire

Test C: polyurethane fire

The following heat release rates are recommended:

- Diesel fuel: heat release rate 8.5 MW/m²
- Wood: heat release rate 15.0 MW/m²
- Polyurethane: heat release rate 22.5 MW/m²

Figure 1: Heat release rates of different fuel arrangements in tunnels.

Figure 2: test set-up test A
Test B: Medium Class A fire: 180 dry Euro transport pallets piled on a concrete bed simulation a truck load. Estimated peak heat release: 50MW

*Figure 3:* Test set-up test B

Test C: Large Class A fire: 360 dry Euro transport pallets piled on a concrete bed simulation a truck load. Estimated potential peak heat release: 100MW

*Figure 4:* Test set-up test C

**FIRE SPREAD TARGETS**

During all test fires, a 200 litres steel barrow with water was located 2,5m down-stream the test fire, and pile of dry wooden Euro Transport pallets was located 6m down-stream the fire.

**TEMPERATURE MEASUREMENTS**

During each test fire the temperatures in the tunnel was measured:

Tunnel ceiling surface temperature: Measured in dry location above the centre of the fuel package. (Yellow curve on temperature graphs)

Tunnel gas temperatures up-stream fire: Measured 40m upstream the fire set-up in the tunnel centre 2m,3m,4m,5m above road surface.

Tunnel gas temperatures down steam fire: Measured 5m and 840m down-stream the fire set-up in the tunnel centre 2m,3m,4m,5m above road surface.

For all three test fires we see a fast knock down of the ceiling surface temperature above the fire (yellow curves), when the fine water spray (blue line) is turned on. The fine water spray does not wet or direct cool the ceiling surface directly above the fire. The stored heat in tunnel ceiling material (Rock) which in test B and C was heated to approximately 1000°C before the release of fine water spray, continues to keep the surface hot after the initial temperature reduction until the system manage to fully suppress the flames from fire, and the heat input to the tunnel ceiling stops.

The curves clearly show a fast and sustainable drop in gas temperatures at all heights in the tunnel as soon as the fine water spray is released. This prevents the fire from spreading to...
fuels located downstream the fires in tunnels where a Tunprotec System distributes its fine water spray.

CALORIMETRIC MEASUREMENT OF FIRE HEAT RELEASE RATES (HRR)

The calorimetric method calculates a fire's heat release rate from measuring the amount of oxygen a fire consumes on the fire combustion gases.

1kg of Oxygen consumed => 13 MW (HRR)

During the fire tests the air temperature, the air velocity and the oxygen concentration were measured in the centre of the tunnel cross section 740m downstream the test fire, 60m from the tunnel outlet.

The calorimetric method was hereafter applied to calculate estimations for the heat releases from test fires. The measured average air velocity was hereafter applied to track the estimated heat release rates back in time, as if the heat releases were measured on the location on fire.

We will later see large differences in air velocities measured at different locations in the tunnel cross section upstream the test fires. Said differences, and the fact that the oxygen concentrations were measured only 60m from the tunnel exit, make absolute peak HRR values become very uncertain values.

However the graphs of calculated HRR values clearly show that the Tunprotec system fully suppressed the test fires, which also the temperature graphs did indicate.

DIRECT TEST RESULTS FROM FIRE TESTS:

The Tunprotec Fine water spray did in all fire tests suppress the tunnel fires and temperatures in the tunnel. The fine water spray did also prevent the target fuels from igniting, and the barrow from being heated to temperatures higher than 35°C, which indicates that fires will not spread in tunnels protected by a Tunprotec Fine Water System.
SMOKE & TUNNEL VENTILATION:

Two jet fans installed in the tunnel ceiling approximately 100m from the tunnel entrance applied the tunnel ventilation during the fire tests.

Air velocities were continuously measured 0,6m and 3m below the centre of the tunnel ceiling 40m upstream the fire.

The measured air velocity graphs clearly show that the air velocity in the centre of the tunnel was approximately 3m/s when the fires were ignited, and that the air velocity 0,5m below the tunnel ceiling was approximately 1m/s less than the air velocity in the centre of the tunnel.

The tunnel velocity graphs clearly show that the air flow 0,5m below the ceiling changes direction to go against the ventilation during the pre-burn of the fire.

This phenomenon is called smoke back layer. The smoke back layer moves smoke up-stream the 2-3 m/s ventilation with a velocity of 3 m/sec app. 10,8m /sec.

When the combustion gasses cools the back layer smoke mixes with the ventilation air stream to make a dense smoke atmosphere upstream the tunnel fire, making it difficult finding escape routes upstream a tunnel fire.

The air velocity graphs also clearly shows that the back layers disappears when the Tunprotec system releases it’s fine water spray in the vicinities of the tunnel fire.

The back layer is super heated fire combustion gasses, which from heat of fire expands its volume, and continuously are pushed away from the location of the fire along the tunnel ceiling.
When Tunprotec System releases its fine water spray, the fine water spray cools the super heated combustion gasses. The volumetric combustion gas production decreases from the cooling of the gasses, and the cooled gasses falls down from the tunnel ceiling and mix with the air in the whole cross section of the tunnel, making it possible for the existing 2-3 m/s air ventilation system to prevent smoke back-layer in the tunnel.

The photo shows the visibility and persons without extra breathing equipment than a paper mask standing 20m up-stream the large (100 MW) test fire C, with active fine water spray from Tunprotec system and 2-3m air ventilation in the tunnel.

VISIBILITY DOWN-STREAM FIRE IN TUNNEL FIRES:

The graph shows the visibility in the test tunnel 100m from the tunnel exit, during and after the 22 MW diesel fire test. The test was conducted during the day with sun shine outside the tunnel exit. Car headlights were located 60m, 70m, 80m 90m from the tunnel exit, and the lights were visually monitored from a position 100m from the tunnel exit. The fire was ignited and had a 240 sec pre-burn time before the Tunprotec system was activated to distribute fine water spray. The fine water spray extinguished the fire approximately 30 sec. after activation. The tunnel ventilation was 2-3m/s. The graph shows that the observer lost full sight of the tunnel opening 955 sec after ignition, and could see the tunnel exit again after further 10 min 3 sec. The observer lost sight of car light 10m from the observer 990 sec. after the fire was ignited and did first see the light again after 5 min.

The example shows that all sight in a tunnel completely disappears in tunnel fires, and that the visibility only comes back because the fine water spray extinguished the fire.

It also shows that if the ventilation had been faster, it would have taken a shorter time before visibility completely disappeared in the tunnel.

CONCLUSION:

The tunnel fire tests clearly showed that the technical simple low maintenance Tunprotec fine water spray system provides:

Reliable fire suppression of tunnel fires
Reliable protection of tunnel structures against fires
Improved rescue possibility for people.
Increased abilities for fire fighters to access tunnels to fight tunnel fires
Reduced demands to tunnel ventilation rates.
Taking advantage of theories and models on human behaviour in the fire safety design of underground transportation systems

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ABSTRACT
Fire accidents in underground transportation systems, e.g., tunnels and underground stations, can cause many fatalities. It is therefore important in fire safety design to give adequate consideration to all aspects related to evacuation. The paper provides a review of two previously reported fire accidents based on a theoretical framework, namely four accepted human behaviour theories. These theories provide qualitative guidance on human behaviour in the event of fire in underground transportation systems, and it is therefore argued that they need to be considered in the fire safety design of these facilities.

KEYWORDS: tunnel, underground station, fire, human behaviour, evacuation, egress, behaviour sequences, role-rule model, affiliative model, social influence.

INTRODUCTION
In recent years the number of rail and road tunnels have continuously increased, and during the last 20 years there has been a trend to build exceptionally long tunnels. Examples are the 24.5-kilometre long Lærdal tunnel in Norway and the 50.5-kilometre long Channel tunnel between France and the UK, which opened for traffic in year 2000 and 1994 respectively. By moving these types of transportation systems underground a more effective flow in traffic can be achieved, distances and travel time can be reduced, and the environment above ground can be preserved. However, the relocation from above ground to underground introduces a new set of hazards, like fires, which have to be considered.

The fact that fire is an important issue is sadly illustrated by many past accidents in both rail and road tunnels, such as the fires in the Mont Blanc tunnel [1,2], the Baku Metro in Azerbaijan [3,4] and the Kaprun tunnel [5,6]. Another underground facility that has to be included in this context is underground stations which are often integrated in larger metro systems. A fire at an underground station can also result in many fatalities. This is demonstrated by the King’s Cross fire [7] which resulted in more than 30 fatalities, as well as the fire at the Jungangno Metro station [4] where over 180 people were killed.

In order to avoid these types of devastating accidents it is necessary to consider the human behaviour aspects already in the design phase of a tunnel or underground station. Much of the data concerning human behaviour in the design for fire safety are, though, by tradition based of experiments related to building fire safety. Still, much of the data may be applicable also for underground constructions, but it is important to identify the causes for different behaviour compared to human behaviour in buildings by additional experimental data collection.
An important factor is information, which is relevant both for initiating evacuation and for directing people to appropriate exits. Previous accidents have shown that it is sometimes difficult to get people to respond. This is illustrated by both the Mont Blanc tunnel and Tauern tunnel fires [2] where some people remained in their vehicle and subsequently died. Once the evacuation is initiated it is also important that people find their way to a safe place. This can be difficult due to such aspects as lighting conditions or presence of smoke.

Today egress time-line models are frequently used in the fire safety design process to provide data for quantitative calculations, e.g., computer simulations or hand calculations of fire development and evacuation [8]. However, this type of basic model does not provide any guidance towards the understanding of human behaviour, which has been pointed out to be essential if fire safety measures are to be brought in line with occupants’ needs during a fire incident [9]. In order for the designer to choose solutions that support occupants the designer should therefore seek guidance in the existing theories and models of human behaviour in fire, namely the behaviour sequence model [10], the role-rule model [10,11], the affiliative model [12,13,14] and the theories on social behaviour [15,16,17].

The four theories/models mentioned above can be seen as a relatively complete theoretical framework of human behaviour in fire. The use of this type of theoretical framework can help explain the human behaviour in past fires in underground transportation systems. However, it is also argued that the same framework can be useful in the fire safety design of these constructions since it provides qualitative guidance. If society is to meet the demand to handle fire and evacuation safety in underground transportation systems it is therefore recommended that the fire safety design emanate from this framework. The paper aims to present this theoretical framework in detail and to show how it can be applied to explain previous accidents. The intention is also to highlight the use of human behaviour theories in design of future underground constructions.

The paper is based on [18] in which a more comprehensive description is presented.

**THEORETICAL FRAMEWORK FOR HUMAN BEHAVIOUR**

A discussion of human behaviour in the event of fire in underground transportation systems can greatly benefit from the use of a clear theoretical framework. In this paper, human behaviour is analysed based on four commonly used and accepted theories, namely the behaviour sequence model, the role-rule model, the affiliative model and social influence. All these theories are deemed valid and relevant for fire evacuation in underground transportation systems and can be used to explain human behaviour often observed in fire accidents.

**The behaviour sequence model**

The first theory discussed in the paper is the behaviour sequence model developed by Canter, Breaux and Sime [10] to aid the understanding of human behaviour in fire, see figure 1. The model is based on the results from detailed studies of human behaviour in fires, namely domestic, multiple occupancy and hospital fires. Information about the actions taken by evacuees was gathered by local fire brigades in interviews with survivors. Among many things, it was investigated how people became aware of the fire and how they responded.
It can be seen in Figure 1 that human behaviour in a fire can be described by three sequence categories, or so called nodal points: (1) interpret, (2) prepare and (3) act. Each nodal point constitutes a behaviour sequence, i.e., a sequence of consecutive actions that people perform. The figure also demonstrates that as the sequence of behaviour unfold the potential actions increase in variety, some of which providing a more efficient evacuation than others. Canter et al. [10] do not claim that all types of behaviour in fires are efficient. However, by adopting the model seen in Figure 1, human behaviour in fire can be described without the use of the term 'panic'. Using the term 'panic' is today questioned within the research community as an explanation of human behaviour [19].

In the early stages of a fire, information and fire cues are scarce. Consequently, the decisions that a person makes in the early stages of a fire are associated with great uncertainties. However, as a person receives more information about the fire the uncertainty associated to the decision-making is reduced. When a person receives an initial cue he or she can either ignore it or begin to look for additional information, i.e., investigate. This interpretation stage is common to all evacuation processes and can often contribute significantly to the total evacuation time.

The role-rule model

Behaviour sequences, i.e., how a specific person responds to a fire, have been shown to depend on the everyday role of the person [10,11], e.g., if he or she is a staff member or a passenger. Each role is associated with a set of behaviour rules. The rules can be seen as guiding principles associated to the role that a person has adopted, and they will influence the actions taken in a fire situation. Thus, a person who has adopted a passenger role will not respond in the same way as a staff member. For example, if a station manager is a person of authority during normal operation the same trend can also be expected in case of fire. This was illustrated in the King's Cross fire, in which passengers where reluctant to initiate evacuation even though information was given about the progressing emergency [7,20]. The passengers simply did not want to give up their objective to travel from A to B since it interfered with the rules connected to their roles as passengers.

Occupants' reluctance to evacuate is not unique for underground rail transportation systems. The same type of behaviour has also been observed in past fires in road tunnels, e.g., the fire in the Mont Blanc road tunnel in 1999 [1,2]. During everyday conditions the main objective of motorists travelling in a road tunnel is to drive through the tunnel. Unless given very clear and coherent instructions it cannot be expected of motorists that they will leave their car and evacuate in the event of a fire.
The affiliative model

Another model that greatly aids the understanding of human behaviour in the event of fire is the affiliative model developed by Sime [12,13,14]. The affiliative model offers another possible explanation for motorists’ reluctance to leave their vehicles. The model dismisses the physical science model, which assumes that people always choose the shortest evacuation route when evacuating in an emergency. Instead, the affiliative model assumes that people are more likely to be drawn to places or people that are familiar to them [12,14]. This often means that people choose to evacuate the same way they entered the building, due to its familiarity, and also that the evacuation often takes place within groups to which the person has previous ties. In a road tunnel it is likely that a person's vehicle is more familiar than the outside environment, which to a person can be perceived as both unfamiliar and scary. Consequently, it is argued that people avoid unfamiliar escape routes simply because they are unfamiliar.

To further demonstrate the affiliative model Sime [14] studied a post fire investigation and concluded that the staff members, regularly using a fire exit as a personal entrance and thus familiar with it, used this exit more consistently than the public who were not familiar with it. In the same study he could also see that the three main factors that influence the direction of movement and choice of exit in an evacuation are:

1. A person’s role, e.g., staff member or visitor, and their familiarity with escape routes.
2. A person’s ties to individuals in other parts of the building, e.g., family members and friends.
3. The proximity of emergency exit doors.

The affiliative model should hence be considered in the fire safety design to ensure that the environment supports an efficient evacuation. It is for example perhaps better to design an underground station with two everyday exits also designed as evacuation routes, rather than one everyday exit and two emergency exits. Naturally everyday exits cannot be used everywhere. However, in these cases the fire safety designer must understand that extra measures or systems have to be installed in order for those exits to be used in an emergency.

Social influence in evacuation

In addition to the behaviour sequence model, the role-rule model and the affiliative model, experimental findings also suggest that the presence of others, i.e., social influence, is likely to impinge on a person’s decision to evacuate [15]. Furthermore, a distinction can be made between normative and informational social influence [16,17].

Normative social influence is defined as an influence to conform with the positive expectations of another, where positive expectations means expectations that leads to a positive feeling when fulfilled by another, i.e., the prevalent norms. In other words, people in general are afraid of standing out or making fools of themselves, and their individual judgments therefore often conform to the believed expectations of others. Informational social influence is defined as an influence to accept information obtained from another as evidence about reality. This means that people in general tend to copy the behaviour of other people when uncertain about how to behave [16].

From a design perspective the human behavioural theories are simply not possible to use in engineering calculations. Instead a simpler engineering model is needed in order to describe how the behavioural aspects shall be considered and an egress time-line model is widely used. This model is based on a comparison between the available safe escape time (ASET) and the required safe escape time (RSET) [8]. Although the egress time-line model is a valuable tool for the fire safety design of underground transportation systems, it is an engineering model that provides limited guidance towards the understanding of human behaviour. The model is hence not used in the present paper to analyse human behaviour in fires in these types of facilities.
FIRE INCIDENT APPLICATIONS

The theories described above can be applied to the behaviour patterns observed in many fire accidents in underground transportation systems. To demonstrate this, one well known fire is described and analysed in the context of the theories. In addition, a fire incident is also presented as it demonstrates the importance of clear information provided to the persons involved, in order for them to make a proper decision. The examples presented in this paper are two road tunnel cases but the theories can of course also be applied on other construction types, e.g. underground stations and rail tunnels. A more comprehensive review of human behaviour in tunnel fires is provided by Shields [21].

Burnley Tunnel, Melbourne (2007)

On March 23, 2007, a traffic accident involving both trucks and cars resulted in a fire in the Burnley Tunnel in Melbourne, Australia [22,23]. The tunnel, which is 3.4 kilometres long, runs under the Yarra River and was at the time of the fire used by around 100 000 vehicles per day, of which approximately 14 000 were trucks. It consists of three lanes and traffic is only allowed to travel in one direction. Evacuation routes from the tunnel consist of emergency exit to the adjacent Domain tunnel or an emergency egress tunnel [23]. There are also three safety shelters and one lift to the surface. A total of three people were killed in the fire, all of whom were involved in the initial collision.

The accident occurred around 1.4 kilometres inside the tunnel, just at the end of a downhill grade. Due to a tyre blow-out a truck was forced to stop in the left lane (Australia has left-hand traffic). This was recognized by the CCTV system, and around two minutes later the tunnel operator closed the left lane and also reduced the speed limit by changing speed signs in the tunnel. However, the driver of a second truck did not acknowledge the halted truck and initiated a collision including five cars and three trucks. The collision was followed by a number of explosions. According to Dix [22] a fire generating tens of megawatts was instantaneously initiated. The cars in front of the accident were able to drive out of the tunnel. However, approximately 400 people in 200 vehicles had to evacuate.

Emergency procedures were in place very quickly, which meant that people received many cues in the early stages of the fire. Around thirty seconds after the collision the tunnel operator initiated an emergency response, which among other things meant that the tunnel was closed. Ninety seconds after the collision at least two radio messages had already been broadcasted in the tunnel, the smoke extraction system had been started, and the fixed sprinkler system had been activated. People quickly left their vehicle and walked either back to the tunnel entrance or used an emergency exit leading to the Domain Tunnel. None of the evacuees were injured by the fire.

The people involved in the tunnel fire seem to have taken action very quickly. One explanation for this rapid transition is that people were provided with many clear cues and the uncertainty in the initial phase of evacuation was therefore minimised. The first cue was probably the explosion, which was also mentioned by many survivors. Other cues, which all were presented within a few minutes, include smoke from the fire, radio messages, activation of the sprinkler system, activation of the smoke extraction system, etc. Also, people could see others evacuating which is also a powerful cue (informational social influence) that prompts people to evacuate. The Burnley tunnel fire is hence a good example of the type of fast response that can be expected when people, having the role of motorist, are given clear and coherent information.

The choice of exits in the Burnley tunnel fire can partly be explained by the affiliative model. Some people chose to evacuate to the tunnel entrance in spite of the fact that they observed an emergency exit to the Domain tunnel. This is illustrated by a group of people who began to use an exit to the parallel tunnel, but who changed their choice of exit when realising that the emergency exit led to the Domain tunnel [24]. One possible explanation for this behaviour is that the Burnley tunnel was seen
as a more familiar environment, and that it was therefore chosen in accordance with the affiliative model.

A combination of a fast response from the tunnel operator, and the effectiveness of the fixed fire suppression system and the ventilation system seem to have contributed to the few deaths and injuries. Furthermore, the damages to the tunnel were so small that it could re-open in the next couple of days. It seems as if the motorists took the radio broadcasted messages seriously, because they initiated an evacuation quickly. Johnson and Barber [23] argue that the success of the emergency management system was due to a combination of pre-planning, fire drills and other training.


The fire incident in Årsta Tunnel on 16 June 2008 started in the truck engine, which made the truck driver to stop well inside the tunnel, in the left lane (Sweden has right-hand traffic). The Årsta tunnel is part of a tunnel system, Södra Länken, in Stockholm and important for providing Stockholm with a rational traffic environment. The tunnel is unidirectional with 2-3 lanes (depending on the location) and has a length of 3,8 km. The fire as such was rather small but obviously it created a lot of thick smoke. Fortunately, no one was injured at the incident but the remarkable is the behaviour of the motorists arriving to the tunnel and being in the tunnel at the incident [25].

When the fire had been detected the alarm was activated, which included information signs with the text evacuate the tunnel. In Södra Länken a number of information signs are located just beneath the ceiling, which can display messages to the motorists. In the case of a fire the Traffic Management uses the signs to communicate to the motorists about what they shall do. The intention with the signs in case of a fire is that the motorists shall behave in a way to decreases the hazard to themselves i.e. to evacuate the tunnel. By doing so the rescue services can safely get access to the location where the fire is without being hindered by the motorists driving in the tunnel. To achieve this desired effect it is extremely important that the motorists also interpret the message on the information signs in this way. If the system is poorly designed people can easily miss it or interpret it in an inappropriate way and this was exactly what happened in the fire incident the 16th of June.

The message on the information signs said ‘Evacuate the tunnel’. The intention was that motorists should have stopped in the tunnel, exited their vehicles and evacuated on foot through one of the emergency exits leading to the parallel tunnel tube. However, some motorists interpreted the message differently; they continued to drive through the tunnel, though the dense smoke, and passing the location of the fire on their way out. The interpretation is clearly not wrong considering the conditions the drivers were faced with. In their mind the obvious task would be to, as quickly as possible, leave the tunnel, i.e., to evacuate the tunnel. As they were driving a vehicle it was natural to evacuate with the vehicle as that would lead to an even faster evacuation compared to leave by foot.

The theoretical models presented earlier; the affiliative model and also to some extent the role-rule model can explain this type of behaviour. The role-rule model can explain the fact that the motorists followed the directions provided to them by the authority, in this case the Traffic Management. Though, perhaps not by behaving as was previously intended. But continuing with the task that usually is the normal in this situation is supported by the message as the motorists interpreted the message. This is proven by interviews by some of the persons involved, they assumed the correct behaviour was to drive out of the tunnel after having read the message. This behaviour is also supported by the affiliative model presented by Sime saying that people do and choose what is the familiar in the current situation. In this case, to continue to drive in an ambiguous situation, following what others are doing, which is a typical example of social influence from others on the behaviour of motorists driving after others. The interpretation was to leave the tunnel and the most obvious way to do this was by continue to drive through the tunnel, not to leave the vehicle and walk away from the fire.

CONCLUSION
The theories of human behaviour reviewed in the paper can aid tunnel designers to design the tunnel evacuation system that supports decision-making in the case of an emergency. For example, the role-rule model can help the designer to understand the difficulties associated with initiating evacuation at an underground station where people have the role of passenger, and thereby help him or her to come up with appropriate design solutions. As has been shown in the two fire cases the behaviour of the people can be explained by human behaviour theories and if used in design they can lead to a safer environment for persons being in a tunnel in the case at fire starts.

REFERENCES

Ways of improvements in quantitative risk analyses by application of a linear evacuation module and interpolation strategies

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Abstract
The application of various methodologies of quantitative risk analysis have shown, that the calculation of casualties is either extremely work intensive (in case of models based on the accumulation of flue gases) or cannot cover all required aspects of the self rescue process (in case of limit based models).
Furthermore it is necessary to perform this calculation of casualties subsequently with a variation of fire location vs. nearest emergency exit and based on simulations of fire development and smoke propagation on a certain number of locations in the tunnel and with different traffic scenarios in order to get representative numbers for the assessed tunnel.
In order to understand the necessity of further improvements in the area of egress simulation the paper starts with a short overview of currently available methods and how they are applied. Then the modified tool for egress simulation in a tunnel environment is presented as well as the application in risk analysis and the strategy of interpolation in order to minimize the amount of time consuming three dimensional simulations of smoke propagation.

Keywords: Quantitative risk analysis, egress simulation, accumulation model, traffic statistics, interpolation

Current situation
For the calculation of casualties in a tunnel fire as representative input values for the subsequent analysis in an event tree or a probabilistic network there are currently two models available which widely differ in approach and application. The following paragraphs will give a brief summary and outline their strong and weak points:

1. Limit based evacuation simulation

These models are widely in use (e.g.: Germany, Japan, etc.) because they are relatively simple in application and do not require automated routines for calculation of casualties numbers.
The idea behind the model is that self rescue fails if visibility drops below a certain level. For this purpose the visibility is derived for a height of 1.8m above walking surface by use of three dimensional fluid dynamics simulation environments.

Pros:
- The calculation of casualties can be easily performed in 'ruler and pencil' style on a printout of the furthest point affected by smoke vs. time if limited to a limited number of scenarios and locations (i.e. the fire is always exactly in front of one emergency exit)
An extended application can be programmed (quite) easily allowing to subsequently shift the fire location vs. the configuration of emergency exits in order to get representative numbers for the entire tunnel.

Cons:
- Let's assume a tunnel equipped with smoke extraction via air duct and dampers over the entire length. After the fire starts the smoke will be carried away by the longitudinal airflow in the tunnel until the fire is detected, ventilation system is activated and the exhaust fans deliver enough exhausted volume in order to reverse the flow on the downwind side and remove the smoke from the tunnel.
- People in this part of the tunnel will be exposed to the smoke and flue gases only for a short time and would probably survive, even if staying in place until environmental conditions have improved but in the model they are accounted as victims.
- This results in problems when performing relative comparison of a longitudinally ventilated tunnel with a tunnel equipped with smoke extraction or transversal ventilation as the benefits of transversal ventilation systems are underestimated by relying on this method.
- The results will always depend on the chosen limit for successful self rescue. Therefore the casualties’ numbers need to be calibrated to real scenarios. (Un)Fortunately the data on this side is still very limited. Furthermore the calibration will only be valid for one type of tunnel (i.e. calibration for a longitudinally ventilated tunnel should not be applied in a transversally ventilated tunnel)
- If the intention is to simulate the egress of different kinds of agents with differing walking speed, reaction times, etc the model gets as tricky to implement as an accumulation based model

2. Accumulation based evacuation simulation

Accumulation based evacuation models are mainly used in commercial evacuation environments such as buildingExodus [3] or open source projects as FDS+Evac. They are normally based on the theory of accumulated intoxication by Purser [1], [2] and assess the effects of concentration and duration of exposure. These programs also allow for simulations on a two dimensional evacuation grid and simulation of bottleneck problems such as doors and sidewalks. The idea is to calculate the total amount of flue gases the evacuating agent has accumulated over the entire period and compare it to a given threshold or probit function.

Pros:
- As the theory is calibrated to human physiology and not to a low number of widely differing incidents that have occurred in the past the model can be applied for comparison of different ventilation systems with a high accuracy.
- Some simulation environments allow the input of gas concentrations for different levels (walking level, crawling level)
- Different kinds of agents can be defined in order to create a set of agents (persons) representing the country's population
- Undesired reactions, drop of egress speed in poor visibility, congestion forming at emergency exits etc. can be included.

Cons:
- Data transfer from CFD environment is extremely time consuming unless there is a link between CFD and evacuation environment which is only the case if both are purchased from the same supplier (FDS+Evac)
Results depend on the density of input data, i.e. the spacing between two zones should not be larger than a maximum of 20m. This is because the data (visibility, concentrations) is constant over the zone which leads to inaccuracy in agents' reaction and intoxication.

As the distribution of agents in the evacuation grid is arbitrary the simulation has to be rerun a certain number of times in order to obtain a representative average.

The simulation has to be rerun with different fire location vs. nearest emergency exit in order to obtain a representative value for the entire tunnel.

**Requirements for evacuation tool**

Because of these limits in application the intention was to develop a new easily applicable tool for the simulation of the self rescue process during tunnel fires which combines the benefits of both approaches. Basically the requirement was the design of an integrated tool for egress simulation in direct combination with quantitative risk analysis methodologies for road tunnels.

This leads to the following requirements for the evacuation tool:

- Capability of dealing with different types of hazards (such as convective heat, radiating heat, carbon monoxide, carbon dioxide, hydrogen cyanide, visibility, etc.)
- Capability of simulation of different types of agents with different attributes (such as age, walking speed, etc.)
- Possibility of defining a number of people which react the wrong way (like staying in their vehicles, walking the wrong direction, etc.)
- Possibility of defining the exact positions of emergency exits
- Possibility of direct data import from CFD simulation results
- Compatibility with office applications as MS Excel

On the other hand there are a number of features which are available in complex evacuation environments which are not needed in this case. These are:

- 2-dimensional evacuation grid (the width of the tunnel is negligible against the distance to the next emergency exit)
- Simulation of congestion in front of bottlenecks (the total number of people in a road tunnel is not large enough and they don't arrive at the door at the same time)
- Simulation of crowd behavior such as patience, social interactions, etc. (experience with application of two dimensional accumulation based simulation environments has shown that the density of people is not large enough in road tunnels)

**Implementation**

Based on these requirements a linear evacuation tool was implemented in VBA with the following functionality:

The input data is imported from .csv files containing the local environmental parameters for various inclinations covering the tunnel's minimal and maximal inclination. Ideally the data should be available in time steps as short as possible. Same is true for the spacing in between the locations the environmental parameters are recorded. If the spacing is larger than one the data has to be interpolated in order to get environmental data at the agent's position with an accuracy of 1m at every second.

The effects of gas concentrations are evaluated by the following formulas based on the research of Purser [1], [2], [4], [5]:

Intoxication by carbon monoxide:

$$FICO = \frac{3.317 \times 10^{-7} \times CO(t)^{0.36} \times RMV}{PID}$$

(1)
Intoxication by hydrogen cyanide:

\[ FICN = \frac{e^{-tHCN}}{220} \]  

(2)

Intoxication by carbon dioxide:

\[ FICO_2 = \frac{1}{e^{6.1623 - 0.5189 \times CO_2(t)}} \]  

(3)

Effects of hypoxia (lack of oxygen):

\[ FIO_2 = \frac{1}{e^{8.13 - 0.54 \times (20.9 - O_2(t))}} \]  

(4)

Increased respiratory volume by increased concentration of carbon dioxide:

\[ VCO_2 = e^{\frac{1}{2} \times CO_2(t)} \]  

(5)

The overall intoxication at a given time is obtained by integration over the total time of exposition:

\[ FIN = \int_{t_{\text{exp}}} \left( FICO + FICN + FICO_2 \right) \times VCO_2 + FIO_2 \, dt \]  

(6)

In addition to the effects of toxic gases the effects of radiant and convectional heat is taken into account:

Convective heat:

\[ FIH_c = 2.0 \times 10^{-8} \times T(t)^{3.4} \]  

(7)

Radiant heat

\[ FIH_R = \frac{60 \times q(t)^{1.33}}{D_r} \]  

(8)

The total effect of heat at a given time is obtained by integration over the total time of exposition:

\[ FIH = \int_{t_{\text{exp}}} \left( FIH_c + FIH_R \right) \, dt \]  

(9)

Furthermore the impairment of flue gases, heat and poor visibility have negative influence on the agents' egress velocity [3]:

Effects of intoxication on agents' mobility:

\[ M_I = \begin{cases} 
1, & FIN \in [0; 0.9] \\
0.9, & FIN \in [0.9; 0.95] \\
0.8, & FIN \in [0.95; 1] 
\end{cases} \]  

(10)

Effects of poor visibility on agents' mobility:

\[ M_S = 1.105 - 0.488 \times K - 0.161 \times K^2 \]  

(11)

Total influence of intoxication and poor visibility on agents' mobility:

\[ V = V_I \times M_I \times M_S \]  

(12)

If one of the impairing effects - total intoxication or heat - reaches the threshold of 1 the agent is accounted as incapacitated and the egress cannot be completed without assistance.

Definitions:

- \( t \) ...................................................................... Time [min]
- \( CO(t) \) ................................................................. Concentration of carbon monoxide [ppm]
Application for a given tunnel
This procedure is repeatedly applied for each of the 6 types of agents with 3 different initial walking speeds each and at all initial positions in the tunnel resulting in zones without the chance of self rescue for a given fire location. By moving the fire location along the tunnel in 1m steps a risk map of the tunnel can be drawn if sufficient data is available. This means that the simulation of smoke propagation normally has to be simulated for different locations in the tunnel and traffic situations. Particularly in case of bidirectional tunnels the location of the fire and the distribution of traffic (symmetric of highly asymmetric) have a large influence on the longitudinal velocity and therefore the propagation of smoke.

An overview of influencing factors is given in Figure 1. The effects of these influencing factors is calculated by means of a relatively simple one dimensional fluid model and applied as boundary condition to a representative section of the given tunnel in the three dimensional simulation of smoke propagation.

Figure 1: Influencing Factors and application in CFD model
Some of the listed factors such as time of closure, reaction time of the ventilation system etc. can be assumed as constant as they are either physical properties of the tunnel or defined in the methodology. Other factors such as traffic volume and symmetry show large variations and have a significant impact on the longitudinal airflow in the tunnel. Unfortunately it is not possible to cover all these parameters with high resolution variation and perform three dimensional simulations. Therefore the focus is to cover important factors with a certain number of variations in the numerically intensive CFD and egress simulations and to use interpolation strategies in between these support points.

*Figure 4 and Figure 5* illustrate how such an approach can increase accuracy and quality of a risk analysis for a given tunnel.
Scenario selection and interpolation strategy
In a first step the traffic data for the tunnel needs to be analyzed. This data can either come from an automatic counter in close proximity of a tunnel project, measurements in an existing tunnel or the prediction based on specific time variation curves for day, week and year. For further use as basis for the selection of representative scenarios the data is converted into a histogram.
If the aim is to perform 3 sets of three dimensional simulations of smoke propagation the normalized area under the graph needs to be divided by 3 and the scenario to be simulated has to be the center of the section. These three scenarios will be used as representative for low traffic, medium traffic and high traffic.
Additionally the fire location in the tunnel needs to be altered. This is to take effects into account that occur when the traffic comes to stop behind the fire. Especially in bidirectional tunnels this can have high influence on the longitudinal airflow and therefore the propagation of smoke. The minimum required number of locations in a tunnel depends on the tunnel's properties but should be at least 2 in case of a tunnel with constant longitudinal gradient and 3 in case of tunnels with changing gradient (tunnels with high point).
For each of these scenarios the smoke propagation is simulated in a three dimensional CFD environment (FDS) and the environmental data is recorded in 1m and 1s spacing for use in the egress model described above.
As the next step the egress simulation is performed with an alteration of the fire location in 1m steps over the tunnel. If more than one location has been simulated in 3d the smoke data (visibility, concentrations, etc.) from the first simulation is applied from the left portal to the first scenario location. In between first and second scenario location the data (lengths of zones without self rescue) is interpolated in a linear way. This approach of interpolating zone lengths is also a valid approach in case of changing gradient in the tunnel the interpolation of local concentrations on the other hand is not. This results in a precise risk map which shows the potential casualties for a fire at any place in the tunnel and with the traffic volume selected as representative scenarios.
By combining the risk map for each type of agent and the share of the agent in the tunnel's population the average number of casualties for the selected traffic scenario can be calculated.
Finally the traffic statistics can be used to obtain a distribution of the frequency of events by combining the histogram of traffic volume with the accident rate/fire rate as a function of traffic volume. In order to apply the data obtained by the simulation of egress for the selected scenarios in the most precise way the numbers of casualties are interpolated in a linear way for traffic volumes in between the minimal and maximal scenario. Below the minimal and above the maximal scenario the numbers are constant.
This results in a fairly accurate number of victims per fire incident. At the moment the limit of accuracy is the availability of computational power and therefore the number of numerical simulations that can be run for one risk analysis.

Example for benefits of higher accuracy
The approach of interpolation of results of three dimensional smoke propagation and application to a wide range of traffic volume was applied in terms of the dangerous goods risk analysis of a motorway tunnel in Germany (ref. Figure 3).
The methodology for dangerous goods risk analysis compares the calculated FN curves to an accepted line. If the FN curve is entirely below the accepted line the tunnel can be opened to dangerous goods vehicles. On the other hand the tunnel needs to be closed to either certain groups.

![Figure 3: Example where the normal approach does not fulfill the criteria but the accurate one does](image-url)
Figure 4: Procedure of calculating average casualties for a given traffic distribution - part 1
Figure 5: Procedure of calculating average casualties for a given traffic distribution - part 2

REFERENCES

RING! RING! ... ‘Fire in the facilities of Hagerbach Test Gallery! I have hit a vessel with some liquid with the fork lift. I am slightly injured and not really sure about ……’. Then, the ‘victim’ lost consciousness.

INTRODUCTION

Safety and security of underground facilities must be seen in a new context since we are able to go deeper and deeper with facilities for passenger transportation and services related to convenience goods. In the frame of ERRA Task A5 – ‘Safety and Security of underground hubs’, and together with the annual main training event of the public volunteer first responders of the region Flums, Switzerland, an evacuation exercise was organized in the facilities of Hagerbach Test Gallery. Involved parties included the Rescue Service Center of Sankt Gallen, both Heads of the regional Fire and Police Departments as well as two groups of visitors and the ERRA A5 partners. For the iNTeg-Risk partners, the main objective of the exercise was to prove and evaluate the Emerging Risk Issues which have been defined in the first phase of ERRA A5.

In order to better understand the ERRA A5 point of view with regard to the evacuation exercise, Emerging Risk issues identified for underground facilities will be explained first.

EMERGING RISK ISSUES

ERRA A5 is dealing with “Safety and Security of underground hubs with interconnected transportation..."
services and shopping centres”. So why are underground hubs considered as an Emerging Risk Representative Application? Given the technological development in the underground construction area and, in addition, the increasing need for public transportation, more and more tunnels are built and underground spaces are used for more than only transportation of passengers. New construction methods allow deeper tunnels and hubs, interconnecting several modes of transportation with shopping malls or parking spaces. As tunnels and underground facilities in general are built and used for almost 150 years, a close look at specific issues will explain what makes related risks new and emerging.

Partly, it can be seen as a result of new technologies or as a consequence of changing boundaries, environment or society for instance as well as technical issues (in the very context with underground infrastructure and safety installations). Even perception is subject to change due to incidents happening and rising awareness of the specific risk related to confined spaces. Perception as a driver of human behaviour can also cause or solve critical incidents. This is relevant where lots of person need to share very limited space available – like in underground hubs.

As soon as it comes down to safety and security, vulnerability of a system is an important issue. Vulnerability is always linked to specific risks. Regarding underground hubs, it is the spatial concentration of activities and infrastructure which makes the system vulnerable in case of incidents where persons have to escape or to communicate or to orientate or a combination of all of these. Growing underground hubs are complex infrastructures. Complexity can provide safety, as it may be more difficult to really hurt the system. But complexity can make a system also very vulnerable, as the reaction on incidents is complex too and requires a high level of interaction between system components, stakeholders and users (which of course are stakeholder as well). General development leads to changing boundary conditions and thus emerging risk. The risk may change due to new technologies, the increasing number of transportation systems and due to construction challenges such as depth and new types of architectural solutions. The need for mass transportation systems increases all the time which in turn press the engineers to come up with solutions which can overcome the limits for conventional knowledge in safety. It is difficult to predict when these boundaries may be exceeded. The only way to predict it is to do theoretical analysis of possible risks and consequences.

Complex hubs may vary considerably in structure and architectural solutions. This means that there are numerous technical solutions that need to be considered. As architectural challenges make it possible to build different types of hubs, one challenge is to find the critical points before incidents occur. The complexity consists of the number of different transportation systems, for example metro, trains, busses, terminals and the multiplication of the activities in the hubs, with shops, pubs, events and restaurants. The complexity controls the emerging risks, because complex system with many passengers increases the emerging risk. The risk together with the consequence dictates the emerging risk, and what countermeasures should be implied in order to reduce the risk.

Deeper stations mean that emerging risk increases. Evacuation becomes more difficult to handle, both for the operator of a hub, the safety persons on-board of the transportation vehicles and the traffic controllers. The deeper a system is, the more difficult is it to keep track on people that are in the system. If the system is both complex and deep, the emerging risk increase as there will be more parameters to control for the safety responsible and those who have to take care of the consequences, i.e. the rescue team, which has its base up on the ground, far away from the real accident, and people needing assistance.

To describe the problem, a certain set of Emerging Risk Issues may be taken into consideration being aware of the fact that these ERIs are aiming for making the emerging risk measurable and quantifiable by KPIs but never will cover the whole range of difficulties and challenges emerging from deepness and complexity of underground hubs with a large and broad variety of stakeholders involved. Consequently, ERRA A5 has introduced ERIs trying to cover all dimensions of the Emerging Risk Management Framework ERMF with the following result:
ERI 1 – Passenger volume
ERI 2 – Escape routes
ERI 3 – Ventilation
ERI 4 – Orientation
ERI 5 – Communication

All of these Emerging Risk Issues are significantly changing when underground facilities are going deeper and developing more complexity whereas complexity is growing in geometries of tubes and subsurface spaces, but also in terms of users including passengers, professionals, operators, action forces, whomever. The involvement of several stakeholders, e.g. constructors, operators, users and first responders, is leading to a challenging situation in case of an incident followed by the need for evacuation, for example. Being aware of this emerging risk and offering solutions how to manage such a situation, will increase the users’ trust in underground infrastructures and facilitate the safe use and operation of underground transportation infrastructures. The innovation needed is a new concept for both the design of ventilation and escape routes as well as a concept for evacuation respecting our society changing with regard to age distribution.

Impact of new technologies is a term that becomes important when considering emerging risks. Based on the complexity, the depth and the need for technical information to the people that need to escape, the technical protection system plays an important role. The impact may vary considerably depending on how the system can be backed up by personnel and controller. If a train is driverless, one could expect more difficulties because there is no person that can give orders to people on how to evacuate and call for help. So driverless trains are from an operational point of view very good for the operators of the transport system, but from a safety point of view it may create some difficulties.

Figure 2: Map of VSH Hagerbach Test Gallery
THE EVACUATION EXERCISE

In general, the evacuation exercise can be observed from two different points of view – an external and an internal one. From the external point of view, persons were alerted, and then communicated and tried to understand and react on a specific situation of emergency which happened in the location of the complex facility. The external view is a rather general, with better overview of the whole situation but lacking knowledge about details of the incident. During the exercise, some involved persons have changed from the external to the internal point of view. Consequently, they had access to other information and did face problems different from the ones they have had before. The internal point of view is the one of the persons having been present in the facility when the alert was launched. They had very limited information, concentrated to the particular location where they were. At the moment of the alert, the internal view – even if in a different way – was shared by the victim, his colleagues and employees of VSH and one group of visitors led by a guide through the facility.

In the following section, all five ERIs will be discussed from both points of view, including some changing views of persons groups depending from their external or internal sight to the evacuation and the incident as a whole.

ERI 1 – Passenger volume

*External point of view*
In the very beginning, external persons had no information about how many persons were in the facility. When arriving at the VSH, the incident manager was able to find out the number of persons in the facility from the RFID based access control system. What he did not know in the very first moment, was whether or not more persons than the victim only would be involved in the accident leading to the fire. However, the number of persons in the facility was one of the most important information for the incident management on site, since evacuation and the rescue of all persons must be guaranteed.

*Internal point of view*
From the victim’s point of view, this was no issue any more as he lost consciousness. For other VSH employees it was a big issue, of course, because they did know about their colleagues being in the facility and the guided visitor group. In the moment of the alert, they did not exactly know where the guided group was located at this particular moment. The group members in fact where not really concerned about whatever passenger volume, whereas the guide was really keen on keeping all persons together – by permanently being in contact with them (he had chosen one person being the last one in the group) and taking care of their safe evacuation through the emergency exit.

ERI 2 – Escape routes

*External point of view*
VSH is a network of galleries with many possible escape routes depending on three criteria which are • first of all where an incident happens,
• secondly the specific ventilation conditions at this moment, and
• last but not least where persons are in the moment of the incident.

Following, the incident management can not know from the very beginning who will use which escape route to leave the facility. Even worse, he can not know how many persons are located where in the facility. At least, he can quickly find out access and escape route from and to the main entrance where he was entering the facility to find out more details about the situation. Furthermore, he did quickly know about the second exit to the open air which is the end of the fire test gallery.

*Internal point of view*
Of course, the employees of VSH did exactly know where to go as they are well acquainted with the network of tunnels, tubes and galleries of the VSH facilities. From their point of view, the complexity of the tunnel network is an advantage in such a situation, since it offers most of the time – and wherever you are – more than one option to escape. So far the situation regarding safety of their own life. Another aspect is the check for other persons in the facility. During normal operation, the employees are not necessarily informed about other persons, colleagues or clients, in the facility. So when escaping, they quite easily can take care of their own safety – but there is always some uncertainty left to the question for other persons being in some parts of the tunnel network.

Also for the guide of the visitors group, it was very clear from the moment when he heard the alert where to leave. Guides are familiar with the facility as well, and in this specific exercise, the visitors group was lucky enough to just passing the fire test gallery when the alert was launched. The fire test gallery has a direct exit to the outside. But still, a little bit strange in that situation is the fact that you leave the test facility without having any idea for what reason – and the severity of the incident.

ERI 3 – Ventilation

External point of view
In case of an incident with fire, ventilation of course is one of the most critical issues, as air streams in underground facilities heavily influence the environment of potential escape routes. The external point of view – the one of the incident commander – is a rather uncertain and difficult one, since one needs to understand the actual ventilation situation in the facility. Understanding air streams, knowing about the location of the incident/fire and knowing the emergency modes of the ventilation control system are needed to take a decision on whether or not to activate whatever ventilation mode. Support to the incident commander was given by our General Manager, who was contacted immediately – since he is part of the alert chain – and a couple of minutes later on site.

Internal point of view
Persons internally involved in the incident are not really aware of the ventilation issue. Possibly, in other types of facilities (especially when you have steep slopes in your underground facilities) it would be a great benefit it they were. In the specific case of the VSH evacuation exercise, people in fact did not really think about ventilation, since air streams are quite slow and smoke distribution was not too fast due to the small amount of smoke produced. So for those not being familiar with VSH, it was just the easiest way to leave facility without thinking about it. For VSH employees, it would be an option to think about activating the emergency mode in case they are sure what is needed. During the exercise, the ventilation system was not activated by internal persons.
ERI 4 – Orientation

External point of view
Orientation from external point of view includes getting overview of the situation in terms of locations, means what happens when and where, who is involved and where, and how to distribute available action teams. The incident commander, he is from the fire brigade Flums, has a map of the VSH facility. This is part of the VSH safety concept, that the fire brigade has base information of our facility available at any time. As he knows the facility, it is not too difficult to get overview of the location. On the other hand side, the psychological pressure on persons must not be underestimated, since we also made the experience, that one person well acquainted with the test gallery wanted to quickly show where something happened and was really not aware that he held the map of the facility upside down in his hands. The second “episode” was that the first team of the fire brigade did not immediately find the incident site, respectively the fire – at least not at their first attempt. They had been misled by smoke that they found in another gallery connected to the incident site. So the criticality of orientation in underground facilities was well proven by these two details of the evacuation exercise.

Internal point of view
As long as persons in an underground facility well know where they are, orientation is no big deal, of course. Employees can easily create their virtual map of the situation in their minds, as they see what is relevant for them. This is not the case, if you have persons in underground facilities which are not familiar with their location. In such a situation the danger of panic of course is significant.

Figure 4: Bridge between external and internal communication

ERI 5 – Communication

Possibly, the distinction between external and internal points of view regarding communication is not the most clever approach, since communication is about exchanging information from the different points of view in order to create a common operational picture. However, the idea was to keep the approach – in terms of consistency of this paper’s concept – and elaborate on how communication is contributing to bring all these different pieces of the jigsaw puzzle together.

External point of view
The external communication is triggered by the emergency call to the call center in St. Gallen. They inform the fire brigades in charge of the specific area as well as medical services and the police. Once first responders have received the alert with some base information, there is hardly any more information available until they reach the incident site. As soon as the first fire brigade teams enter the facility, they gather information and communicate with the incident commander in order to contribute
to clarify the situation. This is the first bridge from the internal to the external persons. Of course, the incident commander needs to get a clear and complete picture of the incident, so he has great interest in setting up communication to internal persons. He is immediately observing the site and positions persons to specific locations in order to contact all persons leaving the facility through whatever exit. By entering the facility, searching for the incident site and victims and working on solving the situation, the incident commander closes the loop from external to internal communication.

**Internal point of view**

Internal communication starts at more than one places. First of all, the emergency call is coming from inside. The alert system of VSH was activated as well. Following internal communication starts at every place where people are at the moment of the activated alert signal. The internal communication is much less target oriented, since people are just organizing themselves and as soon as they feel safe there is no need for further action – until they are approached by the fire fighter to pick them up in order to gather information from their point of view and experience of the incident.

As a general remark, communication may be seen like a shadow behind all of the other emerging risk issues, since communication is important for orientation, to decide and control ventilation modes, to inform people not familiar with the facility about escape routes and – last but not least – to get an idea of the volume of persons being involved in the incident. So communication is the critical link between all ERIs.

**CONCLUSION**

The evacuation exercise was a very interesting experience involving all relevant stakeholders of an underground facility, i.e. Owner/operator, employees, visitors, different types of first responders and emergency centers. For VSH, it was useful to prove the operational functionality of the safety concept including some improvements which have been made based on the experience of the exercise and on discussion with the corresponding authorities.

As a conclusion regarding iNTeg-Risk, all Emerging Risk Issues were proven through the evacuation exercise. In addition, criteria for the development of Key Performance Indicators have been identified as a result of the work done in ERRA A5 and the evacuation exercise.

ERRA A5 partners include VSH Hagerbach Test Gallery (Switzerland, Task leader), SP (Sweden), STUVA (Germany) and INERIS (France).

**KEYWORDS:** Emerging risk, deep underground facility, safety, security.

Table of figures:

- Figure 1: Organisation of the evacuation exercise ................................................................. 637
- Figure 2: Map of VSH Hagerbach Test Gallery ................................................................. 639
- Figure 3: Incident command on site ...................................................................................... 641
- Figure 4: Bridge between external and internal communication ........................................... 642
DESIGN OF VOICE ALARM SYSTEMS
FOR TRAFFIC TUNNELS:
OPTIMISATION OF SPEECH INTELLIGIBILITY

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ABSTRACT

The design and optimisation of voice alarm (VA) systems for traffic tunnels is discussed. The acoustic conditions in traffic tunnels are generally very hostile to sound systems. The present study focuses on the improvement and optimisation of speech transmission quality under these conditions. Electroacoustic guidelines are given for the design of VA systems in tunnels on the basis of a dedicated Asymmetric Boundary Flare (ABF) horn. A new optimisation tool is introduced which measures STI using the STIPA method and calculates the required pre-filtering of the speech signal to achieve optimum intelligibility under the actual acoustic conditions in the tunnel. This optimisation algorithm has been tested by measurements on site. The results show that a significant improvement of speech transmission quality can be realised in traffic tunnels.

KEYWORDS: voice alarm systems, public address, speech intelligibility

1 INTRODUCTION

Tunnel owners and operators around the world have realised the need for public address/voice alarm and announcement systems in tunnels. This is because they provide the only means of communication between tunnel operators/emergency services and the passenger in the tunnel once they are outside of their vehicles. These systems have to meet stringent criteria with respect to speech intelligibility. Unfortunately, the acoustic conditions in traffic tunnels are generally very hostile to sound systems, caused by the long reverberation and the high ambient noise levels.

In order to achieve sufficiently high levels of speech intelligibility several measures are available. First, increasing the direct-to-reverberant ratio by taking room acoustic measures such as adding acoustic absorption. This is often very costly and impractical. Secondly, reducing the background noise by applying quieter ventilation systems. Technically this is possible, but not always realised in practice. Moreover, the noise caused by the traffic itself cannot be eliminated, giving a fixed lower limit for the background noise.

The alternative is to use dedicated, highly directional loudspeakers. For this purpose Duran Audio developed the Asymmetric Boundary Flare (ABF-260) horn. Due to the high front-to-back ratio of the directivity pattern and the relatively low signal distortion, a significant improvement of sound quality and intelligibility can be realised in tunnels.

A well-established objective measure of speech transmission quality is the Speech Transmission Index (STI). Although speech transmission quality is not the same as speech intelligibility, it's often used as such.

In many situations the intelligibility of speech in noise may be assumed to be independent of the presented sound level and is primarily determined by the signal-to-noise ratio. However, at high speech levels, the subjective intelligibility is found to decrease. This decrease is not predicted by the original STI. For that reason, level-dependent auditory masking was introduced in the latest revision
of the STI standard (IEC 60268-16:2003). As a result the objective rating of speech intelligibility by means of STI changed dramatically for PA and VA systems in tunnels. The STI of a sound system producing high sound levels (up to 105 dBA) is rated significantly lower using the revised standard, compared to the old standard (dated 1998). As a result it has become very hard or even impossible in many situations to meet the minimum STI requirements in tunnels.

To overcome these problems, in this paper a dedicated STI measurement and optimisation tool is introduced; the OpSTImizer®. Using this PC based measurement and filter optimisation tool the STI can be measured using the STIPA method and the required pre-filtering of the speech signal is calculated to achieve optimum intelligibility under the actual acoustic conditions in the tunnel. This new method has been tested extensively by on site measurements.

2 ACOUSTIC CONDITIONS

2.1 Operating scenarios for PA/VA

A PA/VA installation will be used in various situations, like calamities, accidents and also less pressing problems such as traffic jam or car breakdown. These situations can be divided into a few, clearly discernable scenarios. Each scenario should be well described regarding:

- target audience, e.g., one person or all persons in the tunnel.
- position listeners in the tunnel, e.g., in car or next to vehicle.
- traffic speed, e.g., high speed traffic in case of a broken car on the emergency lane, or slowly moving or standing traffic in case of a traffic jam.
- ventilation active or inactive.

For each of these scenarios the minimum speech transmission quality requirements should be met. The two most important factors that affect speech intelligibility are the acoustics of the tunnels and the ambient noise spectrum of the traffic and the ventilation system.

2.2 Reflections and reverberation

The acoustic conditions in traffic tunnels are generally very hostile to Public Address (PA) and Voice Alarm (VA) systems. Speech intelligibility is often severely compromised. Due to the low sound absorption coefficients of the acoustically hard finishes of the inner tunnel surfaces, the reflections are hardly attenuated. This leads to a long reverberation time and high reverberant level. As a result the ratio between the level of the direct sound of a loudspeaker and the excited reverberant sound field is very poor. Further, the long reverberation time also contributes to the high background noise levels in the tunnel. Both factors have a detrimental effect to speech intelligibility.

In a typical traffic tunnel with hard finishes (concrete or tiled walls and ceiling, asphalt concrete road surface) the reverberation time is usually very long and ranges from a few seconds at higher frequencies to more than 10 seconds in the low-mid frequency bands. The reverberation time and reverberant level could be reduced by taking acoustic measures such as adding acoustic absorption. However, these measures are often very costly and impractical from a maintenance point of view.

2.3 Background noise

As discussed above, speech intelligibility of PA and VA systems in traffic tunnels is also compromised by high ambient noise levels. The two main noise sources in tunnels are traffic noise and ventilation noise. The sound levels caused by the ventilation fans can be very high (up to 100 dBA), depending on the positioning and the type of fans.

The traffic noise mainly depends on the traffic speed and is caused by the car and truck engines and the tyre noise. With a traffic speed of 100 km/h the sound level is about 95 dBA. Table 1 shows some
typical octave band levels for various noise sources measured in the Schipholtunnel\(^1\), in The Netherlands.

Table 1: Some measured noise spectra in the Schipholtunnel, The Netherlands

<table>
<thead>
<tr>
<th>Noise source</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>2 kHz</th>
<th>4 kHz</th>
<th>8 kHz</th>
<th>Total (A-weighted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast traffic</td>
<td>90</td>
<td>85</td>
<td>88</td>
<td>92</td>
<td>88</td>
<td>74</td>
<td>62</td>
<td>95</td>
</tr>
<tr>
<td>(100 km/h)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fans w/o deflectors</td>
<td>89</td>
<td>86</td>
<td>86</td>
<td>82</td>
<td>81</td>
<td>85</td>
<td>83</td>
<td>91</td>
</tr>
<tr>
<td>Fans w/ deflectors</td>
<td>94</td>
<td>94</td>
<td>94</td>
<td>91</td>
<td>84</td>
<td>85</td>
<td>82</td>
<td>96</td>
</tr>
</tbody>
</table>

From the above it's clear that in order to obtain a sufficiently high signal-to-noise ratio, high speech levels are required. On the other hand, the signal levels shouldn't exceed 105 dBA in order to avoid hearing damage. This puts severe demands on the quality of the loudspeakers that are used. Particularly, the maximum long term (RMS) SPL specifications and the distortion figures are very important.

3 SPEECH TRANSMISSION QUALITY

A well-established objective measure of speech transmission quality is the Speech Transmission Index (STI). Although speech transmission quality is not the same as speech intelligibility, the STI method can be used to predict or to measure the speech transmission quality with respect to intelligibility. The STI is expressed as a number between 0 and 1. In table 2 the STI values and the corresponding ratings are summarised.

Table 2: Rating of speech transmission quality by means of STI

<table>
<thead>
<tr>
<th>Speech transmission quality</th>
<th>STI [-]</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.75-1</td>
<td>Excellent</td>
</tr>
<tr>
<td></td>
<td>0.6-0.75</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>0.45-0.6</td>
<td>Fair</td>
</tr>
<tr>
<td></td>
<td>0.3-0.45</td>
<td>Poor</td>
</tr>
<tr>
<td></td>
<td>0-0.3</td>
<td>Bad</td>
</tr>
</tbody>
</table>

The preferred method to measure STI in traffic tunnels is the STIPA method. This STIPA method requires a special test signal consisting of several simultaneously modulated frequency bands, having a male frequency spectrum. In contrast to impulse response methods, using MLS noise or swept sine signals, the STIPA method is able to measure the STI reduction due to harmonic distortion of the loudspeaker. Impulse response methods require a linear system, as distortion will cause undesired measurement artefacts.

With the introduction of level-dependent auditory masking in the latest revision of the STI standard\(^2\) (IEC 60268-16:2003), the objective rating of speech intelligibility by means of STI changed dramatically. As a result, the STI of a sound system producing high sound levels (as in tunnels) is rated significantly lower using the revised standard, compared to the previous standard (dated 1998). To illustrate this effect, the (revised) STI for a single, perfect loudspeaker (with a flat frequency
response and no distortion) in a reflection-free, noiseless environment (free field conditions) as a function of the sound level of male speech is plotted in Figure 1.

![Figure 1: Revised STI as a function of the sound level of male speech (no reflections, no noise).](image)

The 'stair cased' curve is generated using the current STI standard. The smooth one is calculated in a way which the level dependent masking is not divided into 10 dB intervals, as in the current standard, but an interpolated function of SPL. It's clearly shown that STI is “penalised” when the sound level exceeds 75 dB(A). In fact if the system is operating at 105 dB(A) then the maximum achievable STI (i.e., under anechoic conditions) is around 0.72. According to the 'old' 1998 STI-standard the STI would be (close to) 1 for all sound levels.

Under more realistic acoustic conditions, i.e., with reverberation and ambient noise, the effect of level-dependent auditory masking on the STI is less severe but still significant. For a typical tunnel PA/VA system producing a sound level of 105 dBA at the receiver positions, the "penalty" in the revised STI is close to 0.1. From this it is evident that achieving the specified STI values under real-life tunnel conditions has become even a greater challenge. As a complicating factor, the minimum STI specifications have also become more demanding over the last years.

4 DEDICATED TUNNEL HORN

Conventional horns (e.g. re-entrant horns) exhibit a limited frequency range and a relatively high signal distortion. Moreover, as the acoustic output of a single horn is often too low, often horn clusters are used. This clustering causes undesirable effects in the frequency and polar response.

To improve sound quality and speech intelligibility, Duran Audio developed the Asymmetric Boundary Flare (ABF-260) horn, as shown in Figure 2. The ABF-260 can be used in road traffic tunnels to form a part of the voice alarm and announcement systems.

![Figure 2: ABF-260 tunnel horn](image)
The Asymmetric Boundary Flare (ABF) geometry is based on the principle of acoustical mirroring. The ABF is designed to be mounted on the ceilings of a road tunnel. The ceiling acts as a large boundary plane. As the acoustic centre of the ABF is very close to the ceiling, the ABF and its mirror image can be seen as one acoustical source with twice the sound pressure. In contrast to a conventional horn, which has to be mounted at some distance from the wall or ceiling, no sound pressure cancellations due to phase difference between the direct and reflected sound will occur over a wide frequency range. This principle is illustrated in Figure 3 and 4.

**Figure 3:** Acoustic mirroring of a conventional horn compared to the AXYS® ABF-260

**Figure 4:** SPL distribution (direct sound+ceiling reflection) in the vertical plane in a tunnel for of a conventional horn mounted 0.2 m below the ceiling compared to the AXYS® ABF-260 (octave centre frequencies 250 Hz to 4 kHz)
The ABF-260 is driven either by a 50W or a 100W 2" compression driver with a 100V impedance transformer. Figure 5 shows the measured half-space directivity balloon for the ABF-260 mounted against a horizontal boundary plane. Besides the high directivity, the balloon exhibits a very large (>20 dB) front-to-back ratio, which is a desirable feature when using multiple ABF horns in a tunnel. In addition, the ABF has an extended frequency response up to 8 kHz.

**Figure 5: Measured half-space directivity balloon (500 Hz-2kHz average) for the ABF-260 mounted against a horizontal boundary plane**

### 5 DESIGN GUIDELINES

As ambient noise can be as high as 100 dB(A), signal levels of up to 105 dB(A) are necessary. Higher levels are to be avoided to prevent hearing damage. Although the sound level of an ABF horn in a tunnel only slowly drops with distance (typically, 2-3 dB over 50 m), the maximum spacing between ABF horns should be limited to sustain sufficient signal-to-noise ratio. Typically, a spacing of 50 m is required in most situations. A typical set-up for a "two-lane" tunnel tube is shown in Figure 6.

**Figure 6: Typical ABF set-up for a "two-lane" tunnel tube (maximum width approx. 15 m).**

The ABF horns are positioned along the centre line of the tunnel and should be aimed opposite to the traffic direction. Near the exit two ABF horns are mounted to cover the entire width of the tunnel. In order to create a coherent sound wave through the tunnel, each horn should be delayed back to the time-zero horns near the exit.
In tunnels tubes wider than approx. 15 m usually two or more ABF horns are required every 50 m in order to obtain a sufficiently high sound level and adequate coverage across the width of the tunnel. This is illustrated in figure 7.

![Figure 7: Typical ABF set-up for a wider tunnel tube (width >15 m).](image)

### 6  OPTIMISATION OF SPEECH TRANSMISSION

#### 6.1  The OpSTImizer

In order to obtain optimum speech transmission quality in tunnels using the ABF horns, a dedicated STI measurement and optimisation tool was developed which is introduced here; the OpSTImizer®. Using this PC based measurement and filter optimisation tool the STI can be measured using the STIPA method and the required pre-filtering of the speech signal is calculated. The optimisation procedure is as follows:

1. First, measurements are done at a number of relevant receiver positions in the tunnel using a flat EQ setting of the system. Usually 5 to 10 measurements are sufficient. Each measurement takes about 16 s. The STIPA signal should be played at the actual sound level that is required in the tunnel. In this way any degradation due to harmonic distortion and the appropriate masking levels in the STI calculation are taken into account. As the measurements are usually carried out in a "noise-free" situation (no traffic, no fan noise), the expected worst case ambient noise spectrum is added mathematically to the STI algorithm.

2. On the basis of the measured modulation transfer function including the additional ambient noise spectrum, the optimum filter for the system is calculated by the OpSTImizer algorithm. The software immediately predicts what the expected STI will be using this filter.

3. The filter settings are transferred to the Axys PB800 Amplifier, which is recommended to be used in combination with ABF. Next, the final measurements are carried out to verify the actual STI values using the optimum filter.

This new method has been tested by measurements in several traffic tunnels. The results of two of these on site measurements will be discussed.

#### 6.2  Test set-up 1

The first test set-up was built in a 1.6 km long tunnel tube. The width of this tube was 15 m and the height was approx. 5.5 m. The inner tunnel surfaces were acoustically hard. No absorptive measures were taken. The set-up in the 15m tube consisted of four progressively delayed ABF-260/100W horns with a spacing of 50 m, as shown in Figure 8. The set-up was built in the middle of the tunnel, far away from the entrance and exit.

All four ABF horns were active, but only the STI in the last three 50m sections was evaluated. The first ABF was merely used to build-up the sound field. The measurement positions were positioned along the centre axis of the tube (row 1) and along a parallel line, 1.5 m away from the side wall (row
2). The distance between the measurement positions was 5 m. The microphone height was 1.5 m above the road surface.

![Figure 8: ABF test set-up and measurement positions in the 15m wide tunnel tube](image)

Before the final measurements were done, the STI was measured at 10 positions in the first relevant section (0-50m) with a flat system EQ. The playback sound level was set to 103-105 dBA and for the STI calculations a fast traffic background noise of 95 dBA was assumed (see Table 1). With a flat EQ the mean (revised) STI is 0.39. According to the old 1998 STI standard the STI would have been 0.47. On the basis of these measurements the optimum filter was calculated using the OpSTImizer algorithm and was transferred to the PB800 amplifiers. Next the STI was measured along the two measurement rows, starting at 0 m to 150 m, as indicated in Figure 8. The results are displayed in Figure 9. Using the optimised filter the mean STI for the 95 dBA ambient noise condition equals 0.49 with a standard deviation of 0.02. Without background noise the mean STI equals 0.53.

The results show that a significant improvement of speech transmission quality can be achieved by applying adequate pre-filtering of the signal.

![Figure 9: Measured STI values in the 15 m wide tunnel tube using optimised signal filtering and assuming 95 dBA fast traffic noise. Signal level is 103-105 dBA.](image)

### 6.3 Test set-up 2

The second test set-up was realised in a parallel tube having a width of 20 m. The length and the height of the tube were identical to the previous one. The set-up in the 20m wide tube consisted of four pairs of progressively delayed ABF-260/100W horns with a spacing of 50 m, as shown in Figure 10.
Again, all four ABF sections were active, but only the STI in the last three 50m sections was evaluated. The first pair of ABF horns was merely used to build-up the sound field. The first measurement row was positioned along the centre axis of the tube. The second parallel row was on-axis to one of the horns in each pair. The third row was 1.5 m away from the side wall. The distance between the measurement positions was 5 m except for the third row where a spacing of 10m was used. The microphone height was 1.5 m above the road surface.

Before the final measurements were done, the STI was measured at 14 positions in the second section (0-50m) with a flat system EQ. The playback sound level was set to 103-105 dBA and for the STI calculations a background noise of 95 dBA was assumed (fast traffic, see Table 1). Using a flat EQ the average (revised) STI is 0.41. According to the old 1998 STI standard the STI would have been 0.49.

On the basis of these measurements the optimum filter was calculated using the OpSTImizer algorithm and was transferred to the PB800 amplifiers. Next the STI was measured along the three measurement rows, starting at 0 m to 150 m, as indicated in Figure 10. The results are displayed in Figure 11.

Using the optimised filter the mean STI for the 95 dBA ambient noise condition equals 0.48 with a standard deviation of 0.03. Without background noise the mean STI equals 0.51.

The results show again that a significant improvement of speech transmission quality can be achieved by applying adequate pre-filtering of the signal.
7 SUMMARY AND CONCLUSIONS

In this paper the design and optimisation of voice alarm (VA) systems for traffic tunnels is discussed. Due to the hostile acoustic environment it is very hard to obtain sufficiently high levels of speech transmission quality. With the introduction of level-dependent auditory masking in the latest revision of the STI standard (IEC 60268-16:2003), the objective rating of speech intelligibility by means of STI changed dramatically. The STI of a sound system producing high sound levels (up to 105 dB(A) as in tunnels) is rated significantly lower using the revised standard, compared to the old standard (dated 1998).

In this paper a new measurement and optimisation tool is introduced; the OpSTImizer®. Using this PC based measurement and filter optimisation tool the STI can be measured using the STIPA method and the required pre-filtering of the speech signal is calculated to achieve optimum intelligibility under the actual acoustic conditions in the tunnel. This approach has been verified by extensive measurements. The results show that a significant improvement of STI (+0.1) can be realised.

8 REFERENCES

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2. IEC 60268-16 3rd edition 2003-5 Sound system equipment, objective rating of the speech intelligibility by speech transmission index.
Emergency Escape and Evacuation Simulation in Rail Tunnels

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ABSTRACT
Evacuation and escape from rail tunnels suffer from some typical difficulties. Rail tunnels are characterized by widely different safety standards, particularly with respect to the distance of emergency exits (no exits, one exit every 1'000 m, every 500 m or every 300-350 m). Additionally, varying numbers of passengers in trains complicate the estimate of escape time and therewith the assessment of the safety level in tunnels. The different tunnel characteristics and regulations are briefly discussed. Then different calculation and simulation approaches for evacuation are briefly reviewed. The escape time for different tunnel geometries, trains and person loads is calculated using a commercial microscopic simulation tool. Based on the resulting evacuation times, a simple, linear correlation is presented, which allows estimating the escape time in function of the main parameters emergency exit distance, person density and escape velocity.

KEYWORDS: Emergency escape, evacuation simulation, railway tunnel, evacuation time

1 INTRODUCTION AND OBJECTIVES
In underground traffic infrastructures the safety of persons represents a primary concern. The kinds of incident and problems faced depend mainly on the structure considered. In underground infrastructures, such as road tunnels, rail tunnels or metros, fire generally represents the highest risk for persons. Thereby not the fire itself but the smoke produced endangers the persons, as smoke is easily transported by air currents and can spread very rapidly, especially in closed environments like tunnels or underground stations. The highest priority for all safety systems is enabling adequate conditions for the self-rescue phase. Underground structures are usually characterized by adverse conditions (limited escape routes, limited space, high person densities, etc.). Uncontrolled smoke propagation in most cases represents an additional, extremely grave obstacle. Safety assessments are therefore best conducted as scenario analysis. The safety engineer’s task is basically the analysis of the tunnel conditions during the whole self-rescue process. For the evaluation of safety it is of primary importance analyzing the evacuation process and calculating the total evacuation time.

The present paper is focused on the analysis of the evacuation process from trains blocked in rail tunnels. Representative simulation results are presented and a simple expression for the quick assessment of evacuation time is developed based on the results. A critical discussion and a few recommendations complete the paper.

2 TUNNEL FIRES AND SELF-RESCUE
2.1 The Role of Self-Rescue
There are usually four levels of safety: 1. prevention, 2. mitigation, 3. self-rescue, 4. intervention and rescue. Evacuation or self-rescue plays a decisive role in case of incident. Successful and effective evacuations have to be completed as rapidly as possible. The allowable time span is actually dictated by the incident type and its development time scales. In case of fire, the available time for evacuation, which depends on smoke propagation velocity, can be estimated using design fire curves and physical
Different factors affect the time required for escape. These factors should be kept in mind when calculating evacuation times, since different simulation methods consider them on different levels:

- Geometric configuration
- Human behavior
- Fire development and smoke propagation.

### 2.2 Regulations

National and international regulations impose minimum requirements for the distance of emergency exits, for the width of emergency walkways and for other important safety elements.

<table>
<thead>
<tr>
<th>Guideline</th>
<th>Maximum distance between emergency exits (single / double tube) [m]</th>
<th>Minimum width and height of escape walkway [m]</th>
<th>Dimensions of emergency door [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSI – SRT (EU)</td>
<td>1'000 / 500</td>
<td>0.75 x 2.25</td>
<td>1.4 x 2.0</td>
</tr>
<tr>
<td>UCI – Code 799-9</td>
<td>1'000 / 500</td>
<td>0.7 – 1.2 x</td>
<td></td>
</tr>
<tr>
<td>SIA 197/1 (Switzerland)</td>
<td>1'000 / 500</td>
<td>1.0 x 2.2</td>
<td>1.0 x 2.0</td>
</tr>
<tr>
<td>EBA (Germany)</td>
<td>500</td>
<td>1.2 x 2.25</td>
<td>1.0 x -</td>
</tr>
<tr>
<td>BOSTRAB (Germany – city trains, metro)</td>
<td>600 (max. 300 m walking distance)</td>
<td>0.7 x 2.0</td>
<td></td>
</tr>
<tr>
<td>NFPA 130 (USA)</td>
<td>762 (2500 ft) / 244 (800 ft)</td>
<td>0.61 – 0.76 x 2.05</td>
<td>0.81 x 2.1</td>
</tr>
</tbody>
</table>

*Table 1 Minimum requirements for emergency exits.*

The maximum allowable distance between emergency exits is typically either 1’000 m or 500 m, depending on tunnel concept (single or double tunnel). This difference is certainly justified based on economic considerations, but not from the point of view of safety. Most recent long Alpine tunnels (particularly Lötschberg, Gotthard, LTF Lyon-Turin, Brenner etc.) have cross passages every 300 – 350 m. This represents de facto the state-of-the-art for long and very long single-track tunnels.

The different walkway dimensions have not a major influence on the evacuation process. Considering that a single person typically needs a path width of about 0.6-0.65 m, overtaking is not possible without leaving the walkway, especially with limited sight as it is the case in tunnels.

### 2.3 Human Behavior

Human behavior represents a multi-faceted, complex issue, which shall not be addressed in detail here-in. The crowd’s mood can stay calm or become panic, which implies the loss of social behavior and rush for an exit. However, the occurrence of panic during fire incidents is rare and the people concerned usually show rational behavior [9].

A further human factor is reaction time on alarms, i.e. the time from the beginning of the alarm or incident till awareness of the situation and beginning of escape. The reaction time is an individual property, changing from person to person, and can take up to several minutes. The differences result from different perceptions of the current situation. Thus, escape could be delayed by underestimating the thread of a certain incident (e.g. smoke in a room) or by ignoring an alarm signal (e.g. because it is considered as a false alarm) [10].

The third human factor presented here is the individual decision for an escape path. The choice of the escape path is influenced by crowd behavior like “herd instinct” (i.e. the natural tendency to follow the other persons and go with the crowd) or by specific knowledge of the building (usually one takes the same path out of a building as the one he used while entering). In tunnels, persons do not have
knowledge about the structure, they don’t know in which direction the closest exit can be found. Directional signs are usually provided for orientation but they could be covered by smoke or ignored due to stress. In such a case, crowd behavior will play a major role for the selection of the evacuation path (e.g. Kaprun fire in Austria).

Most simulation methods do not (or not properly) account for human behavior. In the best case this represents a boundary condition which has to be predefined. But it is possible considering different human characteristics. The influence of different individual properties like speed or size can be modeled.

2.4 Fire Development and Smoke Propagation
The absence of smoke on the evacuation path is crucial for the success of an evacuation. The presence of smoke drastically reduces the chances of a successful evacuation. The escape velocity is reduced due to the presence of irritant or poisonous gases and decreased sight, orientation becomes difficult. Depending on smoke concentration, loss of consciousness can occur after an exposure time of a few minutes or even seconds. Including the effect of smoke in escape simulations is quite difficult. Smoke propagation is coupled to the movement of air and hence to aerodynamics, whose simulation is generally quite challenging and time-consuming. Three different approaches could be used:

1. Smoke propagation is not calculated. The evacuation time is deemed acceptable if it is lower than a fixed threshold.
2. Smoke propagation and the evacuation process are simulated separately and independently. By superposing the two results, the exposure time to smoke and hence the influence of smoke onto the escaping people can be estimated.
3. Smoke propagation and the evacuation process are simulated in a coupled manner.

3 ESCAPE SIMULATION
3.1 Macroscopic - Fluid Dynamic Model
Fluid dynamic models are variable in complexity. The simplest allow for simple hand calculations. These models assume free walking speeds for wide areas and person capacity for stairs and doors. Thus the total evacuation time is estimated by adding the time needed to cover distances and the time spent for queuing in front of bottlenecks (e.g. doors, or stairs). This approach is illustrated e.g. in NFPA 130, which also specifies walking speeds and capacities for stairs, escalators, etc.

More elaborated methods (e.g. Predtetschenski & Milinski [4]) divide the evacuation paths into sections, for which path width, walking velocity and person density is determined. Thereby, escape velocity depends on person density in the corresponding section and can therefore change from section to section and over time.

Despite the different complexity levels of fluid models, they cannot entirely reproduce the reality since they generalize persons based on average characteristics. They represent, however, an excellent tool for carrying out rapid estimates, particularly in the early design phases.

3.2 Microscopic - Individual Model
Individual models account for individual influence factors, such as walking speed. The fee is the higher calculating effort required for this approach, because every individual person is accounted for separately. They all have an individual starting location, walking speed and body size. Particularly important is the ability to estimate the individual smoke exposure time and its influence on the evacuation process.

There are two approaches for simulating person movement used by individual models. Network methods separate the whole space in small fields. Thus, the person movement can be modeled by letting them jump from field to field. Some rules have to be considered for this movement, as e.g. occupied fields are blocked for entering. The second approach is the so called “social force model” as explained
e.g. in [7][8]. It assumes that every person is exposed to different forces with different direction and magnitude. One of these forces corresponds to the desire to leave the endangered zone with a certain velocity. Other forces arise from obstacles, like walls or persons. They are directed away from these obstacles and become stronger with decreasing distance.

Microscopic models are close to reality as they consider individual person characteristics and movement. However, while interpreting simulation results one shall keep in mind that it is still impossible to reliably reproduce social behavior (e.g. transition from rational behavior to panic, influence of “herd instinct” and movement of groups).

3.3 Validation and Practical Applications
The verification of escape-time calculation methods is based on comparison with egress experiments for simple geometric layouts and analysis of real evacuation events. Data from real events is better suited for the validation but quite rare and generally not sufficiently detailed. Most of the validation work was carried out based on data from experiments. For that purpose, clearly defined test cases, as e.g. proposed by RiMEA (Richtlinie für Mikroskopische Entfluchtungs Analysen) [11], are used. A particularly interesting investigation is presented in [6], which compares the results from microscopic simulation methods (ASERI 3.4c, buildingEXODUS V 4.0 Level 2, PedGo 2.1.1 and Simulex 11.1.3) and the method of Predtetschenski & Milinski [4]. It was found that the resulting evacuation times delivered by the different methods show small differences for low person density but considerably growing deviations with higher person density. The differences reach up to 100% of the evacuation time. The accuracy of the investigated methods might have improved in the meantime and the conclusion might no longer be entirely correct. However, these results show that caution and a critical use of simulation tools are necessary. Furthermore the validation with real experiments seems to be essential for obtaining good results. The simulation tool used for this work, ASERI [1], was validated in real escape experiments like the unannounced evacuation of a theatre described by Weckmann and Lethimäki [2] and in laboratory experiments (see [3]) with excellent results.

4 TEST CASES
4.1 Trains
The investigation accounted for two different train types, an intercity and a regional train. Both are common types currently in use in Switzerland. The first type, serving mainly intercity lines, is a double-deck train (the data for this train were based on the new IC2000 train). A composition consists of eight coaches with a total length of 200 m. Two of these compositions can be coupled together building a train with a total length of 400 m. Both lengths have been used for the investigation. The coaches have two stairs connecting the upper deck with the doors on the lower deck. Each coach has four doors, two on every side, measuring 1.4 m in width.

![Double-deck intercity train (type IC2000 by Bombardier & Alstom).](image)

The second type, serving mainly regional lines, is a modern low-floor train with a barrier-free interior.
The characteristics of this train are based on Stadler Rail’s FLIRT vehicle. The composition investigated consists of four coaches with a total length of 96 m. Up to three or four compositions can be coupled together and build trains with a total length of 298 m or 394 m. A fully modeled version of this train (including seat benches, compartments, toilets, etc.), consisting of three compositions, was used for the investigations. Each coach has four doors (two on each side), measuring 1.32 m.

Figure 2  FLIRT composition by Stadler Rail.

4.2 Populations
The simulations were carried out using different person loads, called populations. The populations were chosen based on experience from daily operation in Switzerland. The occupancy of intercity trains (see Table 2) was defined according to the number of seats available, which is 759 for the considered model of 200 m length. The number of seats in the real train is 696. Since local passenger trains often have no free seats, the maximum populations for these trains (see Table 3) were determined based on person density.

<table>
<thead>
<tr>
<th>Person number [200 m / 400 m]</th>
<th>Population denomination</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>784 / 1’568</td>
<td>Exceeding person load (UB)</td>
<td>All seats are occupied and additionally some persons are standing in the corridor</td>
</tr>
<tr>
<td>470 / 940</td>
<td>High person load (HB)</td>
<td>Two thirds of the seats are occupied</td>
</tr>
<tr>
<td>235 / 470</td>
<td>Medium person load (MB)</td>
<td>One third of the seats are occupied</td>
</tr>
<tr>
<td>89 / 178</td>
<td>Low person load (TB)</td>
<td>Almost no persons in the train (11% of maximum)</td>
</tr>
</tbody>
</table>

Table 2  Person loads of intercity train.

<table>
<thead>
<tr>
<th>Person number</th>
<th>Population denomination</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1’440</td>
<td>Exceeding person load (UB)</td>
<td>All seats are occupied and corridor is full of persons</td>
</tr>
<tr>
<td>864</td>
<td>High person load (HB)</td>
<td>All seats are occupied, a few persons are standing in the corridor</td>
</tr>
<tr>
<td>432</td>
<td>Medium person load (MB)</td>
<td>About two third of the seats are occupied</td>
</tr>
</tbody>
</table>

Table 3  Person loads of local train.

Within populations not only the number of persons is defined but also further properties like velocity and size of persons, which have an influence on the simulation output. For these two properties typical Gaussian distributions were assumed. Escape velocity is a widely discussed topic in the specialize literature (an overview is provided in [5]). It is influenced by person characteristics like age, sex and size. But also external factors such as temperature, path altitude and path slope have to be considered. There is statistical data too. However, all these data are not allowing for a specific prediction of the composition of a population and therewith of its “physical” characteristics, as time and location of a possible incident are unknown. Therefore, average values and standard deviations are used:
• Velocity = 1 / 1.3 m/s ± 0.4 m/s (see Figure 3, left)
• Body size = 0.13 m² ± 0.00055 m² (see Figure 3, right)

Figure 3  Distribution of individual walking velocity (left) and body cross-section (right).

4.3 Simulation Tool
The commercial code ASERI [1] has been used for the simulations. This software is a very well validated microscopic simulation tool, specialized for the simulation of escape processes. People’s behavior is influenced according to predefined and selectable options. ASERI supports several options for choosing the escape paths (shortest path, equal distribution of person load to exits etc.). All calculations presented herein were carried out with the option “dynamic decision”, which lets the individuals choose the escape path along which the fastest escape could be expected, considering walking distance and person density on the path (the result is an approximately balanced distribution of the person load for all exit paths). Further adjustment possibilities are alarm and reaction time. As the investigations were focused on the evacuation process itself, immediate reaction has been assumed. Alarm and reaction time were set to zero. There are additional possibilities provided by ASERI for influencing human behavior and person properties, but these were not used, or used with default values.

5  TRAINS IN A TUNNEL
5.1 Geometric Layout
Evacuation calculations were carried out for a train stopped in a single-track tunnel. The model considers an escape path with a width of 1 m leading to three emergency exits. The width of the escape route corresponds to one person lane, overtaking is impossible. The emergency exits were defined with distances of 333 m, 500 m and 1'000 m. It was assumed that the train is stopped in the tunnel with a fire located in the middle of the train. As a worst-case assumption under these conditions, the train is assumed to stop in such a way, that the fire is located in front of the central emergency exit. Therefore, this exit is blocked and passengers have to use the two remaining exits. The emergency exit doors have a width of 1.4 m.

Figure 4  View of the simulation set up for a double-deck train of 200 m length in a single-track tunnel with emergency exits.

The fire could of course be located on a different part of the train, e.g. in the foremost coach. Consider-
ing again the case where the train comes to stop at a location, where an emergency exit is blocked by the fire, only one escape direction and emergency exit would be available for all the passengers. Comparing qualitatively this scenario with the one presented in Figure 4, it is certainly worse for high person loads because the escape capacity is reduced. On the other hand the distance to the emergency exit is smaller for the last coaches. Therefore, the average evacuation time will be smaller for low person loads. Based on the results for the basic case illustrated above, the discussion of other situations is straightforward.

5.2 Results

Some illustrative results showing the detailed evolution of the evacuation process are presented in Figure 5. The results are typical for evacuation of trains in tunnels, where the space outside of the train is limited. The initial phase is characterized by a rapid decrease of the number of persons on the train. After some ten seconds the escape path near the train reaches saturation and the evacuation process of the train is slowed down to a value, which is constant until the end of the evacuation process. As shown in Figure 5, several executions of the same run lead to slightly different results. This scattering, typical for microscopic methods, leads to uncertainties reflecting the unpredictable factors of the real world. For the simulations conducted herein the uncertainty is of the order of 5% of the total evacuation time.

![Figure 5](image)

**Figure 5** Evolution of evacuation process for regional trains with high person load and emergency exit distances of 500 m (left) and 333 m (right).

![Figure 6](image)

**Figure 6** Scattering of result for regional trains with high person load and emergency exit distances of 500 m (left) and 333 m (right).

The duration of the evacuation process is dominated by a few geometrical characteristics such as the distance to the nearest exits or the width of escape path. The key parameter for geometrically identical set ups is the person density in the train, i.e. the number of persons per unit train length. Figure 7 shows clearly a linear dependency between evacuation time and person density for the three different emergency exit distances.
5.3 Synthesis

The evacuation time of trains in tunnels is higher at least by a factor 4 than on outdoor tracks. However, the same influence factors have to be considered, person load and train geometry. Additionally the distance of the emergency exits and the walking speed have a significant impact on the evacuation time. Based on the linear distribution of all results (see Figure 8) a simple expression was derived, that allows estimating the evacuation time in function of the variables emergency exit distance, train length, minimum of exit door width and walkway width, walking velocity and number of persons:

\[
T_{eva} = 0.7029 \cdot \frac{P_{train}}{1.465 \cdot c} + 1.863 \cdot \left(\frac{L_{exits} - 0.5 \cdot L_{train}}{v}\right) = 0.7029 \cdot T_{wait} + 1.863 \cdot T_{walk}
\]

(1)

\[
c = \min \left(\text{exit door width [m]}, \text{walkway width [m]}\right) \cdot 1.365 \left[ \text{P/m}^2 \right] \cdot v \left[ \text{m/s} \right]
\]

(2)

With:

- \(T_{eva}\) Evacuation time [s]
- \(P_{train}\) Number of persons on the train [-]
- \(L_{train}\) Train length [m]
- \(L_{exits}\) Emergency exits distance [m]
- \(v\) Walking velocity [m/s]
- \(c\) Person capacity coefficient [P/s]
- \(T_{wait}\) Waiting time scale [s]
- \(T_{walk}\) Walking time scale [s]
The aim while developing this simple correlation was not to calculate the evacuation time as accurately as possible, but rather to find a fast evaluation method allowing for rough but quick estimates applicable for a wide range of trains and tunnels. The difference between the estimated and computed evacuation times is presented in Figure 8. The standard deviation is 3.17 min and the average deviation 8%, which is comparable to the likely uncertainty of the simulated results. It can be concluded that the empirical correlation allows approximating the evacuation times in a manner, which is probably sufficiently accurate and reliable for most preliminary estimates.

6 FIRE SCENARIOS

The time available for evacuation depends mainly on fire characteristics and smoke propagation. The safety assessment for a given configuration can be best conducted by means of the analysis of the relevant fire scenarios. The smoke-propagation and evacuation process are simulated in a detailed manner, using CFD codes and simulation tools such as ASERI. The correlation presented in section 5.3 could integrate or replace the evacuation simulation. The safety assessment is based directly on the comparison of both times. Safety is achieved if, for every selected scenario, the conditions along the whole escape path are satisfying during the whole self-rescue process. This provides to every person involved a fair chance of safe escape.

The conditions along the escape path (thermal and radiant load, concentration of asphyxiating and irritant gases, visibility [12]) are evaluated using the results of three-dimensional simulations (CFD). Typical relevant toxic substances are CO, CO₂, and HCN. Our experience shows that the evaluation of visibility and thermal load is sufficient for most applications in design and design verification. A few illustrative results are presented in [15].

7 DISCUSSION

The simulations presented herein showed that the two main parameters influencing evacuation time are the distance between the emergency exits and the passenger density. The most important factor is the distance between the emergency exits. For low person densities evacuation time and emergency-exit distances are approximately proportional. The second factor of importance for evacuation time is passenger density, i.e. the total number of passengers divided by the train length. Again a proportional relation to evacuation time was observed. The train length has no significant influence of the evacuation time for the conditions considered herein. As shown in Figure 7, this allows developing a quite accurate linear correlation. The influence of different train or fire positions can be easily accounted for, at least on a semi-quantitative basis.

Looking at the evacuation time and at the smoke-propagation process in typical fire scenarios, it becomes obvious that emergency-exit distances above 1’000 m do not fulfill the requirement for a fair chance of self-rescue. Evacuation times in the range of 25 minutes are too large in case of fire with a significant intensity. For such events even distances of 500 m, with evacuation times between 12 and 17 minutes, are critical. If we consider that smoke, which was not considered in the simulations, would certainly lead to lower walking speeds and therewith to longer evacuation times, we can say that only in case of emergency exit distances below 500 m a fair chance for evacuation is given for most rail tunnels.

8 CONCLUSIONS

Safety assessments for existing and new critical infrastructures require the detailed analysis of a number of safety-relevant scenarios, in terms of evacuation and smoke propagation. The simulation of evacuation processes represents an essential tool. It allows identifying critical areas, particularly in large and complex structures, and helps devising safer solutions. Microscopic simulation models account for a number of real-life, safety-relevant issues and deliver particularly accurate and reliable results. Using commercial software tools, evacuation simulations can be carried out with limited effort. The computational resources needed depend on model size and person number, but most evacuation
Simulations for rail tunnels require only a few minutes on standard hardware. In spite of the apparent simplicity, attention should be paid to the simulation set up. Simulation software tools usually offer several options for certain parameters and boundary conditions, which influence the results. It is therefore important to have founded knowledge on real evacuation processes and on how to model them correctly with the particular simulation tool used.

A simple but accurate and reliable correlation for estimating evacuation time was presented herein. This allows for very quick estimates and can be used also in the early design phases. The comparison with a large number of simulations, carried out under a variety of conditions, showed that the results are probably sufficiently accurate for many safety-relevant applications.

In the future, simplified models and better computation capacity will allow using coupled smoke and egress simulation models for emergency management in large infrastructures. Such infrastructures are normally supervised and controlled from a command center using a SCADA system. In case of emergency such models will help evaluating the best strategy for the evacuation and emergency management in real time. The people to be evacuated can be guided along the fastest and safest path available to a safe area. Solutions for such applications are under development in the European research project EMILI (Emergency Management In Large Infrastructures).

9 REFERENCES

Experiment for behavior estimation in the egress using electronic devices in the SAVE ME Project

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ABSTRACT

SAVE ME [1] is an EU funded project, which aims at improving the safety of travellers inside transport infrastructure, with a focus on disadvantaged people. In particular, the project has the goal of developing a cellular phone-/smartphone-based system, which, in case of emergency, can provide travellers with information about the available means of egress and about recommended behaviors. At the moment, emergency procedures in big transport infrastructures, mostly underground, do not take the specific problems into consideration which are faced by families with children, elderly people, and physically or mentally challenged people during chaotic situations, when only limited information is available.

Recently, a growing number of strategies for reducing the consequences of emergencies have been developed, considering the use of smartphones or other electronic devices to help endangered people or rescuers take the safest and most appropriate actions.

In order to evaluate the impact of using only electronic personal devices to find escape routes from confined spaces, the SAVE ME project had planned to carry out some experimental activities. A laboratory experiment was carried out in a training facility of the Italian Fire Corps, with the participation of students and teachers from a public school. The experiment involved a total of 78 participants playing the role of evacuees. Among them were adults, children, teenagers and grandparents. In this paper, the impact of low signage conditions on the egress behavior is presented and discussed. In particular, the experiment shows that a locally installed signaling system is generally more helpful than cellular phone-/smartphone-guidance. Smartphones proved to be an effective yet less efficient guidance in the dark when no other physical support was available.

This paper will sketch the preliminary results of the experiment about egress behavior under the condition of low information (but not during emergencies), resulting in some general indications:
A. egress using electronic devices is possible
B. egress using electronic devices needs more time than natural egress
C. young people are more prone in using electronic devices and profit more from them when orienting themselves in low visibility environments

INTRODUCTION

The SAVE ME project is aimed at providing a technological system to aid in the rescue of civilians during emergency situations in traffic infrastructure, particularly metro stations and road tunnels. One of the many components of the system is a guidance tool for travellers consisting in two sub-systems meant to allow an efficient self-rescue. The first sub-system is a cellular-phone- or smartphone-based escape-route guidance tool for individuals, while the other one is a “collective herding guidance” tool and consists in dynamic signaling installations giving visual and audio cues for driving people away from identified sources of danger to safe spots, such as emergency shelters or exits. Both these sub-systems constitute the user interfaces available to the civilians, which they have to perceive, understand and interact with correctly in order to escape[1].

1 When talking about the “user interface” of the self-rescue system, we here refer to all physical and conceptual aspects of the technical systems the “users” or travelers come into contact with (Moran, 1981).
The experiment described here was organized to provide input to two tasks in the project: (i) the design of the user interface and (ii) the modeling of traveler behavior. The former is about making the developed technology highly usable, so that users will manage to escape from dangerous situation, in a shorter time. The latter is instrumental to implementing algorithms predicting crowd behavior, an important input for the calculation of optimal escape routes.

In order to help the interface designers, the experiment was meant to investigate if the provision of mobile guidance would increase or decrease the escape performances of the travelers. This would then allow to identify the best strategy for deciding when to enable mobile guidance: is providing mobile guidance always and to everyone a better strategy than providing it only for complementing the signal guidance when the latter does not respond to specific needs of a user or when signal guidance is not available (e.g., because of a damage having occurred during the emergency or because of bad vision conditions)?

In conducting the experiments, we researched the efficiency of test participants in escaping through a dark labyrinth, using either a certain type of mobile guidance, or installed guidance signals, or both of them. A general condition of all experiments was that all sources of information always provided the same, and the best, instructions for a quick egress. This has to be taken into account when drawing conclusions from the results. Under real conditions, different categories of travelers would need different kind of guidance, or certain sources of information (such as exit signs) may show wrong information to certain types of travelers. For instance, while physically intact people would be sent to a staircase for escaping to a surface exit, wheelchair users may need to be advised to roll to a safe place until rescue teams, also equipped with SAVE ME technology, will pick them up.

From the perspective of the simulation of behavior, the experiment was meant to provide input values: within the test, we measured the movement speed of the participants under predefined conditions, thus allowing the setting of some variables in the crowd simulation model. This was also designed to provide an answer to the question about how many times people choose the wrong way, so that an error-factor can possibly be introduced into the simulation.

A limitation of this experiment is its external validity: the possibility to extend its results to a real-life emergency situation. For ethical reasons, it was not possible to re-create a real emergency situation in a laboratory context. Users were put in a laboratory situation and they always knew that there was no real danger – and thus we cannot draw all kinds of conclusions. Although it would have been most interesting to know how people behave in a real emergency situation, we could not get to know it in this experiment. What we could do was to test traveler behavior under stress – and hope that their behavior during the experiment was going to be similar enough to the behavior of people in real emergencies. Stress can be induced in experimental settings, although it is not the same as the stress felt in a real emergency situation. Usually, researchers induce social stress, as on a biological level, the consequences are the same as those resulting from physical danger. In our experiment, decreasing visibility by providing only low light was expected to make it the setting more realistic and stressful.

Another limitation was the actual extent of the experiment. Since it is a small part of an R&D-project, and not a research work funded on its own, we had rather limited resources to use. Moreover, we had only a limited time to prepare the experiment, run it and analyse the outcomes, as the results needed to be fed quickly into the subsequent development work. As the facility is usually used by firefighters for training courses, we had a total of seven days for setting up, with just two subsequent full days devoted to carrying out the tests.

**RESEARCH HYPOTHESES**

SAVE ME aims at combining individual traveler guidance through a handheld end device, coupled with collective guidance through pre-installed signaling equipment in the investigated facility. As said
above, the experiment was intended to provide certain hints for behavior modeling and for the design of user interfaces. A more realistic situation that included, for example, displaying misleading information on the signals could not be tested.

Concerning our goal to provide input to the behavioral modelling, we did not need to make specific hypotheses. We just had to define the measurement dimensions for assessing the participants’ behaviors and collect the data.

The hypotheses we made refer to the user interface design. We approached this problem with the largest theoretical openness. Due to the many possible factors of influence determining the escape speed, we considered it impossible to predict ex ante if mobile guidance was better or worse for escape efficiency. Thus, we opted for a two-tailed testing approach, even if this comes with a loss of testing power (Bortz, 2005). Whether the mobile guidance would either positively or negatively influence escape efficiency, we considered both possible findings equally important. Looking for differences, again, was considered more important than trying to prove the different guidance solutions to be equally efficient on a statistically significant level. Thus, our hypotheses read:

H11: Travelers using an individual guidance on their mobile phone in an environment that does not feature any collective herding guidance escape more or less effectively compared to travelers who follow collective herding guidance only.

H12: Travelers using an individual guidance on their mobile phone in an environment that does not feature any collective herding guidance feel more or less overall workload compared to travelers who follow collective herding guidance only.

METHODOLOGY

This section describes the methods used in this experiment. This includes:

- the test design and the sample
- methods and materials used within the experiment, and
- the statistical analyses to be used for the interpretation of the results.

The test was conducted in a firefighters’ training facility, at the end of January 2011. The Italian Firemen Corps of the Ministry of Interior of Italy (CNVVF) is a partner of the SAVE ME project and owns a firefighter training facility in Montelibretti, Italy. The facility features a real-scale road-tunnel and a metro-tunnel, both used for training firemen in realistic catastrophic scenarios. The road-tunnel was chosen for the experiment given both its size that allowed several tests to be carried out in parallel, and the availability of blinds at its ends needed to create a dark indoor environment for the tests, much alike a realistic egress situation.

We mounted three different labyrinths within the tunnel, aimed at testing the travelers’ ability to orienteer themselves and escape using different orientation tools.

A distinctive approach of this research is that the experimental unit is not a single person but an “experimental subset”, i.e. a heterogeneous group of two or more persons. This approach takes into account that, in the case of an emergency, people who need to escape will not necessarily be alone – they may even depend on somebody. In reality, it is the performance of such subsets that counts. Parents, for example, are not expected to leave their children behind.

Usually, sample sizes are calculated taking into account both known variances of the variables to measure and expected effect sizes. However, in this case, there were not any previous data to draw values such as expected variances of the measurement variables from. Furthermore, the primary goal was not to prove an effect that is expected due to theoretical work. Thus, we could not base the sample selection on a test-power calculation. Instead, we oriented it at practical restrictions: we acquired the maximum number of participants that could fit into the two-day interval within which we were able to use the facility. As there were two experimental groups, we considered $N = 2 \times 20 = 40$ “subsets” as the minimum acceptable number. Thus, it was planned to recruit between 40 and 60 participants.
The sample was meant to represent the entity of people travelling in Italian traffic infrastructure – concerning their gender, age and disabilities. Nevertheless, people with critical disabilities, were excluded due to ethical and safety reasons. It should worth noticing that only Italian participants took part to the experiment. A first practical reason for this was that introducing people from other cultures we would have added another independent variable, thus either requiring an increase of the overall sample size or adding a limit to the interpretability of the results. Secondly, foreigners would have faced a higher personal risk (because of possible communication problems with local firefighters) and, finally, they would have required a higher budget for travelling to the Italian facility. For security reasons, people suffering from heart- or lung/breathing-diseases were not allowed to participate. In order to assure the participants’ safety, both the questionnaire to be filled in the forefield of the tests and the informed consent forms included a check for these kinds of diseases.

Six subgroups of the entire population of “travelers” were considered within the experiment. They are described in Table 1. We did our best to recruit an equal numbers of men and women. The percentage of special participants, such as children, was obviously higher than it would be in the real population of travelers. This was done on purpose, since (i) a special focus of the SAVE ME project is on vulnerable users, and (ii) we considered all types of users as equally “important” for being saved. This way, we were sure to have a sufficient number of test subjects within each group to calculate representative statistics, such as the mean moving speed. Our analyses of the results took this into account. With respect to the behavioral modeling, only group-specific values were used, while mean-values of the entire sample were not calculated. Concerning the testing of the hypotheses, we used the sample as it was because SAVE ME shall particularly serve the more vulnerable users. We did not want to decrease the influence of the needs of certain users (like children) only because they represent a rather small part of the entire population.

<table>
<thead>
<tr>
<th>User group</th>
<th>Description</th>
<th>Acquired subsets</th>
<th>Number of persons</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>1 child from primary school (5-6 y.o.), accompanied by 1 parent</td>
<td>12 groups</td>
<td>12 children, 12 adults</td>
</tr>
<tr>
<td>GRC</td>
<td>1 or 2 children from primary school (5-6 y.o.), accompanied by 1 grandparent (in good health and without physical impairments)</td>
<td>5 groups</td>
<td>7 children, 5 adults</td>
</tr>
<tr>
<td>Y</td>
<td>teenagers from junior high school (13 years of age.)</td>
<td>12 individuals</td>
<td>12 individuals</td>
</tr>
<tr>
<td>A</td>
<td>adults between 25 and 50 years of age</td>
<td>12 individuals</td>
<td>12 individuals</td>
</tr>
<tr>
<td>G</td>
<td>groups of 5 children, guided by 1 professor</td>
<td>3 groups</td>
<td>3 teachers, 15 children</td>
</tr>
<tr>
<td></td>
<td><strong>Total:</strong></td>
<td></td>
<td><strong>44</strong></td>
</tr>
</tbody>
</table>

**TEST SITE AND TEST DESIGN**

At the test site, three labyrinths were set up inside the road-tunnel. The tunnel was closed at its ends, so that the daylight could not enter (Figure 1). The construction of the labyrinths in the available confined space was a problem of its own. Actually, the labyrinths were set up by ramming a total of 200 poles into the ground. Then, thick, non-transparent polyester curtains were used to create the walls between the poles.
The participants were told that a real danger situation was being simulated and it was their primary objective to escape as fast as possible through a labyrinth.

Three experimental conditions were considered:

- **Experimental Condition 1** was a condition in which the participants were provided with the SAVE ME collective herding guidance only, in order to escape from the infrastructure. The information provided was always relevant with respect to the evacuation guidance, i.e. no misleading piece of information or noise was introduced.

- **Experimental Condition 2** was a condition in which the participants were provided with a prototype of the SAVE ME mobile guidance only, in order to escape from the labyrinth. All indications were consistent with the actual evacuation path. Yet there was not any “collective herding guidance”.

- **Experimental Condition 3** is a condition in which the participants were provided with both, a collective herding guidance and an individual guidance. The collective herding guidance showed the correct information needed to go to the exit; thus, we are able to test the real performance-increase or -deterioration due to the mere existence of individual guidance.

Experimental conditions 1 and 2 had been designed so that we could directly compare the efficiency of users using collective guidance in the one case and using the mobile guidance in the other case. Putting both, collective and mobile guidance in Condition 2, we would have run the risk that some people would not have used the mobile herding guidance and thus, we would not have been able to compare their efficiency. Experimental condition 3 served to determine what the users would do in a real scenario – and we do not need to compare their efficiency in this case to the “theoretical” efficiencies from Conditions 1 and 2.

The schemes of the labyrinths 1 and 2, used to compare the participants’ behavior in test conditions 1 and 2 were inverted (point-reflected) versions of the same structure. Thus, the paths were completely comparable yet learning effects were diminished. In Labyrinth 1, there were 4 correct right-hand choices and 6 correct left-hand choices. In Labyrinth 2, this was reversed. The external perimeter of each labyrinth was 19 m in length and 7.20 m wide. Each corridor of the labyrinths was 120 cm wide, assuming two 60 cm wide modules as the needed space for a walking person (according to current building criteria); this width was occasionally doubled at the entrance or exit of the labyrinths. The total correct path (i.e. not including possible wrong turns at forks) was 64 m. long for Labyrinth 1 and 2 and 57 m. for Labyrinth 3.

Labyrinth 3 served for the third experimental condition: The use of combined mobile and herding guidance information. This condition did not need to be comparable to conditions 1 and 2. Thus, a labyrinth was chosen that was similar to the others but not totally equal. In Labyrinth 3, there were 5 correct right-hand choices and 5 correct left-hand choices.
Design of the mobile prototype:
The device held by the participants during the experiment was a Windows Mobile 6-based PDA. At the time the experiments were conducted, the SAVE ME mobile guidance was not developed yet. Thus, we created a PowerPoint presentation that simulated the planned SAVE ME guidance application for smartphones. The concept of the guidance was basically the same of a picture gallery, known from Android OS and iPhone OS. Each segment of the way to the exit was represented by a photo of the next way-fork with an arrow indicating the correct way to take. These photos were ordered in a sequence and participants could pass through this sequence by pressing either a “previous” or a “next”-button.

Each of the way-forks (“bivio”, as shown in Italian in Figure 3) was numbered, in order to help the participants understand at which way-fork they currently were. This is justified for the following reasons: (i) compared to a metro station, in the labyrinth it is much more difficult to realize which way-fork one is currently at, (ii) the Labyrinth was dark and there were no architectural clues or posters on the walls to help the participant, furthermore (iii) sometimes two equally shaped way-forks followed in a row (e.g., Forks 1 and 2 in Labyrinth 1/2).

The users were assigned to the experimental groups by the following pattern:

<table>
<thead>
<tr>
<th>Experimental group</th>
<th>First Test</th>
<th>Second Test</th>
<th>Third Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Condition 1</td>
<td>Condition 2</td>
<td>Condition 3</td>
</tr>
<tr>
<td>2</td>
<td>Condition 2</td>
<td>Condition 1</td>
<td>Condition 3</td>
</tr>
</tbody>
</table>
During the course of the experiment, the participants were filmed using normal and thermal (infrared) video cameras. For each subset, the following variables were recorded:

1. **Time to complete**: The time that participants needed for the egress was measured at an accuracy of 1 second). The time was counted from the first step into the labyrinth (in the optimal case, a start line is provided on the floor and the test instructor sends the participants into the labyrinth) until the participant exited the labyrinth. The data is taken from the recorded videos. This allows also the calculation of the **Average speed**.

2. **Total Number of errors**: From the start to the completion of the labyrinth, the number of times that participants picked the wrong direction was counted. This includes entering into a dead end and going back to the beginning instead of continuing on the right track.

3. **Variance of speed**: When observing the video recordings, the observers divide the run through the labyrinth into segments. For each segment, the speed is calculated. Using these data, the variance of speed was calculated using the formula:

   \[ \text{Var}_{\text{speed}} = \frac{\sum (\text{Speed}_{i,x,k} - \text{Average speed}_{i,x})^2}{N_k} \]  

4. **Mean Decision Latency**: This is the arithmetic mean of the amount of time spent before each fork without moving, pondering which direction to take.

5. **Total time spent looking on the mobile screen**: For descriptive purposes, we detected how much time the participants spent looking at the screen of the mobile device.

6. **Satisfaction**: The perceived usefulness of the guidance system used was measured with some custom items, as we have not found any validated usefulness-scale that would help us in this case. However, items were formulated with similarity to existing instruments. All items had been phrased positively. As we have experienced that in long usability trials, people make more errors when items are inverted (because they do not see the inversion), we decided not to invert items. This is not critical here, as our only intent was to measure differences between the two guidance systems. Possible acquiescence-effects would equally affect all measurements. We could not test the instrument for its psychometric characteristics but we suppose that it consists of items pertaining to the following sub-dimensions: Efficiency of escape (E), Unambiguousness (usability) (B), Usefulness of the system (F), and overall system rating (O).

7. **Perceived difficulty**: We measured the subjective difficulty of the self-rescue through the labyrinth using the NASA TLX (Hart, 2006).

**PRELIMINARY RESULTS**

The complete analysis of the results will be a time consuming process, due to the fact that many gigabytes of video data need to be analysed, frame by frame, in order to detect and classify relevant events. However, here we will provide a selection of the most important results, using pre-calculated times and questionnaire data.

According to our preliminary values, there is a statistically significant difference between the egress efficiency in Conditions 1 and 2. With a mean of $M=04:33,7$ min of labyrinth-completion time
(SD=03:13,8 min), the participants spent nearly twice the time in labyrinth with the mobile guidance, than in the labyrinth with the signal guidance (M=02:39 min, SD=02.01,3 min). This effect is significant with p=.02 (T=-3.377, df=42). However, we see that there are large interpersonal differences. Some participants were equally fast in both conditions, while one participant needed 10:00 min more when using the mobile guidance.

There is a statistically significant difference between the mean values of the NASA TLX, which measures the workload. The analysis of variance between the 3 groups showed this effect (p=.032, F=3.619, N=39, df=1.98). In a subsequent t-test, we could identify the pair of Labyrinths 2 and 3 as the one with the only significant difference (p=.02, T=2.433, df=39). With a mean of M=4.1 (SD=2.81), the workload was significantly higher in the condition with mobile guidance only, than in the condition where both navigation sources were available (M=3.1, SD=2.45). As a statistically not-significant trend, such an effect is also visible in a comparison between conditions 1 and 2, where the mean of condition 1 is M=3.50 (SD=2.87) and the mean of condition 2 is M=4.11 (SD=2.82) (p=.130, T=-1.548, df=38). The different means for condition 1 for the different comparisons are due to missing values.

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**Time to complete the labyrinth**

![Time to complete the labyrinth](image)

Fig. X: Time needed to complete the labyrinths 1 and 2 (mean values and standard deviations).

**NASA TLX**

![NASA TLX](image)

Fig. X: NASA TLX scores of all three experimental conditions (mean values and standard deviations).
The satisfaction measured with our own, not-validated questionnaire seemed to show a ceiling effect, as the majority of the participants scored between the values 4 and 5, with 5 representing maximum satisfaction. Due to the small standard deviations, the small differences between the mean values came close to being significant ($p=.065, T=1.896, df=41$). This small difference between $M=4.8$ (SD=0.29) using the herding guidance and $M=4.7$ (SD=0.42) should obviously not be overinterpreted here.

The participants’ behavior in the third labyrinth (and their subsequently uttered preference) tells us more about their attitudes than these basically equivalent answers to a questionnaire which was unable to detect any differences in satisfaction between the experimental conditions. In the third labyrinth, 30 of the 44 subsets mainly used the collective herding guidance, 2 mainly relied on the mobile guidance, and 12 relied on both systems equally. Thus, the herding guidance was significantly preferred ($p=.00, \chi^2=27.455, df=2$). The same can be stated for the question about which system they would use in the future: 28 would mainly rely on the collective herding guidance, 5 on the mobile guidance and 11 on both ($p=.00, \chi^2=19.409, df=2$).

A difference in the egress time depending on the strategy chosen in Labyrinth 3 could not be proven ($p=.334, F=1.128, df=2$).

**DISCUSSION AND FUTURE WORK**

The preliminary results of this test seem to suggest that when it comes to leading people to an exit within the shortest possible time, even the simplest form of mobile guidance (in terms of user-interaction and display of information) we can think of has some disadvantages over a clearly readable and error-free signaling installation.

Moreover, the condition that featured only mobile phone guidance was perceived as yielding the highest workload. The other conditions were rated lower in workload, the one with the combined guidance even significantly lower.

The majority of the participants preferred the installed guidance over the mobile one, possibly because many of them were more efficient in the first Labyrinth. Although the questionnaire used showed a ceiling effect, the participants’ behavior in the third condition where they could chose which source of information to use, proves that most participants preferred the wall-mounted signals. We cannot explain the ceiling effect of the questionnaire. The instrument might not have a sufficient validity.

Concerning the escape times in the third labyrinth, one has to bear in mind that there were only few participants opting for mobile guidance or using the combined information sources. A finalized analysis of the experimental data will shed further light on the participants’ behavior inside of the tunnel, and specifically how many errors occurred at forks and whether they were caused by a misinterpretation of the indication or by any interaction among the participants (where groups where concerned). Eventually, a detailed measurement of the Mean Decision Latency will provide a more precise insight into the decision making process.

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French initiative to implement PIARC’s recommendations regarding HGV driver training in France

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1 INTRODUCTION

The most dreaded event in a tunnel is when vehicles catch fire. Everything possible must be done to ensure that it does not happen again, but, if it does happen again, then every possible measure must be taken to ensure that the people present in the tunnel can get out safe and sound. In order to better meet this requirement, the strategy for protecting users during a fire in a road tunnel makes a distinction between the phase of self-evacuation (before the arrival of rescue services) and the phase of intervention by the intervention and rescue services whose priority objective is to rescue people who are still in the tunnel.

These principles were already stressed in France before the major fires that occurred in 1999 and 2001; they were then strengthened by the statutory regulations adopted after these major events. Unfortunately, the feedback of experience following the first phases of upgrading of road tunnels clearly revealed the occasionally considerable divergence between the fundamental safety principles underlying the regulatory requirements and the observed behavior of users in real situations. This observation was all the more worrying because the process of safety upgrading of road tunnels is based on the principle of self-evacuation by users (the user is actively involved in and responsible for his/her safety well before the intervention and rescue services arrive on the scene). In fact, an analysis of several real events and safety exercises (including in structures that were recently renovated and perfectly well equipped) showed that users often had surprising reactions, inappropriate for the context of the structure and its facilities, and completely out of touch with the fundamental principles that were taken into consideration when defining the technical specifications.

All these findings greatly mobilized the scientific community and all the players concerned (public authorities, clients and owners of projects, operators, engineering design firms, surveyors, etc.) at both national and international levels. As a result, in 2004, CETU launched an ambitious research program on this topic with the key aim of improving the user communication and training system. This research has largely built upon the results of the “ACTEURS” project (Improve links between Tunnels, Operators and Users to Increase Safety) [1] carried out concurrently by several contract motorway company operators. More recently, the World Road Association (PIARC) has also made groundbreaking contributions to this topic. This paper presents an overview of this body of research and highlights how PIARC’s recommendations have been implemented in France to upgrade HGV driver training.

2 IMPROVING THE CONSIDERATION OF HUMAN AND ORGANIZATIONAL FACTORS

The program of work in research and doctrine concerning “The consideration of human and organizational factors in safety” was started by CETU in late 2004 for a fixed period of four years (2005-2008). It was largely sustained by A. Auboyer’s research work as part of her thesis [2] jointly supervised by CETU and SFTRF (Société Française d'exploitation du Tunnel Routier du Fréjus / French Operating Company of Fréjus Tunnel), under the direction of the risks and crises research centre at the Mines ParisTech Graduate School of Engineering.

This work was generally aimed at understanding human behavior in order to take action aimed at
the user, the operator (and the intervention and rescue services) and the tunnel (design of the civil engineering structure and the equipment and facilities, and definition of the detailed ways and means of operation). More precisely, the objective was to improve knowledge of the behavior of the various players involved in safety (users, operators and rescue services) and of the factors that determine this behavior, in order to optimize the design of the structure, communication and training for these players.

During the implementation of this work program, it was decided to pay special attention to the definition of different types of tunnels that may possibly determine the recommendations: for example, in a longitudinally ventilated one-way tunnel, is it appropriate to ask users who are upstream of the fire to go to emergency exits although they are protected by the ventilation system? When this work was started, it was decided that, according to the results of the work, the most uniform measures possible would be proposed for tunnels (to simplify messages in particular).

The article [3] presents the work conducted in this context to improve knowledge of human factors. The main lessons learnt regarding users’ behavior in case of crisis (fire) in the context of this project were:

- Disbelief of the situation,
- Lack of knowledge and underestimation of the actual risk,
- Difficulty to take the decision of self-evacuation,
- Importance of the “leadership effect” (as soon as a few users take the decision of self-evacuation others spontaneously follow them),
- Major need for adequate communication means towards users,
- Major advantages in combining a diverse range of means (visual, auditory, etc.).

On the basis of this knowledge, several actions targeting users have been proposed. This report presents below one of the most important actions focusing on communication and training.

![Figure 1](image1.jpg) (a) User approaching a tunnel - (b) HGV driver driving through a tunnel

### 3 PIARC RECOMMENDATIONS

Aware of the major challenges involved in improving the behavior of users in road tunnels, as early as 2004, the World Road Association (PIARC) also decided to refocus part of its research activities on user communication and training issues.

It was against this background that, in 2008, Workgroup 3 “Human Factors for Tunnel Safety” of the Technical Committee C4 “Road Tunnel Operation” of PIARC produced a report entitled “Human factors and road tunnel safety regarding users” [4]. This report has been supplemented in 2011 by a second report entitled “Recommendations regarding road tunnel drivers’ training and information” [5].
This second report is a logical continuation of the previous one published in 2008 and addresses a specific point raised in the conclusion of the 2008 report: “drivers need to understand the behavior to be adopted in tunnels”. The intended audience of this report is those organizations and individuals who develop and deliver training and information programs for road tunnel users. It applies to national, regional and local programs. Its objective is to provide stakeholders with the methods and tools to implement these types of programs. The workgroup has paid great attention to the educational process for helping users to better understand the behavior to be adopted by drivers in tunnels. The report is structured so as to follow the actual experience of users while traveling through a tunnel in three separate situations; normal driving conditions, minor incidents and major incidents.

With regard to training, it is necessary to remind that in June 2008, the European directive 2008/65/EC, amending the Directive 91/439/EEC on driving licenses has introduced “safe driving in road tunnels” as part of the driving curriculum for all EU member states. It has to be applied to both the theory test and the practical test for all classes of driving licenses. Driver skills and behaviour have to be tested in tunnels during the practical test when that particular part of road infrastructure exists locally. Consequently, theory guidance and practical guidance on “safe driving in road tunnels” have to be provided in all European countries. As a result, driving instructors and test examiners have to be trained and certified.

The report commences with a brief review of the principal aspects relating to our knowledge of human behavior in road tunnels. Then it develops proposals for teaching items for instructors, followed by practical instructions intended for the users. The document finally offers a number of suggestions and proposals that may be useful for the delivery of training and communication activities.

In addition to recommendations for all drivers training, the report stresses out professional drivers training. The continuing professional training given to drivers of commercial vehicles is a good opportunity for creating awareness of risks in tunnels and the associated consequences, particularly during a fire (for example highlighting the effects of fires: speed of smoke propagation, toxicity, level of heat). This will also provide an opportunity to explain to drivers the background to this complex regulation. Consequently, it can be reasoned that during serious incidents in tunnels that non-professional drivers will instinctively recognise the competent actions of professional drivers (HGV, buses, taxis…) who will act as leaders during the evacuation process. Faced with a real situation, an understanding of its possible evolution should lead the professional drivers to assist other users in taking suitable action for their safety. The objective is not to make professional drivers the accepted references with full knowledge of all circumstances, but rather, to give them the means, under certain
situations, for acting in a manner that leads to an active and positive behaviour for all the other persons present in the tunnel. In short, to play the role of leaders. As an example of a corresponding action, we can mention the initiative taken in 2004 by both the French and Italian companies responsible for the Fréjus road tunnel (SFTRF and SITAF) which is 12.9 km long and has a heavy through flow of HGV traffic (2,050 HGV/day – annual daily average in 2010). The aim of this action entitled "Safety, a professional's reflex" was to use professional drivers, frequent users of the Fréjus tunnel, to apply and disseminate safety rules in the event of fire.

Figure 3 The comic strip-style information sheet for HGV drivers entitled "Safety a professional’s reflex"

This successful operation was modified in order to accommodate its expansion to include users of the Mont Blanc tunnel, another very long tunnel with a heavy through flow of HGV traffic.

Moreover, other French managers of national road networks have licensed agreements with training centres for professional drivers to conduct visits to tunnel sites. These site visits help to show the safety equipment and their use. The more that professional drivers are made aware of the safety problems in tunnels the better their reactions will be in case of serious incidents. These training sessions are developed for truck drivers and also for regular bus drivers that route through the tunnels.

The principal conclusions of the report are summarized below:

- Understanding human behavior in road tunnels is an important element for structuring this type of action.
- Drivers of goods vehicles and other professional drivers (taxis, public transport, etc.) could play a leadership role in incidents, particularly in situations where users have to be evacuated. This category of users is therefore considered a special target group for the development of training and information programs.
- Organizations responsible for developing and implementing training programmes are invited to refer to a specific chapter of the report entitled “What has to be taught to the tunnel users”. This chapter describes the general knowledge available with regard to driving experience in tunnels. It also provides trainees with the basic knowledge that has to be assimilated during the training.
- Instructions to be communicated to users through the selected media (information brochures, radio messages, etc.) have to be very brief.
- With respect to training, programs may be developed for deployment at either national or local level (for example, where one or more tunnels belong to the same network or tunnel operating body).
- With respect to communication, it is important to maintain consistency between national and
local education and training programs

The last PIARC’s report is the result of an interactive and interdisciplinary process with the participation of technicians, specialists from intervention teams and psychologists.

4 HGV DRIVER TRAINING IN FRANCE

This section sets out the HGV training initiative piloted by CETU since 2009. This initiative is mainly based on PIARC’s recommendations presented in the previous paragraph.

4.1 The training system for HGV drivers in France

In France, the initial qualification for drivers of goods or passengers vehicles is delivered either via long vocational training (minimum of 280 hours) evidenced by the awarding of a professional driving license, or via accelerated training (minimum of 140 hours) referred to as Mandatory Minimum Initial Training (FIMO).

Initial training is supplemented every 5 years by Mandatory Further Training (FCO).

Long vocational training is delivered primarily by vocational training institutes. There are over a hundred such institutes offering the driving qualification in France. FIMO and FCO are delivered by State-approved training bodies. These bodies may be training organizations or training centers internal to road haulage firms.

4.2 Targeted objective regarding the training of drivers on driving in tunnels

The objective of this action is to define the content of a training program initially addressing instructors of commercial/goods vehicle drivers. In fact, several points have been noted regarding this category of users:

- Goods vehicles are the source of aggravating factors in cases of fires in tunnels,
- Concerning passenger transport: due to the high number of passengers in such vehicles, it is vital that the driver evacuates the passengers and gets them to safety in the event of any incident that requires it;
- HGV drivers are professional road users and are particularly aware of safety issues and factors associated with safety. They are therefore expected to demonstrate exemplary behavior,
- In line with French regulations, all goods vehicles are equipped with extinguishers.
- Drivers are generally instructed in the use of extinguishers,
- Drivers undergo mandatory initial and further training and can therefore be targeted easily,
Drivers can take on a leadership role identified as determinant during incidents, particularly in situations where users have to self-evacuate from the tunnel. Training of this type can thus make a significant contribution to tunnel safety.

This training can be used as a vector for communicating the right messages relating to safety so as to ensure that these professional drivers are able to contribute to effective management of such an event should it occur.

A second phase will target other categories of professional driver, such as bus/coach drivers, driving school instructors, taxi drivers, etc. Coverage may be extended to include groups composed of similar users, such as drivers from corporate fleets.

### 4.3 Working methods

CETU initiated this action in the summer of 2009, after which it also became responsible for its supervision. The first step was to notify all the relevant training organizations and companies (around fifteen in all) of the approach, and then invite them to take part. An assessment of existing training materials and initiatives was organized at the launch of the action. This assessment highlighted the following points:

- The current availability of a broad range of materials, the content of most of which was, however, directed solely towards a presentation of the regulatory aspects (the instructors did not have the necessary background information enabling them to explain the fundamental principles underlying the regulations to trainees),
- A certain level of variety in these materials and the difficulty encountered by instructors in grasping the many different situations that users may be likely to face in a tunnel,
- A strong focus on illustrating the theme developed using video extracts taken from real events,
- A strong commitment on the part of the instructors to enhance the current teaching approach by using the knowledge base built up by CETU in the field of the behavior of users in road tunnels.

Based on this observation, the workgroup steered by CETU then met on around ten occasions between September 2009 and May 2011 in order to adapt the teaching process and develop the resulting training materials. This collaboration proved particularly successful inasmuch as it provided an effective means of synergising the instructors’ skills and experience in terms of teaching approaches, CETU’s skills and experience in road tunnel safety, and knowledge of the levers governing the behavior of users in these structures.

### 4.4 Results

#### 4.4.1 Teaching worksheets for instructors:

These are briefing papers designed for instructors that aim to provide them with:
- the necessary items of knowledge regarding human factors and the safety context in road tunnels;
- the general information required to enable them to deliver the training under the best possible conditions;
- the main messages to be communicated to drivers during these training sessions.

The document sets out the items of knowledge that instructors need to be familiar with, together with those that they have to impart to drivers. The document content is not designed to be communicated directly to drivers; more precisely, the messages should be relayed via training modules. The document contains all the messages relating to safety in road tunnels. It is designed around 3 teaching worksheets:
- Worksheet 1: Driving through a tunnel in normal traffic conditions (importance of the driver learning about the tunnel environment),
- Worksheet 2: Behavior to be adopted in the event of minor incidents (breakdown, driver health issue, etc. resulting in a need to stop the vehicle),
- Worksheet 3: Behavior to be adopted in the event of a crisis situation (development of smoke or fire, regarding their own vehicle or another vehicle).

From a teaching standpoint, the items on each worksheet are presented chronologically following the order in which they are experienced by the user when travelling through a tunnel.

Experience demonstrates that drivers are only able to memorize the key data relating to their safety. In a constructive teaching process, however, instructors will have to have sound knowledge of the fundamental principles of safety in tunnels and the main safety equipment. The instructors' level of knowledge will enable them to supplement the main information to be remembered by users by explaining the fundamental principles that underpin the key messages. With this in mind, the data is presented in tables, with all the information that the instructor should know in the left-hand column, and all the information that they have to impart to users in the right-hand column.

Lastly, the document does not seek to provide an exhaustive description of the highway code on open roads, which users are expected to know already. Rather, it focuses on the specific rules and recommendations relating to the behavior of drivers in tunnels.

### 4.4.2 The slide show - training media:

The above-mentioned document "Teaching worksheets" is accompanied by visual media (slide show) designed to be used during training sessions.

This slide show covers the whole structure of the document "Teaching worksheets", by summarizing the messages in order to present the key points only. Each item relating to worksheets 1, 2 or 3 has been color coded in order to distinguish between data relating to the regulation's fundamental principle, and data relating to the instruction to be followed.

Depending on how much time they have and the type of public involved, instructors can decide to develop some sections to a greater or lesser degree and to focus on certain specific items.

![Figure 5 Extract from the slide show used during the HGV driver training sessions for the item "Safety Equipment" developed in Worksheet 1 "Normal traveling situation"

The explanations and instructions are illustrated, in the right-hand column, by photos and video extracts. These extracts may correspond either to images of real events or to photos taken specifically to illustrate a given message. The pedagogical role of images taken from real events is obviously preferred and used to its best advantage.
The decision of some operators to show video extracts of real events has made it possible to illustrate the concepts developed in a very satisfactory teaching manner. It goes without saying that these video extracts have been blurred to prevent the identification of people or vehicles, and that their use is strictly limited to HGV driver training sessions.

4.4.3 The information and training seminar:
The two products described above were presented at a seminar held in Lyon in June 2011. The participants in this seminar were instructor educators and training managers representing most of the training centers in the Rhône Alpes region; thus, some 70 people participated in the awareness-raising process at this seminar. These participants represented: training organizations, road haulage firms, and one vocational training institute.

During the seminar, a tour of the Chamoise tunnel (motorway A40), temporarily closed to traffic, was organized jointly with the operator (APRR). This enabled participants to get a better grasp of the topics and messages presented in the seminar room and to develop a fuller awareness of the context surrounding the evacuation of people and tunnel operation.

Figure 6 (a) Instructor information and training seminar - (b) Tour of the Chamoise tunnel

The project's strategy in terms of information deployment is based on scaling up the transmission of messages: since July 2011, training managers who attended the seminar have been relaying training content and the related instructions to their colleagues. Some drivers whose training post-dates July 2011 are already benefitting from these new training materials.

4.5 Outlooks for extending the initiative on a national scale:
As indicated in the project schedule, the next step will be to extend the scope of the actions taken to date by developing the materials with the main actors involved on a national scale (training organizations, road haulage firms with internal training centers, vocational training institutes). This development work could be carried out during a national seminar. As with the one in Lyon, the objective of this seminar would be to inform and train instructors and teaching managers by increasing their awareness of the specific nature of driving in tunnels. The aim is then to reach the greatest possible number of HGV drivers responsible for transporting goods and passengers (i.e. an approximate potential of 360,000 HGV drivers across the whole of France). After this phase of extended deployment, nearly 50,000 drivers could receive this training every year.

5 CURRENT STATUS IN EUROPE

According to the EU requirements of Commission Directive 2008/65/EC of 27 June 2008 amending Directive 91/439/EEC on driving licenses, there is a need for an extended driver education regarding behavior in tunnels in EU countries. This is a small step in the right direction of tunnel safety education for road and tunnel users.
The PIARC document [5] may be used as a basis for this EU requirement; it provides guidelines on what kind of information to include in driver education in order to achieve better behavior in normal situations, incidents and accidents. Although the effects of training may be limited, every effect should be deemed a major benefit. We believe that the effects of training may be limited since it is a known fact that information that is taught but never practiced will fade from memory. Only if these actions are trained on a regular basis will this knowledge-based behavior become a skill.

Naturally, the initiative presented in this paper makes a direct contribution to the implementation of the above-mentioned European directive in France. As regards other EU member states, a combination of discussion and feedback has enabled PIARC to identify certain countries that have carried out specific initiatives aimed at delivering training to professional drivers with respect to driving in tunnels (Norway, Italy, Germany).

At this stage, however, the French initiative remains fairly novel both in terms of its scope, the productiveness of the deployed approach, and the strong synergy with PIARC recommendations. The training materials developed to date target the situation in France but can be easily adapted to fit other European countries (even on an international scale). In a bid to maximize the impact of the report [5] and the French initiative, in its upcoming work cycle (2012 – 2015), PIARC is planning to adapt the materials developed by CETU and then make them available to interested countries. This issue is expected to be discussed when preparing the next PIARC cycle, to be held in 2012-2015. Where applicable, training materials developed and translated into English will be made available on the PIARC website at: http://www.piarc.org/fr/.

6 CONCLUSIONS

This HGV driver training initiative rolled out between 2009 and 2011 is the culmination of long-term research and development of doctrines steered by CETU since 2004. Its success has been boosted by a dynamic collaboration between organizations responsible for driver training and specialists in tunnel design and engineering. Initial feedback on the resulting training materials has highlighted one point in particular: the ease with which instructors are able to take ownership of the training media, and the clarity and relevance of the information and instructions imparted to trainees.

This initiative is a good example of a “two way” process during which:

- France uses previous PIARC material [4] to deploy training actions targeting all users,
- The new PIARC report [5] then factors in the experience gained in France,
- France finally reintegrates this material to train professional drivers.

The next step by CETU, scheduled for 2012, will be to extend the approach across the whole of France, after which, supported by PIARC, this work will be developed on an international scale.
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Quantification of fire damage of concrete for tunnel applications

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ABSTRACT

A concrete tunnel structure exposed to fire will deteriorate to a certain degree when the temperature increases in the cross-section. The thermal diffusivity of concrete is low which causes a high thermal gradient close to the exposed surface during fire exposure which results in a gradient of deterioration in the structure after fire exposure. In traditional core testing for evaluating residual properties of fire exposed concrete, the weakest part of the core will have a high influence on the measured elastic modulus and compressive strength. To obtain a better picture of the damage, not only for safety reasons but also for economic reasons, it would be preferable to measure the change in damage level continuously. By using an optical full-field strain measuring device, which uses a Digital Image Correlation (DIC) technique, during compressive strength tests the mechanical response at different depths away from the fire exposed surface can be studied. In this study a typical Swedish tunnel concrete were used. In addition, a similar concrete mix with reduced aggregate size was tested. The test samples were exposed to the standard fire curve ISO 834-1:1999 or a temperature rise of 10 °C/min. The DIC measurements were complemented by Ultrasonic Pulse Velocity measurement and Polarising and Fluorescent Microscopy (PFM) in order obtain a reliable picture of the residual mechanical properties and the residual durability.

KEYWORDS: concrete, damage assessment, ARAMIS, ultrasonic pulse velocity, microscopy

INTRODUCTION

Concrete is used in prefabricated tunnel elements and in shotcrete linings for support of hard rock. It is durable and has satisfactory fire performance in most instances of fire exposure. Despite this there will always be combinations of certain constructions and fire scenarios where the concrete is seriously damaged and, in extreme cases, collapses.

After a fire incident it is necessary to determine whether the tunnel construction can be refurbished or, in extreme cases, needs to be replaced. The appropriate choice of action will be based on an assessment of the status of the structure. Mapping of damages and the assessment needs to be accurate to ensure a good level of safety and the best solution from an economic point of view. There are some calculation methodologies that may assist an evaluation but to guarantee a good safety level the assessment should be based mainly on on-site inspections supplemented by laboratory testing when necessary [1].

Concrete is not a single material, rather it can be considered as a family of related materials with sometimes rather different physical properties. Therefore, it is no simple matter to provide a
comprehensive overview of the influence of temperature but some general trends can be seen. The mechanical properties of concrete deteriorate at elevated temperatures. Eurocode 2 [2] states the loss of compressive strength at high temperatures is defined for two types of aggregates: siliceous and calcareous aggregate. Above 100 °C the compressive strength starts to decrease and at about 1200 °C the concrete has lost all its strength. The values stated in the code should only be interpreted as general trends as the reduction of compressive strength is strongly dependent on whether the concrete is loaded during heating or not [3].

Derived the change of stiffness with temperature from the stress-strain relationship defined in Eurocode 2 is not applicable. This is because the effect of transient creep is implicitly taken into account as a reduction in stiffness. A large variation in experimentally determined values of the elastic modulus can be found in the literature. Most of the results were found in the region between two simple linear models where the stiffness reduction factor goes from 1 to 0 in the temperature range of 20 – 600°C and 20 – 800°C, respectively. When the concrete has cooled down to room temperature it has been observed that the strength is reduced further [1]. The reason for this additional reduction is the continuing disintegration of the microstructure during cooling.

The residual strength of a concrete structure is influenced by the maximum temperature attained, the duration of the heat exposure, the mix proportions of the concrete, the load conditions and the stress level during heating and will consequently vary greatly [1]. In reinforced concrete (RC) structures the reinforcement cover will protect the reinforcement against heat. However, in cases with long fire exposure the reinforcement will be exposed to significant heating. Hot-rolled bars shows no strength reduction up to 400 °C, but the elastic modulus starts to decrease above 100 °C and the yield plateau will disappear above 200 °C [4], [5]. At higher temperatures, the loss of strength is more serious, e.g. only 20 % of the original strength is left at 650 °C. Cold-drawn bars, wires and strands are more sensitive than hot-rolled bars to elevated temperatures. A 50 % reduction of the strength occurs at 400 °C and only 10 % of the original strength remains at 650 °C. As long as the temperature is less than 450 °C, the original yield strength of cold worked steel will be restored after cooling. The equivalent temperature for hot-rolled steel is 650 °C. Above these temperatures the residual yield strength will decrease. The loss of strength of the reinforcing steel at high temperatures is usually responsible for any significant residual deflection of RC structures. The free thermal expansion of reinforcing steel is normally greater than for most of the concretes. In a structure, buckling of the reinforcement may therefore occur as a consequence of compressive stresses induced by the thermal expansion of the reinforcement. In case of buckling, the reinforcement bars may loss their bond to the concrete.

The aim of this study was to investigate a new method for assessing damage to concrete after exposure to a fire. Thus measurement of the strain field during compressive load was complemented with Ultrasonic Pulse Velocity measurement and Polarising and Fluorescent Microscopy (PFM) in order to obtain a reliable picture of both the residual mechanical properties and the residual durability. The new method shows directly the change of stiffness in the cross section of the concrete in contrast to the majority of traditional methods as traditional methods are typically indirect.

ASSESSMENT OF CONCRETE STRUCTURES AFTER FIRE EXPOSURE

When arriving at a fire damaged tunnel construction made out of concrete it is important to start the investigation by conducting a general inspection and making observations concerning the extent of the fire, e.g. size and spread pattern of the fire, visible damage, etc. Useful information can often be found concerning the fire development and intensity from the incident report, which can be obtained from the Fire and Rescue Services. When preparing for this general inspection, it is advantageous if relevant technical drawings of the structure are available.

To provide an estimation of the temperature rise during the fire, the effect on installations in the tunnel can be studied. Some useful temperature indicators are shown in Table 1.
Table 1: Effect of temperature on common materials [1].

<table>
<thead>
<tr>
<th>Substance</th>
<th>Typical example</th>
<th>Conditions</th>
<th>Approximate temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paints</td>
<td></td>
<td>Deteriorates, Destroyed</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>150</td>
</tr>
<tr>
<td>PVC</td>
<td>Cables, pipes</td>
<td>Degrades, Fumes, Browns, Charring</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>400-500</td>
</tr>
<tr>
<td>Aluminium and alloys</td>
<td>Fixtures, brackets</td>
<td>Softens, Melts, Drop formation</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>600</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>650</td>
</tr>
<tr>
<td>Copper</td>
<td>Wiring, cables</td>
<td>Melts</td>
<td>1000-1100</td>
</tr>
</tbody>
</table>

It is very useful to start the physical inspection using a hammer and a chisel. Differences in sound can indicate fire damage in the surface layer and delaminated areas can be identified by their typical low frequency sound response.

In many instances, the assessment of fire exposed concrete stops after this general inspection. Knowledge of the fire intensity, together with mapping with hammer and chisel and close study of the drawings of the concrete structure, often provides sufficient information for an assessment. In cases where more detailed information is needed more sophisticated methods should be used. A variety of such methods are described below.

TEST METHODS

Concrete is a non-combustible material with low thermal diffusivity and will therefore usually exhibit good behaviour at high temperatures. However, the low diffusivity causes a high thermal gradient close to a fire exposed surface, i.e. the reinforcement cover, although the thermal damage will rapidly decrease at a short distance from the fire exposed surface. Consequently, only fires with long duration will affect deeper regions of a concrete structure. Numerous test methods suitable for assessing the properties of damaged concrete have been developed internationally. Assessment of fire damaged concrete, i.e. a highly heterogeneous layered-material, is consequently more complicated.

Ultrasonic pulse velocity

This test method has been used for more than 60 years to assess the quality of the concrete. The test equipment is easy to use in the field on structures and in the laboratory on test specimens. The ultrasonic pulse velocity through the concrete is dependent of the elastic properties and the density of the concrete. Therefore, areas with poor elasticity or low density, such as fire damaged concrete, can be detected with this method.

The test equipment consists of a pulse generator, a transmitting head, a receiving head and a measuring unit. The arrival time of the compression waves, i.e. the waves that propagate fastest in the concrete, is measured by the system at the receiving head. In tunnel applications only an indirect method, the so called surface method where the angle between the heads is 0 degrees, can be used as a non-destructive method. It does not give as reliable measurements as the direct and semi-direct methods, but it can be used to identify fire damage and during ideal circumstances estimate the thickness of the poor quality layer.

When estimating the poor quality layer, the heads are first placed close to each other and then moved further away. By plotting the arrival time as a function of the distance between the heads the thickness
of the poor quality layer can be determined in cases where this layer is distinct. When the heads are placed close to each other, the waves will propagate in the upper layer of the material where the amount of fine material is high. This will cause a low velocity, when the distance between the heads is increased the waves will propagate through both the upper layer and lower layers. When evaluating fire damaged concrete, shrinkage and delamination cracks should be taken into account when interpreting the results [4].

Information concerning the depth of damage can be provided by measuring the ultrasonic pulse velocity on cores samples in the radial direction at different depth from the fire exposed surface. This method requires no preparation of the cores and is possible to do directly on site after core drilling. On site measurements allow the operator to increase the number of core samples or cancel planned drilling depending on the outcome of the test. During these tests the relative change in transmission time or velocity compared to the unaffected reference sample is more important than absolute values.

The main advantage of this test method is that it is easy to investigate the uniformity of the concrete, consequently areas of fire damage can be readily determined. A large number of factors influence the pulse velocities, such as type of aggregate and moisture content etc. It is, therefore, not recommended to use the pulse velocity to estimate the compressive strength or the flexural strength without correlation testing.

**Microscopy**

Microscopy can be used for the assessment of the temperature history of a fire damaged concrete structure. A comprehensive discussion of useful and potentially useful reactions is presented in [6]. A summary is given in Table 2.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>70-80 °C</td>
<td>Dissociation of ettringite</td>
</tr>
<tr>
<td>120-160 °C</td>
<td>Dehydration of gypsum to hemihydrate and anhydrite</td>
</tr>
<tr>
<td>&lt;250 °C</td>
<td>Small changes</td>
</tr>
<tr>
<td>200-500 °C</td>
<td>Loss of bound water in the cement paste</td>
</tr>
<tr>
<td>250-300 °C</td>
<td>Reddish discolouration of the cement paste</td>
</tr>
<tr>
<td>375 °C</td>
<td>Hemihydrate to anhydrite</td>
</tr>
<tr>
<td>500-600 °C</td>
<td>The colour of the cement paste turns grey</td>
</tr>
<tr>
<td>500 °C</td>
<td>Changed colour of the cement paste viewed in polarized light</td>
</tr>
<tr>
<td>510-550 °C</td>
<td>Dehydroxylation of portlandite</td>
</tr>
<tr>
<td>500-650 °C</td>
<td>Fracturing of quartz bearing rocks</td>
</tr>
<tr>
<td>573 °C</td>
<td>Quartz changes from ( \alpha ) to ( \beta )</td>
</tr>
<tr>
<td>600-850 °C</td>
<td>Decarbonation of carbonate minerals</td>
</tr>
<tr>
<td>800-1200 °C</td>
<td>Complete disintegration of the structure, cement paste whitish</td>
</tr>
</tbody>
</table>

Cracks in the cement paste, between the cement paste and the aggregate (the inter-transitional zone, ITZ) and through the aggregate induced by fire exposure, lower the strength of the concrete and influence the residual durability. The cracks can be counted by attaching a thin section of the fire exposed concrete to a motorized table and then move the table to predefined levels. By performing the analysis as a linear traverse analysis along lines perpendicular to and parallel to the exposed surface respectively, it is possible to assess the orientation of the cracks.
Optical full-field strain measurement

It is common to drill cores and conduct traditional compressive strength tests on fire damaged concrete, but this only gives a rough picture of the depth of damage. The part of the core closest to the fire will break first and the value of compressive strength from the test is not easy to associate with a specific depth in the cross-section.

By using the Digital Image Correlation (DIC) measurement technique with a stereoscopic camera setup containing high resolution cameras, the strain field can be monitored on a loaded specimen. As fire damaged concrete deforms more under load, the depth of the damage can be determined with this method. The DIC measures the displacement of the specimen under testing by tracking the deformation of a naturally occurring, or applied, surface speckle pattern in a series of digital images acquired during the loading. This is done by analysing the displacement of the pattern within discretized pixel subsets or facet elements of the image. In combination with correlation based stereovision techniques, the measurement of 3D shapes as well as the measurement of 3D displacements fields is possible. During the present study only the surface strain field was determined.

EXPERIMENTAL STUDY

An experimental study has been performed in order to evaluate different methods for assessing the degradation of concrete after fire exposure [8]. Two different fire scenarios and two concrete mixes were used. In total ten test samples were produced and eight of them were exposed to fire conditions. The remaining test samples were used as references.

The concrete mixes were a typical Swedish tunnel mix and a similar mix with reduced aggregate size. This choice of test material facilitated an investigation of the influence of aggregate size on the degradation of the fire exposed concrete. The concrete contained polypropylene fibres (PP-fibre) in order to avoid spalling at the fire exposed surface, as an investigation of the spalling behaviour of concrete was not included in the scope of the investigation. Super plasticizer was added to obtain a good workability of the concrete. To be able to add a suitable amount of super plasticizer in the concrete with reduced aggregate size the water-cement ratio (w/c) was slightly increased. The concrete mixes used are shown in Table 3.

<table>
<thead>
<tr>
<th>Series</th>
<th>w/c</th>
<th>Gravel 0-8 mm [kg/m³]</th>
<th>Gravel 0-16 mm [kg/m³]</th>
<th>Water [kg/m³]</th>
<th>Cement CEM I [kg/m³]</th>
<th>Super-Plasticizer [kg/m³]</th>
<th>Fibre Amount [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-16</td>
<td>0.45</td>
<td>898.5</td>
<td>863.3</td>
<td>180.9</td>
<td>402.8</td>
<td>0.16%</td>
<td>1.0</td>
</tr>
<tr>
<td>0-8</td>
<td>0.47</td>
<td>1637.8</td>
<td>-</td>
<td>181.1</td>
<td>385.5</td>
<td>0.72%</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Ten slabs, five of each recipe, were moulded with a size of: 600 mm × 500 mm × 200 mm. The samples were cured indoors for approximately 6 month after moulding.

Fire exposure and load conditions

The fire exposure of the test samples was conducted in a small scale furnace constructed for fire resistance tests. The furnace had a fire exposed area of 500 mm× 400 mm. Detailed information concerning the construction of the furnace can be found in test standard SP Fire 119 [9]. The furnace was heated with a gas burner and the furnace temperature was measured with an Ø 1 mm shielded thermocouple. The slabs were exposed to the fire from below only.

The two fire scenarios used were the standard time-temperature curve described in ISO 834-1[10] and a temperature ramp, further designated Slow heating, of 10 °C/min to a maximum temperature of
1000 °C. The choice of these two scenarios of thermal exposure allowed an investigation of how the temperature history influenced the strength decay. Five thermocouples were pre-installed at the centre of each slab at different depths. This allowed monitoring of the temperatures at different depths during the test and determination of the degradation of the strength decay as a function of temperature. The duration of the two different heating scenarios were set to 90 minutes and 130 minutes, respectively. This gave a temperature of approximately 310 °C at the position 45 mm from the fire exposed surface at the termination of the both fire scenarios. A one dimensional compressive load was applied in the longitudinal direction of the slabs. Two rigid beams were placed at the short sides of the slabs and were pressed against the slab by two bolts to a load level of 2 MPa. Directly after the termination of the fire tests the slabs were removed from the furnace and cooled down in room temperature.

**Sampling**

Eight cores with a diameter of 60 mm were drilled from each slab. The drilling was conducted from the fire exposed side of the test specimens.

**Ultrasonic pulse transmission time measurement**

The ultrasonic transmission time was measured through cores taken from the unexposed test specimens and the fire exposed test specimens. The ultrasonic pulse transmission times were measured in the radial direction of the cores at a distance of 20, 30, 40, 50, 60, 70, 80, 100, 140 and 180 mm from the fire exposed surface. Measurements were not performed closer than 20 mm from the edges to avoid boundary effects. The result of these measurements are shown in Figure 1.

![Figure 1 Mean ultrasonic pulse transmission time a) Aggregate size 0-8 mm, b) Aggregate size 0-16 mm. V= virgin, Std=ISO 834 heating, SH= Slow heating, 10 °C/min up to 1000 °C](image-url)

The ultrasonic pulse velocity was not calculated in this study; instead the ultrasonic pulse transmission times were compared for different scenarios. The measurements were made with an AU2000 Ultrasonic Tester.

**Mechanical testing**

The experimental setup of the system can be seen in Figure 2. The natural pattern at the surface of drilled cores samples of concrete was used as the speckle pattern for the optical system.
The uniaxial compression tests of the drilled concrete cores were carried out in a GCTS servo hydraulic testing machine. The tests were carried out under load control with a stress rate of 12 MPa/min. The axial load was recorded using a load cell and the axial displacement of the axial actuator was recorded using an LVDT, connected to a high-speed data logger. The uncertainty of the load measurement is less than 1%.

For each of the fire exposed slabs, three cores were loaded to failure. For the unexposed slabs, four cores were loaded to failure. The nominal core diameter was 60 mm and the nominal core height was 122.5 mm. The first 10 mm of the drilled cores was removed due to severe damage from the fire exposure. The core end surface closest to the fire exposure, or corresponding surface of the unexposed cores, was placed against the lower loading plate. During the loading the strain-field was monitored at the surface of the cores by means of full-field strain measurements. The mean axial compressive strains are shown in Figure 3.

Full-field strain measurements were performed on all concrete cores tested in this study. The optical full-field deformation measurement system ARAMIS™ 4M (v6.2.0-6) by GOM was used. The accuracy of coordinate measurements was approximately 2 μm.

**Microscopic analysis**

The microscopic analysis was performed using thin sections with the approximate size of 50 mm × 65 mm. The samples were impregnated with epoxy glue with fluorescent dye, Struers Epodye. Light optical microscopy with bright field, polarization and fluorescence technique was applied. The thin sections covered an area about 65 mm in from the fire exposed surface.
The microscopic analysis shows that thermal alterations in samples from the slow heating and the standard fire are rather similar, see Table 4. For the 8 mm and 16 mm aggregate samples, respectively, there is also a difference in the relationship between the depth to the portlandite and quartz transitions. In samples with 8 mm aggregate this occurs at nearly the same depth while there is a clear difference in the 16 mm aggregate samples. The portlandite reaction is dependent on both temperature and water pressure. Results from the quantitative analysis of cracks indicate that thermally induced cracks are more frequent in the samples with coarser aggregate.

<table>
<thead>
<tr>
<th></th>
<th>0-8 SH-4</th>
<th>0-8 Std-1</th>
<th>0-16 SH-1</th>
<th>0-16 Std-1</th>
<th>0-16 Std-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portlandite (Ca(OH)₂)</td>
<td>19-20 mm</td>
<td>11-14 mm</td>
<td>15-18 mm</td>
<td>14-17 mm</td>
<td>13-15 mm</td>
</tr>
<tr>
<td>Quartz α to β transition</td>
<td>21 mm</td>
<td>13-16 mm</td>
<td>26 mm</td>
<td>25 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>Reddish cement paste</td>
<td>4-12 mm</td>
<td>0.5-12 mm</td>
<td>3-12 mm</td>
<td>2-13 mm</td>
<td>1-14 mm</td>
</tr>
</tbody>
</table>

The temperatures for the colour changes differ between different concretes and possibly also between different heating scenarios.

**DISCUSSION**

Both the full-field strain measurements and the ultrasonic pulse transmission time measurements show a significant degradation at the fire exposed side of the tested cores. To relate the residual stiffness of the fire exposed specimens to the unexposed concrete each measured area was divided into nine segments and a stiffness reduction factor was introduced. As the mean axial stress level is the same in all specimens, the stiffness reduction factor of each segment can directly be related to the segment strain as Eq. 1

\[
k_{c,s} = \frac{\epsilon_{c,sm,unexposed}}{\epsilon_{c,sm,exposed}}
\]  

(1)

where \(\epsilon_{c,sm,unexposed}\) and \(\epsilon_{c,sm,exposed}\) are the mean values of the segment section strain of the specimens from the unexposed and fire exposed slabs, respectively. The mean stiffness reduction factors for the fire exposed slabs are presented in Figure 4. The stiffness reduction factor gives a picture of the damage level within the concrete slabs as a result of a temperature profile caused by the fire heating scenario. The stiffness degradation of the test samples with reduced aggregate size coincides well, while there is a rather big difference between the samples with coarser aggregate with increased distance to the fire exposed surface. The explanation for the latter difference is not known with certainty, but one explanation could be that the scatter in strain values for each segment is larger for specimens with coarser aggregate than for the specimens with reduced aggregate size. The slabs with coarse aggregates exhibited a larger stiffness reduction close to the surface for both fire scenarios, compared to the slabs with reduced aggregate size. Values above 1.0 should not be physically possible and are probably explained by natural scatter and measurement uncertainties.

The dynamic modulus of elasticity is a function of the density, the ultrasonic pulse velocity and Poisson’s ratio [11]. To estimate the reduction of the dynamic modulus of elasticity, a reduction factor analogous to the stiffness reduction factor, was introduced as described below:

\[
R_{E,deo} = \frac{E_{\text{dyn,after fire}}}{E_{\text{dyn,before fire}}} = \frac{\rho_{\text{after fire}}}{\rho_{\text{before fire}}} \left(\frac{t_{\text{before fire}}}{t_{\text{after fire}}}\right)^{2} \cdot \frac{(1 + \nu_{\text{after fire}}) \cdot (1 - 2\nu_{\text{after fire}}) \cdot (1 - \nu_{\text{before fire}})}{(1 - \nu_{\text{after fire}}) \cdot (1 + \nu_{\text{before fire}}) \cdot (1 - 2\nu_{\text{before fire}})}
\]  

(2)

In this study only the change in ultrasonic pulse velocity was considered when calculating this reduction factor. A loss in density will lower the relative dynamic modulus of elasticity. At low
temperatures the reduction of the stiffness is overestimated due to the initial free water loss [4]. The curves may therefore deviate in regions where the temperature rise was low and the moisture content was considerable affected by the fire. Since a change in Poisson’s ratio of the concrete has a low influence on the relative dynamic modulus of elasticity this factor was not considered either. In Figure 4 the dynamic modulus of the elasticity reduction factor \( R \), considering only the change in ultrasonic pulse velocity, is presented together with the stiffness reduction factor obtained from the DIC measurements. The reduction factor, \( R \), for the specimens with reduced aggregate size coincides better than that for specimens with coarse aggregate, as discussed previously. One explanation could be the larger scatter in the 0-16 strain measurement than the 0-8 strain measurements.

The depth away from the fire exposed surface where the crack frequency decreases agrees with a strong change in mechanical properties shown by the DIC measurements and the ultrasonic pulse velocity decay. The change in mechanical properties cannot be explained only by the formation of cracks. This is shown by the crack distribution in the 0-8 mm samples where the crack frequency at 55 mm depth is comparable to the background values for samples that have not been exposed to a fire while the DIC results indicate a reduction in stiffness of about 50 % at this level.

Decomposition of portlandite occurs closer to the surface and therefore at higher temperature than the quartz \( \alpha \beta \) transition which is reversed to the actual reaction temperatures. This may be due either to the kinetics of the reaction or its water pressure dependence, i.e. if the water vapour pressure is higher this decomposition reaction will occur at a higher temperature. The quartz \( \alpha \beta \) transition on the other hand is pressure independent and is a rapid transition that takes place as soon as the reaction temperature is reached.

In this study the loss of stiffness is close to linear where the stiffness reduction factor goes from 1 to 0 in the temperature range of 20 – 600°C, see Figure 5. However, at lower temperatures the linear relationship seems to underestimate the stiffness degradation for the samples with coarse aggregate and the samples with reduced aggregate size exposed to the slow heating scenario. The reason for this might be the development of a crack system in the virgin part of the cross-section caused by extensive thermal expansion closer to the surface. This leads to a bowing of the structure with associated crack formation. In general during fire tests on slabs, cracks open up on the non-fire exposed side of the specimen, often followed by water pouring out in the cracks. During conventional tests of E-modulus, at high temperatures, the test specimens are heated slowly to the target temperature to reduce effects from high thermal gradients [12].

Figure 4: Mean stiffness reduction factor from strain measurement \( K_{c,s} \) and estimation of the dynamic modulus of elasticity reduction factor from ultrasonic pulse transmission time measurements, \( R \). a) 0-8 mm aggregate. b) 0-16 mm aggregate
CONCLUSIONS

Ultrasonic pulse velocity measurements on core samples provide information concerning the depth of damage. On site measurements allow the operator to increase the number of core samples or cancel planned drilling depending on the information from previous cores results. By using the DIC measuring technique on the cores samples a reliable picture of the damage is obtained. To determine the maximum temperature occurred at the reinforcement the depth of the quartz α β transition can be studied in microscope. This transition is rapid and pressure independent. The structure may deteriorate after fire by frost or corrosion of the reinforcement if the fire has caused an increased porosity and a high amount of cracks at the surface layer. An estimation of the durability can be made by counting the cracks along the cross-section of a core in a microscope. Combining these test methods an accurate picture of the fire damage is obtained and the structural engineer can determine required strengthening actions to retrieve the load caring capacity and the durability of the tunnel structure.

REFERENCES

ABSTRACT

During the last decades, a number of subsea rock tunnels are built in Norway to replace ferry connections across the fjords. At the present, the Norwegian Public Roads Administration is developing further a new tunnel concept, the Submerged Floating Tunnel, as an alternative to long and deep subsea rock tunnels.

A Submerged Floating Tunnel (SFT) is a tunnel that floats in water. To the highway traffic, driving through the SFT will be just like driving through any tunnel. However, floating in water, the SFT is a completely different tunnel concept, which gives tunnel safety and security new dimensions to the designer and the owner. In this tunnel concept, there is a very close connection between traffic safety and structural safety.

The consequences of a fire or explosion inside the SFT will be very different, and even more severe compared to a rock tunnel, as the structural strength of the tube might be seriously damaged. Also, the SFT might be damaged by a ship collision against a pontoon, a sinking ship, falling anchor, or collision of a submarine against the structure. In the case of water ingress the SFT may be flooded, and in worst case, it might cause the structure to collapse and sink.

The safety objectives of a SFT consider the number of people potentially involved in an accident. One major question is how to provide safe evacuation of the people inside the SFT in case of an accident, before the SFT structure might be critically damaged.

The particular configuration of the SFT structural system implies to deal with non-conventional safety and vulnerability problems. The problems of an innovative design such as a Submerged Floating Tunnel are very different both in terms of safety objectives and the most critical risk scenarios.

This presentation is limited to the safety of the structure and the traffic during operation, with focus on the difference from ordinary tunnels.

KEYWORDS: Submerged Floating Tunnel, safety to SFT structure, risk analysis of SFT, tunnel safety, tunnel flooding
WHAT IS A SUBMERGED FLOATING TUNNEL

The Submerged Floating Tunnel (SFT) is a concept for crossing water beneath its surface. It consists of a hollow structure that floats in water, supported by its buoyancy, spanning from one shore to the other. The structure is placed deep enough to allow ship traffic to pass over it. In addition to anchoring at landfalls, it is anchored to the seabed by tethers or to the water surface by pontoons. Normally the SFT will end in rock tunnels at both landfalls. There are four major anchoring alternatives: Pontoons on the surface, columns to the seabed, tethers to the seabed, or no anchoring except at landfalls [1]. The submerged floating tunnel is also named Archimedes bridge.

![Figure 1](image1.jpg)  Submerged Floating Tunnel (with anchoring to the seabed), and subsea rock tunnel

The submerged floating tunnel is not a new fjord crossing concept. The concept has been known for about 150 years, however, so far no SFT has been built. Since the late part of 1900s, a number of possible crossing sites have been examined, both in Italy, Japan and Norway. Examples are the 30 km long Funka Bay crossing in Japan, the 5.3 km long crossing of the Strait of Messina in Italy, and the 1400 m long crossing of Høgsfjord in Norway [2], [3].

![Figure 2](image2.jpg)  The proposed Høgsfjord SFT project, one of four alternatives

The Høgsfjord SFT crossing is probably the most extensive of the SFT projects studied until now. This project was taken through fundamental research to development of four alternatives. Four alternative SFT concepts were approved by the Norwegian Public Roads Administration, and were ready for tender competition when the project was stopped due to political decisions [4].
WHAT MAKES A SFT DIFFERENT FROM TRADITIONAL ROAD TUNNELS

Normally, when talking about a “road tunnel”, we think of a tunnel in solid rock or in soft materials. The tunnel may be built as drill and blast, or bored by a TBM. In both cases the tunnel is built through the rock or soil. Inside, there may be a concrete lining to prevent rock from falling into the tunnel, and to keep the tunnel free from water coming in from the outside. The construction and installation of an immersed tunnel is different from the normal road tunnel. The immersed tunnel consists of steel or concrete elements, which are placed in a trench in the seabed. When the elements are connected, they are buried in the seabed, and normally there will be a layer on top to protect the structure.

Floating in the water, only anchored at the landfalls and either connected to the sea surface or to the seabed, the SFT tunnel structure is in fact an underwater bridge structure with inside loads from the traffic and outside loads from the surrounding water caused by waves and current. In addition the SFT-structure may be hit by subjects from marine activities like ship traffic, submarines and fishing activities.

Immersed tunnels and SFT may be constructed and installed in a similar way, but in many aspects they are very different. The immersed tunnel is continuously supported along its length, while the SFT has discrete supports. Hence, the SFT is exposed to a greater number of possible threats, and the consequence with regard to possible damage on the structure is quite different.

Inside the tunnel, all tunnel concepts are normally subject to the same loads and possible threats. But the effect on the structure, and consequently on structural safety, is in some aspects very different.

Outside the tunnel, the SFT structure is vulnerable to quite different loads and possible threats that may be highly critical to the structure and hence the traffic inside the SFT.

Thus, even though the traffic will experience passing through the SFT structure like driving through a high-standard tunnel, to the owner and the designer, there are a number of precautions to be taken with this new tunnel concept.

THE FEASIBILITY STUDY: HOW TO CROSS THE SOGNEFJORD

Along the coastal highway E39, the major highway on the western coast of Norway, there are still 8 ferry connections between Kristiansand in the south and Trondheim in the north. To replace these ferry connections with fixed connections, some of the widest and deepest Norwegian fjords have to be crossed. Until now, the longest subsea rock tunnel in operation to highway traffic, the Bømlafjord tunnel, is 7888 m long. The deepest one, the Eiksund tunnel, is going down to 287 m below sea surface. Both of these are one tube tunnels, with bi-directional traffic.

There are several disadvantages with the long and deep road tunnels, both in terms of construction cost and operation cost. Hence, the Norwegian Public Roads Administration is looking for alternative fjord crossing concepts. A feasibility study “How to cross the Sognefjord” is expected to be an important part of developing new technology and knowledge, and to find new ways to cross the fjords, as an alternative to the very long and deep subsea rock tunnels [5]. The Sognefjord is 3700m wide and 1300m deep at the crossing site studied. A number of large cruise ships are passing.

The feasibility study includes different fjord crossing concepts: suspension bridge, floating bridge, SFT, and combinations of floating bridge and SFT. Regarding tunnel safety, the SFT concepts have
most of the safety problems the subsea rock tunnels have, and in addition specific problems due to the fact that this a floating structure.

Different conceptual SFT alternatives are studied. The alternatives may have one or two tubes, according to the anchoring system chosen.

**Figure 3  Conceptual design, SFT across the Sognefjord (alternative with two tubes)**

**GENERAL SAFETY CONSIDERATIONS**

When pushing borders with regard to the use of new fjord crossing concepts, like the SFT, safety is a very important aspect to the owner. A set of new problems and questions, in addition to the general tunnel safety problems, will have to be answered. Two major questions are:

- Safety to the traffic and people inside the SFT
- Safety to the structure against damages, and in worst case possible collapse

In this case it is not only a question about safety versus economy, it is also a question about public confidence in new crossing technology.

The security of SFT is affected by its surroundings, environmental forces and incidents due to ship traffic. Risk assessment methods should be used to analyze the potential risk of any SFT, according to the specific local conditions and loads [6].

Development of different SFT concepts, and final design, has to be based on specific safety requirements:

1. Possible threats and damage on the SFT should be avoided
2. Possible damage on the structure should be minimized
3. Safe evacuation from the SFT if needed

**NEW CHALLENGES**

As earlier mentioned, the driver will be experienced passing through a SFT just like driving through a normal road tunnel. All the safety aspects from a road tunnel will also be present in a SFT, and the
consequence of a fire or an explosion might be even more critical if the SFT structure is damaged. However, the real difference, is the possibility of uncontrolled inlet of water as a consequence of a threat from outside the SFT. In addition to the problems with smoke and heat from a fire, there is the possibility of water flooding the SFT structure. Uncontrolled flooding will cause the traffic to stop, and, in worst case total collapse of the SFT.

Evacuation of the SFT in case of flooding caused by an incident outside the SFT, may be easier than evacuation in case of a fire. In the case of a possible flooding, there will be no problems to people with regard to visibility, heat, or problems with breathing due to smoke.

Uncontrolled inlet of water may lead to:

- Loss of functionality. Traffic may be delayed or stopped for a short or a longer time. People inside the SFT may have to evacuate
- Severe damage that may lead to collapse of the SFT. In this case it is a question if there is an alternative safe route to evacuate, time enough to evacuation, and possible access to rescue team, before the SFT is flooded to such a degree that the structure will collapse.

Consequently, tunnel safety, when talking about a SFT, is just as much a question of safety from damage on the structure and following uncontrolled water flooding, as it is of traffic accidents and fire.

POSSIBLE THREATS

There are a number of possible threats. Each of them may lead to damages, causing unwanted inlet of water in the SFT. The following list do not intend to be complete.

Incidents inside the SFT:

- Fire
- Car collision with SFT wall
- Leakage from water pipes
- Loss of pumping capacity
- Terror attack

The anchoring system and the structure:

- Damage on a pontoon
- Damage on anchors or tethers
- Damage on land abutments
- Leakage from joints

Environmental incidents:

- Earthquake
- Tsunamis
- Sea waves and current
- Landslides (above or under the water)
Manmade activities:

- Ship collision and drifting ship, sinking ship
- Falling or dragging anchor
- Submarines
- Fishing activity

HOW TO AVOID POSSIBLE THREATS

One way to avoid dangerous situations is to monitor the structure, traffic, environment, and manmade activities. Monitoring of the structure will have to include structural strength and dynamic behavior of the SFT structure, buoyancy, and loading. Also anchors, tethers, and land abutments have to be monitored, as well as water stand in the pump sumps, and functionality of the pumps [7].

Monitoring of environmental loads in terms of wave height and peak periods, salinity of the sea, current speed and direction, will give a warning if external loads on the SFT are higher than expected. Another example of a hazardous environmental load is tsunamis from rock slides. Normally the site of the possible slide will be monitored due to the threat to nearby housing.

Monitoring of ship traffic will to a certain degree make it possible to close the SFT before a ship actually hits a pontoon or a part of the SFT structure. Submarines are a serious threat to the SFT structure and the anchoring system. Monitoring of the sea may tell when a submarine is in the vicinity of the SFT.

It is also possible to make it easier to the ship traffic on the surface to detect the SFT by installing radar reflectors, and actively sending sound waves from the SFT to warn submarines.

HOW TO AVOID DAMAGE, OR MINIMIZE THE DAMAGE ON THE STRUCTURE

Some elements are vital to the strength of the SFT structure. These are the anchoring system, the land abutments, and the tube itself. To avoid damage as a consequence of an unwanted incident, and to avoid a minor damage to escalate to a major accident, design of critical elements should have focus on redundancy and ductility [8], [9].

Consequently, as an example, it has to be possible to replace a tether or a pontoon if needed without any problems to the local or global strength of the structure. There will also have to be a weak link between the pontoon and the SFT, to prevent serious damage on the SFT structure in case of ship collision with the pontoon.

Ductility of the SFT tunnel wall is important to reduce the damage from falling or dragging anchors, as well as an inside collision between a truck and the wall.

Fire protection has to prevent serious damage on the SFT wall, which would reduce the strength of the structure.
HOW TO SECURE SAFE EVACUATION IF NEEDED

Monitoring of the traffic and the structure will tell if evacuation of the SFT should take place. Safe evacuation depends on an available alternative route to escape, and sufficient time to reach a safe area. Rapid access from rescue personnel is important, especially in case of an accident inside the SFT or a fire.

Unlike a car fire, uncontrolled inlet of water cannot be stopped by the people inside the SFT tunnel. Also, it cannot be easily stopped by operators in a traffic control center. Hence, safe evacuation is even more important in a SFT than in an ordinary road tunnel.

How the escape route is arranged in the SFT cross section is important. In a case of a fire, the smoke will be concentrated along the roof of the tunnel, and eventually also the escape route, but may be directed longitudinally by means of ventilators. Water, to the contrary, will naturally seek to the lowest point possible, thus flooding the pavement in the lowest parts of the SFT first. Depending on where and how the water inlet is occurring, it might be possible to drive the car out of the tunnel, or walk on foot, on both sides of the flooded area.

Consequently, the vertical alignment of the SFT is very important. If possible, the water should be naturally drained out of the SFT. If pumping is needed to drain the tunnel, redundancy and extra pumping capacity may extend the time available before the situation becomes critical.

The escape route should be easily reached, and used, by everyone inside the SFT, included disabled people. There should be no threshold or staircase to pass on the way to reach safe areas.

Sufficient time is the second element to safe evacuation. Thus no time should be lost to start evacuation procedures if a critical situation occurs. Hence, monitoring of possible threats is of greatest importance, as well as information to the traffic and traffic regulation inside the SFT. Secondly, it is very important that a minor damage will not escalate to a critical damage in a very short time. Redundancy of critical elements, and ductile materials, are important criteria when designing the SFT.

In case of an unwanted leakage, there will be no smoke inside the SFT, and consequently it is easier to direct people by means of visual information. It may also be expected that there will be less probability that panic will occur.
SUMMARY

There is yet not built any SFT for road traffic. However, the development so far indicates that this might be one of several alternative fjord crossing methods when the water is too deep for an immersed tunnel, or a subsea rock tunnel. Safety to people and the SFT structure is of vital concern to the owner, and should be paid great attention in further design of the SFT. In case of a fire, the SFT might more or less be compared to ordinary tunnels. As a floating structure, however, tunnel safety is in addition highly depending on hazardous external loads that might cause damages and unwanted leakage. Uncontrolled flooding of a SFT might result in total collapse of the structure. Consequently, damages on the structure should be prevented. But, in case of a serious damage, there has to be an alternative escape route, and time enough to evacuate before a possible total collapse of the SFT.

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Mobile furnace for determining spalling sensitivity of existing concrete tunnel linings

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ABSTRACT
Although for new tunnels there are extensive fire testing methods, for existing tunnels a reliable and cost-efficient testing method for fire resistance testing of the concrete lining does not exist. This means that nowadays for existing tunnels it is unclear whether or not the concrete tunnel lining is sensitive to concrete spalling. Due to the current lack of prediction models for concrete spalling fire testing still is the most reliable and cost-efficient way.

Efectis has developed a first version of the mobile furnace, which is capable of determining the concrete spalling sensitivity of concrete tunnel linings in-situ. This mobile furnace is able to qualify and quantify the spalling sensitivity of unprotected concrete under fire loads which correspond to tunnel fires. A first test case of the first version of the mobile furnace in a Dutch tunnel is given. In the coming months a new mobile furnace will be developed with more extensive features.

KEYWORDS: mobile furnace, concrete spalling, existing tunnel linings

1. INTRODUCTION
For new tunnels there are extensive fire testing methods, which in general imply that a special test specimen is manufactured and tested in a fire laboratory. However, for existing tunnels a reliable and cost-efficient testing method for fire resistance testing still does not exist.

The urgency of an adequate and reliable test method for the spalling sensitivity of concrete tunnel linings under a fire load is very clear. A big share of today’s tunnels have been constructed about 40 years ago, which implies that these tunnels will soon need renovation. When renovating tunnels questions arise such as “What is the current fire resistance rating of the concrete lining?” or “How sensitive is the concrete to spalling?”. Several testing methods for existing tunnels have been proposed, such as fire testing on small concrete cores extracted from the tunnel. However none of these methods is able to study a substantial and reliable area of the tunnel and preserving the most important boundary conditions present in a real tunnel, such as compression stress on the concrete and relative humidity.

2. REQUIREMENTS
In order to design an appropriate mobile furnace for testing the spalling sensitivity of an existing concrete tunnel lining the influencing parameters of concrete spalling should be well understood. Therefore the first paragraph in this chapter gives a brief background of concrete spalling. The second paragraph concludes with the heating requirements for the mobile furnace. The last paragraph gives some additional requirements.

2.1 Determining parameters of concrete spalling in relation to a mobile furnace
The occurrence of the phenomenon spalling under fire loading is based on three main mechanisms according to most authors1,2,5,9,10,11,12: (1) deterioration of the cement paste, (2) thermal stresses and (3) pore pressures. In theory each of the mechanisms can lead to spalling. In practice a combination of the mechanisms will determine the spalling behaviour in a given situation. The mechanisms have a number of contributing factors that can increase the probability of spalling, for example the type of
aggregates, moisture content, type of cement, heating rate, restrained thermal expansion, etc.

Firstly, many authors\textsuperscript{1,2,3,4,5,6,7,8,9,10,11,12} agree that the heating rate is very important because it influences the thermal stresses and the pore pressures. Secondly, the maximum temperature is important as well. The maximum temperature influences aggregate failure (e.g. Thames River gravel & limestone), corner spalling (not significant in tunnel fire tests) and dehydration of the CSH & CH in the concrete. Aggregate failure does not happen often due to the fact that failure temperatures of most aggregate types are far above 1000\degree C, so the main concern is the deterioration due to the dehydration. The dehydration leads to a shrinkage of the cement paste and coupled with the expansion of the aggregates grains internal cracking will occur. According to Harmathy\textsuperscript{1} the dehydration of CSH is nearly completed at 800\degree C.

Furthermore, it is well-known that a higher compressive stress in the concrete makes the concrete more sensitive to spalling, as does a boundary condition with restrained thermal expansion.

When the concrete tunnel lining under study is protected with insulation material (i.e. fireproof spray mortar or board material) the maximum temperature of the mobile furnace should be according to the maximum expected fire temperatures in the tunnel. This is due to the fact that some common spray mortars show a chemical phase change above 1100\degree C Celsius, which influences the thermal behaviour of the insulation material.

2.2 Required heating conditions

From the previous paragraph it is concluded that the following requirements for the mobile furnace should be met when checking the spalling behavior of concrete:

1. a steep heating curve similar to RWS fire curve to create conservative thermal gradients inside the concrete AND
2. a maximum furnace temperature of at least:
   a. roughly 800\degree C for unprotected concrete
   b. 1350\degree C for protected (=insulated) concrete (when testing according to RWS fire curve)

3. DESIGN OF THE MOBILE FURNACE

This chapter describes the design of the mobile furnace. The first part describes the general design, followed by a more detailed description of several parts of the furnace.

3.1 General design

With an eye on practical aspects and flexibility, the choice have been made for 3 standard propane tanks of 25kg each which are coupled. The gas flows through a mass flow controller for determining the heat flux. Just after this mass flow controller the gas flow is split in 4 tubes. On each of these 4 tubes 5 burner heads with a nominal power of 26 kW are mounted. The burners are placed in a grid of 4 x 5 with 80 mm centre-to-centre distance. The furnace chamber is made of 27mm thick Promatect-H and covered with 30mm ceramic blanket. In the current design there is flame impingement with the surface, which leads to a higher heat transfer coefficient. As a result of this higher heat transfer coefficient the current furnace will demonstrate a worst-case scenario for the object under study as the fire conditions will be more severe. The exact increase of heat transfer will be part of further research.
3.2 Furnace temperature monitoring
The temperatures inside the furnace are monitored with 2 K-type wire thermocouples on two different
heights. Both thermocouples are placed at a distance of 100mm from the concrete surface. One of
these thermocouples is located in the midpoint of the heated area and the second thermocouple is
located 200 mm above the midpoint of the furnace. This choice is made as a result of the convection
of the flames.

3.3 Heating rate
The heating rate is determined with a mass flow controller, which is placed just after the 3 propane
tanks. The operating pressure of the propane tanks is reduced to 3 bar using pressure reduction valves.

4. DESIGN OF EXPERIMENTS
Initially 2 experiments have been carried out to demonstrate the performance of this first version of
the mobile furnace: (1) spalling test on a spalling insensitive concrete mix and (2) spalling test on a
spalling sensitive concrete mix. These experiments are described in more detail below. The tests will
focus on the occurrence of spalling, time of initial spalling and spalling depth.

4.1 Experiment A: Spalling insensitive concrete slab
This experiment was done using a standard C28/35 concrete slab (dimensions: 1.6 x 1.9 x 0.15 m³) in
vertical orientation which is exposed to fire by the mobile furnace for 10 minutes. The concrete mix
of this slab contained siliceous river gravel with a maximum grain size of 32mm and 340 kg/m³
CEMIII. This concrete mix is also known as the RWS-concrete mix for immersed tunnel linings, as
this concrete mix is approved by the Dutch Ministry of Transport as a spalling insensitive concrete
mix. Fire tests with an RWS fire curve on large preloaded concrete slabs (4 x 4 m²) with this concrete
mix have shown that spalling does not occur.

4.2 Experiment B: Spalling sensitive concrete slab
This experiment is almost identical to the previous experiment only difference is the concrete slab,
which is made of a higher grade concrete (C50). For such high concrete grades it is well-known that
the concrete is very sensitive to spalling. Spalling depths will be measured with a sliding caliper and
measured in relation to the non-exposed concrete surface, which will remain intact. The depths will be
measured in a grid of 10 x 10 cm.
5. RESULTS
This chapter shows the results of the performed experiments described in the previous paragraph. The first paragraph shows the general heating conditions for all experiments, followed by the results of spalling test. Thereafter a comparison is made using a Eurocode calculation of the expected temperatures inside the concrete for a RWS fire curve and the mobile furnace.

5.1 Heating conditions
The heating conditions for all 2 experiments were similar. The heat rate was set to 225 kW. The resulting heating curve of the mobile furnace for experiment B is shown in Figure 2. The graph shows that the maximum temperature of the mobile furnace was limited to about 1250 °C. Besides, the graph also shows that a very rapid increase of temperature is achieved with the mobile furnace. The heat rate in the first 1000°C is equal to 35 °C/s, which can most probably be dedicated to the reaction time of the thermocouples. By comparison the RWS fire curve requires only 5°C/s.

![Figure 2: Temperature curve of the mobile furnace during the experiment performed on the spalling insensitive concrete slab (thick line). The temperature curve is compared to the RWS fire curve (squares).](image)

5.2 Experiment A: Spalling insensitive concrete mix
The spalling insensitive concrete slab (C28/35) did not show any spalling during the first 10 minutes of the experiment. For further research the duration of the experiment was extended with an additional 20 minutes, which stretched the total fire exposure up to 30 minutes. In this extended test period the concrete slab also remained intact.

5.3 Experiment B: Spalling sensitive concrete mix
In the second experiment (B) the spalling sensitive concrete initiated spalling after 3 minutes. The heating of the concrete slab was stopped after 10 minutes and the spalling depths were measured, see Figure 5. The figure shows clearly that an area of about 70 cm in width and 40 cm in height is affected by the fire. The fact that this affected area is larger than the area covered by the burners is mainly a result of the flames spreading at the concrete surface. This can also be seen clearly on the photos in Figure 1. Spalling depths up to 23 mm were measured. The average spalling depth (dashed square in Figure 3) is 11 mm.

A solid validation of the spalling depth with an identical test on a traditional furnace has not yet been performed. However, based on the experience of Efectis with similar concrete slabs under RWS fire conditions, the current result matches the expectations.
Figure 3: Measured spalling depths in mm of the C50 concrete slab after heating for 10 minutes with the mobile furnace. The average spalling depth is taken from the dashed square.

5.4 Temperature calculation within the concrete

In the current version of the mobile furnace the temperature is limited to approximately 1250°C. The RWS fire curve increases up to 1350°C in 60 minutes. The difference in temperature development within the concrete can be calculated using the standard Eurocode calculation for concrete and the time-temperature data shown in Figure 4.

A one-dimensional heat calculation is performed based on the assumption of a concrete slab with 3% moisture content, siliceous aggregate and 2350 kg/m³ concrete density. Furthermore, the slab has a thickness of 15 cm and has infinite width and height. Two calculations are performed with different fire curves exposed to the unprotected concrete: (1) Mobile furnace fire curve and (2) RWS fire curve. The resulting temperatures in the concrete are shown in Figure 4. The difference between the temperature developments for the two fire curves is shown in Figure 5 (negative temperatures means that the mobile furnace fire curve is ahead of the RWS fire curve).
Figure 4: Calculated concrete temperatures for the RWS fire curve and the mobile furnace fire curve at various time steps.

Figure 5: Difference in concrete temperature between the RWS fire curve and the mobile furnace temperature ($\Delta T = T_{\text{rws}} - T_{\text{mobile}}$) at various depths in the concrete.

Figure 5 shows clearly that in the first half hour the temperatures in the concrete are higher for any depth when using the mobile furnace. The majority of fire tests in the lab of Efectis Nederland demonstrate that spalling of unprotected concrete subjected to the RWS-fire curve occurs in the first 15 minutes. This makes the mobile furnace acceptable for unprotected concrete undergoing the RWS-curve, but further research needs to be done concerning the use for concrete with fire protection covers.
6. **TEST CASE: MOBILE FURNACE IN AN EXISTING TUNNEL**

The test case for the first version of the mobile furnace was done in the Dutch tunnel. The main research question for this, currently unprotected, tunnel was to examine the concrete spalling behaviour in a qualitative way for a RWS fire curve. As explained earlier in this paper the first version of the mobile furnace is not able to represent the actual fire conditions of the RWS fire curve. (Future version will be able to represent real fire behaviour for all HCM and RWS fire curves). Therefore the more steep fire curve was used with a maximum temperature of 1200°C. In figure 6 some photos of the test setup in the tunnel are shown.

![Figure 6: Photos of the application of the mobile furnace in an existing tunnel. Left: overview of the test setup with the mobile furnace located at the ceiling. Right: close-up of the mobile furnace.](image)

Two different ceiling sections, located about 25 meters apart, were exposed for 2.5 and 5 minutes to 1200°C. This short period was chosen due to the high spalling sensitivity of the concrete and the request of the client not to expose the first reinforcement layer of the concrete. In addition, by doing so, a prediction could be made of the progress of the concrete spalling for a longer period of fire exposure. The result of the test with the mobile furnace was an average spalling depth for each location and an estimate of the resulting spalling depth after 30 minutes fire exposure.

7. **CONCLUSION AND RECOMMENDATIONS**

Experiments performed with different concrete grades showed that the developed mobile furnace is able to determine the spalling sensitivity of an unprotected concrete lining when subjected to typical tunnel fire conditions. It is shown that the current version of the mobile furnace can determine the spalling sensitivity in a qualitative way. Although the achieved spalling depths are similar to the expected spalling depths of the concrete under study in a standard furnace, further validation is needed in this respect. Calculations according to the Eurocode standard have shown that the mobile furnace is able to show more severe concrete temperatures than the RWS fire curve in the first 30 minutes. Due to the limited mobile furnace temperature of 1250°C temperatures will fall behind after 30 minutes compared to the RWS fire curve. On the other hand it is known that in most cases spalling of unprotected concrete will occur in the first 15 to 30 minutes.

For concrete tunnel linings protected with fireproof material further development of the mobile furnace is needed, in order to achieve the required 1350°C for a RWS fire curve. This peak temperature is needed to show the behaviour of the fireproof material under such high temperature loading. For determining concrete spalling behaviour of unprotected concrete such high temperatures are not needed. However, in order to include all mentioned issues above further research of the mobile furnace will focus on achieving the high temperatures (1350°C or even higher) and validation with test results on a traditional furnace, including tests on a wider variety of concrete grades. In addition, a closer look will be given to the effect of resulting compressive stresses when the concrete slab is subjected to local heating with a cold boundary.
REFERENCES
Temperature Loads and Passive Protection in Structural Tunnels

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ABSTRACT

When a temperature gradient is formed across structural elements, they tend to bend towards the heat source. Heat-induced deformations, when prevented, act as temperature loads on the structural element and internal moments and forces are created. Exposure to heat and fire and the need to protect against them are a common concern in industrial facilities. Test cells for gas turbines and aircraft engines as well as furnaces are examples of such facilities where the temperatures one encounters are similar to those that today are considered for road tunnels during a major fire (±1200°C). An analysis of temperatures loads on industrial facility structures and the choice of linings required are part of the conceptual design, and this procedure is similar to what is presently considered for structural tunnels. How these protective linings are connected is also an important aspect in the design process. There are two families of passive protection used in tunnels: sprayed coatings and panels, and their interaction with the structure differ under temperature loads; sprayed coatings follow the deformations of the structure caused by the temperature effects, while panels, independent from structures, do not. This difference should be accounted for in an analytical design by including a variation of the parameters as a function of the temperature.

KEYWORDS : Temperature load, passive protection, structural tunnels, physical-mechanical properties (structure, passive protection,)

INTRODUCTION

The author of the paper has over 35 years of experience with special structural topics such as explosion-proof design, seismic retrofitting, elevated temperatures in industrial facilities, soil-structure interaction, etc. He is a recognized expert in forensic engineering (structural failures, appraisals for integrity, design audits, strengthening and repair methods, etc.) with papers published by the Institution of Civil Engineers in London, UK. He is a member of the Working Commission 1 “Structural performance, Safety and Analysis” of IABSE (International Association of Bridge and Structural Engineering). From 2009 to 2011 he was a member of a team working on two (2) independent studies of Montreal’s main tunnels: the Ville-Marie Tunnel Complex in the city’s downtown core and the Louis-Hippolyte Lafontaine tunnel which passes under the Saint Lawrence River. This paper reflects the author’s views regarding the temperature effects and associated loads in structural tunnels with passive protection.

TEMPERATURE EFFECTS – GENERAL CONTEXT

All materials behave in a similar way when exposed to heat. They expand according to the change in temperature and the thermal expansion coefficient of the material. A simply supported beam with an increased temperature on its underside will form a “banana shape” due to the temperature gradient created across its section. Such a structural element bends away from the face exposed to heat. A linear expansion is another effect of the temperature increase. For materials with a lower thermal conductivity, heat penetration takes time and the effects of a temperature gradient can be considered of long duration. When the heated elements are free to move without any restriction, the deformations do
not result in temperature loads; however, when the deformations are restrained by supports, bending moments are created internally in the element resulting in temperature loads created by gradient. Restrictions in the free elongation of the element will also lead to the development of axial forces. Figure 1 shows the character of a deformation due to a thermal gradient in a simply supported beam that, and the bending moments created in an element with fixed ends.

![Figure 1 Free (left) and restrained (right) deformations under a thermal gradient.](image)

The most effective way to deal with the temperature loads is to allow the elements to deform freely. We find many examples of such an approach, such as elements designed to be used as linings to reduce the temperature exposure of the structures they have to protect. The lining deforms due to the thermal gradient, and the temperature loads on the protected structures are reduced to a level which allows them to perform safely.

**Passive protection in industrial facilities**

Protective linings against fire and elevated temperatures in industrial facilities are a common example of linings being used to protect against temperature effects and their related loads where free deformations are not permitted. Dealing with exposure to an extreme heat is part of the structural considerations in such cases, where the temperatures encountered are similar to those considered today for road tunnels during a major fire. Test cells for gas turbines or aircraft engines are examples of facilities designed to withstand exposure to extreme heat. Such cells are used for testing and monitoring turbine performance at full capacity with the associated gas and heat emissions. Test cells are usually built as independent, monolithic concrete structures with an appropriate lining inside. The structures are designed for temperature loads which are then used as criteria for the degree of required protection.

![Figure 2 Test cells for engines; example of a concrete structure and lining. Courtesy of Kalitta Air (photo on the left) and CENCO (photo on the right).](image)

![Figure 3 Examples of refractory linings in industrial furnaces. Courtesy of IMASA (photo on the left) and PROFIL KOMERC (photo on the right).](image)
Figure 2 above shows an example of a test cell structure and the lining inside. The linings used for test cell are made of stainless steel panels. The panels are attached to the concrete in such a way as to eliminate the thermal stresses which otherwise would be generated by their deformation due to the heat. In the example shown below, the fasteners are aligned in one row along the middle of the wall. Figure 3 shows another example of linings, those used in industrial furnaces. The refractory bricks inside the cylindrical furnace deform very slightly under the temperature loads and preserve their integrity to protect the steel structure they are built on.

**Passive protection in special applications – The Space Shuttle**

As we know, refractory linings were also in use on the Space Shuttle and their performance was subject of concerns when some tiles were damaged on the shuttle’s surface during Columbia’s final mission. The temperature that the tiles were designed for was upwards of 1650°C, in order to sustain an exposure to 1260°C when entering the atmosphere. The degree of protection provided by the tiles was quite high; the maximum temperature the body of the shuttle, made of aluminum, would be exposed to was 175°C. Figure 4 shows the tiles of the refractory linings on the shuttle [1].

![Figure 4](image)

**Figure 4** Use of refractory tiles for protection of the Space Shuttle [1].

The use of refractory tiles on the highly sophisticated Space Shuttle, and the criteria used in their design and “translated” in the characteristics of the system reflect the aspects that one must keep in mind while choosing a lining. The refractory tiles on the shuttle were normally 150 mm by 150 mm and, depending upon the heat load, varied in thickness from ± 25 mm to ± 125 mm. They were composed of high purity silica fibers with entrapped air taking up 90% of the volume [1]; Figure 5 shows a detail of the tiles used on the shuttle. We can see in Figure 5 that the tiles were attached to the body of the shuttle using only silicon-rubber glue (labeled “Glue” in the figure). The glue also played the role of “thermal breaker” between the tiles and the airframe and it allowed a free deformation of the tiles without inducing temperature loads due to a thermal gradient.

![Figure 5](image)

**Figure 5** Lining on the Space Shuttle; detail of the tiles [1].
TEMPERATURE EFFECTS ON TUNNELS

From a structural point of view tunnels can be divided into two categories; tunnels bored in rock (non-structural tunnels), and tunnels built as concrete structures (structural tunnels). The risks associated with fire are different for each.

Tunnels bored in rock
In the case of tunnels bored in rock, damages which result from a long exposure to elevated temperatures are limited to the concrete lining that is applied to the surface of the rock. Such concrete linings play a limited structural role; they form a barrier between the rock and the air in the tunnel to prevent a weathering of the rock surface. The Mont Blanc fire in 1999 demonstrated that even after two days of continuous fire, the bored hole in the mountain remained intact. Figure 6 shows the aftermath Mont Blanc tunnel fire.

Figure 6 Mont Blanc Tunnel fire aftermath in 1999.

Tunnels built as concrete structures
A fire of similar magnitude to that which occurred in Mont Blanc would have led to very different results in a tunnel built as a concrete structure. Tunnels built using the “cut and cover” method, as well as all immersed tunnels built as prefabricated caissons, fall into this category. A progressive loss of integrity leading to the total loss of the tunnel would be a consequence of a fire of such size. Figures 7 and 8 show an example of a progressive collapse of a tunnel of this type.

Figure 7 Failure mechanism of a structural tunnel - Initial stage.
Figure 8 Failure mechanism of a structural tunnel – Subsequent stages
As shown in Figure 7, the failure mechanism would be initiated by the loss of integrity in the middle of the ceiling where the bending moments and the tensile stresses reach their maximum in the zone exposed to the fire. The failure of the ceiling would be followed by the collapse of the outside wall and the floor slab. Water and backfill would enter the first traffic tube and begin to fill the tunnel. The failure of the second traffic tube would immediately follow the loss of the first tube. As shown in Figure 8, with the loss of the first tube the symmetry of the structural system would also be lost. Positive bending moments in the ceiling and in the floor would increase significantly, and these elements would not withstand the pressure from the water and backfill. The second tube would then fill with water which would trigger the failure mechanism of the tunnel’s central tube.

TEMPERATURE LOADS ON TUNNEL STRUCTURES

From a structural point of view there are two effects from exposure to fire. The first is a progressive deterioration of the concrete as a structural material. This includes the loss of material due to spalling and a decrease in the capacity of both concrete and rebar with the raise in temperature. The second effect is an additional load on the structural system that results from the thermal gradient across the sections exposed to the heat. A structural analysis that includes temperature loads should be a part of the design process to define the level of protection required for the tunnel if exposed to a fire. These needs are clearly expressed in many publications and documents such as “Comportement au feu des tunnels routiers” issued by Centre d’Études des Tunnels (CETU) [2] and “Résistance au feu des tunnels routiers: l’approche réglementaire française” [3], both published in France. These documents could be used as references.

In the concrete frames of structural tunnels, free deformations of the elements exposed to heat are prevented by rigid connections between the members in the corners of the frame. Bending moments due to temperature increases are developed in the system. The bending moments and the resulting cracks in the concrete frame are a function of the temperature increase, the geometry of the tunnel system and the physical-mechanical properties of structural elements. In the case of tunnels backfilled with granular soil, passive pressures on the side walls are also developed by linear expansion on the ceiling. The principle of development of bending moments in the corners of the frame is shown in Figure 9 hereafter. Bending moments from external pressures (backfill and/or water) are increased by the bending moments resulting from the temperature loads.

![Figure 9 Bending moment diagrams for loads acting on structural tunnels](image)

Existing tunnels were designed to withstand backfill and water pressures and, if not overdesigned, the quantity of rebar within the structure would be sufficient to carry only those loads. Additional bending moments in the corners caused by temperature loads would lead to the yielding of the rebar and the development of large, permanent cracks on the cold side of the structural frame. Cracks developed on the cold side of the frame during a major fire would not be visible and therefore impossible to be assessed as a potential risk in a tunnel’s post-event life. Occurring at the level of steel yielding, the cracks would open the way to water or moisture penetration inside the concrete, leading to corrosion and progressive deterioration.
An investigation of the effects of temperature loads in existing tunnels was performed by Efectis Nederland in the Netherlands and presented in “Emerging Problem for Immersed Tunnels: Fire Induced Concrete Cracking” [4]. Deformations and stresses under temperature loads were obtained in analytical models and confirmed afterwards by the results of fire tests performed at reduced scale. The results from the analysis and the location of permanent cracks observed after the fire tests are shown in Figure 10 (the white lines in the photo indicate the location of the permanent cracks). The location of cracks in the corners of the frame corresponds to the high tensile stresses obtained by the analysis.

**MAXIMUM ALLOWABLE TEMPERATURE LOADS FOR A TUNNEL STRUCTURE**

To prevent excessive stresses and the resulting permanent cracks on the cold side of the frame, a tunnel should be analysed to define the maximum temperature it can be exposed to. This temperature is also a criteria for choosing a passive protection. The maximum temperature to avoid concrete spalling and a decrease in rebar capacity is 380°C.

**Analytical model – Family of Parameters**

The structural analysis is a quite complex procedure which involves a number of parameters that are temperature dependant. The analysis to establish the temperature load limits would be done in two steps. The first step is to establish the performance of the tunnel under permanent loads such as backfill and water pressure. The second step is to analyze the structure for the combination of permanent and temperature loads. An analysis of temperature loads only and the addition of their effects to those of the permanent loads would not be adequate. Such a simplified approach would not take into account a variation of the mechanical parameters of concrete as material (the change with temperature) and changes in the stiffness of the elements due to cracks of the concrete sections. These changes have an effect not only on the forces and bending moments from the temperature loads but also on forces and moments from the loads acting permanently on the tunnel. For this reason, the temperature loads and the permanent loads should be used in combination. Table 1 below shows the parameters to be considered in the analysis. The parameters are dived in two categories: “inside” (the zone exposed to the heat) and “outside” (the zone on the cold face of the tunnel frame).

**Table 1** Parameters to be considered in an analytical model.
In the case of permanent loads, an analysis is performed in using conventional methods; all characteristics are constant and there are no adjustments required in the model. In the second analysis, which in the present case refers to temperature levels of 200 °C and 380 °C, the temperature effects are taken into account. The “depth” of the zone exposed to heat is a result of the temperature increase, and all characteristics affected be the increase should be adjusted. The stresses on the cold face of the tunnel should be verified and compared to the limit for cracking. If cracks appear, the stiffness of the “cracked elements” should be decreased in the model and a new run of the analysis should be performed. The results for the given temperature should be reviewed to verify the stress levels in the rebar at the cold face to see if the yield stress has been reached causing permanent cracks in the concrete. The thermal gradient as the heat penetration in the concrete is probably the most important parameter in the modal and it depends on the concrete’s properties as a material. Figure 11 below shows the curves for thermal gradient, according to different sources, and following different temperatures at the surface (200 °C, 380 °C, 700 °C and 1200 °C).

Figure 11  
Thermal Gradient in a Concrete Section, according to different sources [5], [6], [7].

TEMPERATURE LOADS IN TUNNEL STRUTURES WITH PASSIVE PROTECTION

Passive protection
There are two families of products used as passive protection for tunnels: panels, which are attached to tunnel surfaces with mechanicals fasteners, and coatings, which are applied by spraying. The interaction between the tunnel structure and the passive protection is different for each family because of the effects of temperature loads developed in the system. Figure 12 shows an example of both types of protection.

Figure 12  
Panels and sprayed coatings as passive protection of tunnels.
Thermal gradient
Panels attached by fasteners are independent of the tunnel structure and can deform freely when heated. Sprayed coatings are solid materials that form with the structural elements of the tunnel one single structural element. Figure 13 shows thermal gradients developed during a fire across a tunnel structure for the two families of passive protection.

![Figure 13](image)

Structures protected by panels are exposed to “controlled” and limited temperature loads which result from the degree of protection established as a criteria for choosing the appropriate thickness of the panels. In the case of sprayed coatings, temperature loads resulting from the heat increase are the loads that must be carried by “strengthened” (thicker) ceilings and walls. The resulting “reinforced structure” is exposed directly to the fire and the temperature loads generated in the system are different than in the case of panels. The bending moments (and other generated forces) depend on the physical-mechanical properties of the elements exposed to the concrete and the coating which change with the temperature.

Analytical model

Table 2  Tunnel with passive protection - Parameters considered in an analytical model

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</tr>
<tr>
<td>Δ Temp. + Actual + Coating 1</td>
<td>±400°C f (Temp.)</td>
<td>20°C N.A. const.</td>
</tr>
<tr>
<td>Δ Temp. + Actual + Coating 2</td>
<td>±800°C f (Temp.)</td>
<td>±20°C N.A. const.</td>
</tr>
<tr>
<td>Δ Temp. + Actual + Coating 3</td>
<td>±1000°C f (Temp.)</td>
<td>±200°C Adjust. Required f (Temp.)</td>
</tr>
<tr>
<td>Δ Temp. + Actual + Coating 4</td>
<td>±1200°C f (Temp.)</td>
<td>±380°C Adjust. Required f (Temp.)</td>
</tr>
</tbody>
</table>
Table 2 (similar to Table 1 discussed earlier) shows the parameters to be considered in the analysis of tunnels with passive protection. For tunnels protected by panels, the analysis remains the same as for the tunnel structure as panels are attached independently and there is no structural interaction between the tunnel and the protection. For tunnels with sprayed coatings, the analysis should include the mechanical-physical properties of the coatings. As in the case of concrete, the parameters of the coating are a function of the temperature, and an iterative calculation should be performed in the same manner as for the tunnel structure we described earlier.

The purpose of an analysis for a tunnel with sprayed coatings is two folds; the first aspect is the capacity of the tunnel structure “reinforced by the coating” to carry the temperature loads, the second aspect is to define the stresses developed in the coating. Compression stresses will appear in the coating parallel to the structure, and shear stresses will be developed at the face of the concrete. These stresses should then be compared to the maximum allowable stresses for the coating as a material.

**Sprayed coatings – Available information**

Information and data on different products in use as sprayed coatings do not seem to reflect the context presented in this paper. We could not find the parameters at different temperature levels which would allow the creation of an analytical model that could perform the kind of analysis. We also could not find the limits of performance of the coatings (compression and shear strength at the concrete face) for higher temperatures which could be compared to the stresses eventually obtained by the analysis. In addition to these considerations, it should be mentioned that the bond between the coating and the concrete during the life span of the tunnel could be affected in a humid environment; any water penetration trough the concrete would affect the bond and the performance of the coating during a fire becomes even less predictable.

**DISCUSSION**

In the last decade, fire safety in tunnels has become a major international concern. In the case of existing tunnels, passive protection has been recognised as a way to ensure the protection of a structural tunnel should a major fire occurs. Passive protections, both sprayed coatings and panels, are therefore installed in many tunnels, and information expressing and justifying their need could be easily obtained on the internet. Many publications however focus on the performance of the concrete and the rebar as material and the loss of their properties when exposed directly to the flames. The criteria in many documents regarding this topic refer to the temperature requirements which reflect such limits of performance.

The effects of temperature loads on tunnel structures and the associated risks of development of permanent cracks in the corners on the cold side are another criteria for temperature exposure. They should be addressed in an analytical investigation of the tunnel to define the limits of performance and consequently the level of protection the tunnel would require when exposed to a major fire.

An analytical investigation is a complex iterative procedure based on the physical-mechanical properties which are a function of temperature. The goal of the analysis is to allow the structure to crack in a “controlled way”, keeping the width of the cracks within acceptable limits. For the bending moments (and other generated forces) caused by a thermal gradient, cracks act as a stress “reliever”; a decrease in rigidity reduces the forces resulting from the temperature loads.

In the case of tunnels with panels as a passive protection, the analysis does not consider the panels as they are free to deform without restriction in a way similar to the linings used in industrial applications that were discussed at the begging of the paper. These linings are independent from the structures they protect and their connections allow free deformation without inducing unnecessary stresses when exposed to heat.

Tunnels with sprayed coatings however would require an analysis which would take into account the properties of the coatings as a function of temperature. As solid materials, the coatings form one
structural unit with the concrete where stresses created by temperature loads also appear in the coating. The example of tiles used in the space shuttle we discussed earlier shows how these type of stresses could be overcome; the thick glue used to attach the tiles to the shuttle body acted as “thermal breaker” allowing independent deformations of the tiles and the shuttle.

Since the data for sprayed coatings seem to not be readily available, their use and their efficiency should be addressed with caution. An analysis based on the properties of the coatings as a function of the temperature would not be possible and their performance could not be established by such an analysis. Stresses developed in the coatings and the concrete-coating interface would remain unknown and leave unanswered questions regarding their effectiveness. The only way to overcome this aspect would be to eliminate them as a structural component from the analysis. The use of steel reinforcement resistant to high temperatures in coatings, placed in such a way as to act as a rebar in the coating and attached properly to the concrete, could potentially be a solution. The quantity of the rebar as well as type and location of the fasteners should ensure that the integrity of the coatings is preserved when exposed to fire.

REFERENCES

Test methods for determining fire spalling of concrete

Lars Boström*, Robert Jansson
SP Technical Research Institute of Sweden

ABSTRACT

There are today no standardized methods for determining the fire spalling behaviour of concrete. Therefore many different methods and techniques are used for the same purpose. The present paper shows how different methodologies can affect the results and to some extent the difficulties regarding experimental determination of the spalling behaviour. A large range of methods, ranging from small specimens up to relatively large elements have been fire tested using different loads, fire curves and conditioning. The results show that small scale tests may be applicable to determine whether a type of concrete is prone to spall or not, but it is not possible to determine to what extent the spalling will proceed, i.e. the amount of spalling. Another important parameter regarding spalling experiments is whether compressive load is applied during the test or not, and how the load is physically applied. Unloaded specimens spall significantly less compared to specimens loaded in compression. It is also important to apply the load in such way that it does not influence on the results. An external loading arrangement is recommended. The effect of different fire curves on the spalling has also been studied. The results indicate that the fire curve does not influence on the severity of the spalling. The time to spalling is governed by the type of fire curve. In fast heating the spalling starts sooner compared to a slow heating.

KEYWORDS: Concrete, test methods, spalling

INTRODUCTION

In some tunnels, or parts of tunnels, the concrete lining or the shotcrete shall fulfil certain requirements regarding the fire resistance, i.e. the load bearing capacity and/or the fire containment. Often is the fire resistance of concrete structures assessed through calculations based on design codes such as Eurocode. When calculating the fire resistance it is important to consider the possibility of fire spalling. Since it is in practice impossible to assess the spalling behaviour theoretically, fire testing is normally necessary [1]. The available solutions to assess that the spalling is limited to an acceptable level is by using a concrete that is well documented from previous projects, to use some type of fire protection or by fire testing. A problem with fire testing is that there are today no standardised methods for testing the spalling behaviour of concrete or shotcrete for tunnel applications. Therefore numerous of different methods are used today; sometimes even different methods in the same tunnel project. The problem is that the obtained test results to a large extent depend on how the test was performed, the test set-up and the geometry of specimens. There are test set-ups used which are giving completely erroneous results with respect to amount and severity of fire spalling, see for example [2].

A key issue when dealing with fire testing is the cost. In order to predict the spalling behaviour of a concrete structure in a fire, the test set-up must represent the real structure. Because tunnel constructions generally are large and sometimes carrying substantial loads, also the test specimens have to be large and externally loaded which makes the testing complicated and expensive. Since it normally not is possible to test full scale elements some simplifications have to be made, and sometimes these simplifications goes too far leading to a test that does not represent what would happen in a real fire. As long as the spalling phenomenon not is understood, fire testing is necessary and even if it is costly, large tests are required.

If the fire tests could be performed in a similar way, for example with a standardised test methodology
that represents the main characteristics of a majority of constructions; it would be possible to establish a data bank that can be used for the development of assessment rules.

TEST METHODS USED

There are many different test methods used around the world, ranging from small bench size tests up to large tests of complete tunnel segments. Tests of whole tunnel elements with accompanying loading system is the closest we can come to reproduce the cross section and boundaries expected in real fires [3-7]. A disadvantage with the method is that complicated test setups are needed and as a consequence the test becomes very expensive.

There are also many different small scale tests used. One example is a method developed at the Danish Technical University [8]. Here is a cylindrical test specimen used (Ø 150 mm x 225 mm). The test specimen is loaded to a selected stress level along the curved sides of the cylinder and thereafter one of the flat sides (one of the ends) are exposed to a constant temperature of 1000 ºC for 60 minutes. This method is small, simple and cost efficient. With this method can concrete that are very sensitive for heating be identified although the effect of the boundary conditions on the fire spalling behaviour is difficult to define.

At SP in Sweden are two different methods used [9], one using large slab specimens and one using small slab specimens. The small tests are used for development tests while the large test is used for verification. Both methods employ conventional equipment found at all normal fire resistance laboratories.

In addition to the examples on test methods given above there exist many other test set-ups, especially at universities. Generally different types of small specimens are tested, since they do not require large test facilities and they are relatively cheap to carry out. Although, it is important to be aware about the limitations of the method when using small specimens. This limitation with small scale specimens was illustrated during a test at SP when large loaded slabs spalled but unloaded 150 x 150 mm² cubes tested at the same time did not show any tendency to spall.

EFFECTS ON THE SPALLING BEHAVIOUR DUE TO DIFFERENT FACTORS

Specimen size and geometry

The geometry has most certainly a considerable effect on the spalling. A project was carried out to find suitable specimen geometry for the determination of fire spalling [2]. In the study were several different types of specimens examined ranging from small cubes normally used for determination of compressive strength (150 x 150 x 150 mm) to large slabs (1800 x 1200 x 400 mm), see Table 1. The results from the study are presented in Tables 2-3. Table 2 present the results obtained with self-compacting concrete and Table 3 results obtained with tunnel concrete. In this study was the loading system different between the large and small slabs. The large slabs were loaded through post stressing bars going through the centre of the slabs while the small slabs were loaded externally with a loading cradle.

No results are shown for the cubes or the plates with the dimensions 500x500x100 mm since no spalling was observed on any of the test specimens. On the cylindrical test specimens the spalling depth was not measured because of the technical difficulty to measure on a highly curved surface. Instead was the weight loss recorded, which was done for all specimens. The weight loss is a rough measurement since it is difficult to compensate for the water loss.

The results shown in Table 2 indicate that the large slabs and the loaded cylinders give approximately the same amount of spalling. Although, it is difficult to compare these results since the water loss is quite different, the cylinders is exposed around the whole specimen while the large slabs are only exposed on one surface. Hence the weight loss due to water evaporation may be expected to be much
higher on the cylinders compared to the slabs.

Table 1. Different geometries of the test specimens.

<table>
<thead>
<tr>
<th>Type</th>
<th>Geometry</th>
<th>Fire exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab</td>
<td>1800x1200x400 mm</td>
<td>One-sided fire exposure</td>
</tr>
<tr>
<td>Slab</td>
<td>1800x1200x200 mm</td>
<td>One-sided fire exposure</td>
</tr>
<tr>
<td>Beam</td>
<td>3600x600x200 mm</td>
<td>One-sided fire exposure</td>
</tr>
<tr>
<td>Plate</td>
<td>500x500x100 mm</td>
<td>Five-sided fire exposure</td>
</tr>
<tr>
<td>Slab</td>
<td>500x600x100 mm</td>
<td>One-sided fire exposure</td>
</tr>
<tr>
<td>Slab</td>
<td>500x600x200 mm</td>
<td>One-sided fire exposure</td>
</tr>
<tr>
<td>Cube</td>
<td>150x150x150 mm</td>
<td>Five-sided fire exposure</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>Ø = 150 mm, l = 300 mm</td>
<td>Fire exposure around the cylinder (not on the end surfaces) and special test made at DTU</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>Ø = 150 mm, l = 450 mm</td>
<td>Fire exposure around the cylinder (not on the end surfaces)</td>
</tr>
</tbody>
</table>

Table 2. Effect of specimen geometry on the fire spalling (self-compacting concrete).

<table>
<thead>
<tr>
<th>Method</th>
<th>Weight loss (%)</th>
<th>Mean spalling (mm)</th>
<th>Maximal spalling (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concrete: w/p=0.30</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large slabs</td>
<td>15.8</td>
<td>45</td>
<td>65</td>
</tr>
<tr>
<td>Small slabs unloaded</td>
<td>10.0</td>
<td>34</td>
<td>52</td>
</tr>
<tr>
<td>Small slabs loaded</td>
<td>32.1</td>
<td>102</td>
<td>175</td>
</tr>
<tr>
<td>Long cylinders unloaded</td>
<td>1.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Long cylinders loaded</td>
<td>18.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Concrete: w/p=0.40</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large slabs</td>
<td>18.7</td>
<td>45</td>
<td>67</td>
</tr>
<tr>
<td>Large beam</td>
<td>3.1</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>Small slabs unloaded</td>
<td>8.5</td>
<td>28</td>
<td>40</td>
</tr>
<tr>
<td>Small slabs loaded</td>
<td>30.0</td>
<td>102</td>
<td>174</td>
</tr>
<tr>
<td>Long cylinders unloaded</td>
<td>3.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Long cylinders loaded</td>
<td>22.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Concrete: w/p=0.55</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large slabs</td>
<td>15.3</td>
<td>48</td>
<td>68</td>
</tr>
<tr>
<td>Small slabs unloaded</td>
<td>5.0</td>
<td>17</td>
<td>32</td>
</tr>
<tr>
<td>Small slabs loaded</td>
<td>21.7</td>
<td>66</td>
<td>119</td>
</tr>
<tr>
<td>Long cylinders unloaded</td>
<td>2.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Long cylinders loaded</td>
<td>17.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Most spalling in these tests was observed on the small slab specimens (600x500x200 mm). The large slabs (1800x1200x200 mm) spalled much less which looks strange. The reason for this is almost certainly that the large slabs were loaded through pre stress wires, and when the spalling reached the wires was the compressive stress lost, and the spalling stopped. This result illustrates the close connection between external stress and fire spalling.

In Table 3 is a comparison made between large and small slabs with different thickness as well. It is clear that the small slabs show a significantly smaller amount of spalling.

The size of the test specimen affects the severity of spalling. Several tests have been performed on different types of concrete where the only difference has been the size of the samples. The loading was for all specimens applied through post stressing bars going through the centre of the specimens. In Table 4 are results presented where the spalling depth is shown for some different concrete qualities [10-11]. The tests were carried out using slabs with the dimensions 600 x 500 x 200 mm and
1800 x 1200 x 200 mm, i.e. the only difference is the size of the fire exposed surface. In addition several tests were carried out on concrete with polypropylene fibres, but none of these specimens spalled and those results are not included in the table. The results shown are in most cases mean values of at least two tests.

Table 3. Effect of specimen geometry on the fire spalling (tunnel concrete).

<table>
<thead>
<tr>
<th>Method</th>
<th>Weight loss (%</th>
<th>Mean spalling (mm)</th>
<th>Maximal spalling (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/c=0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large slabs</td>
<td>19.4</td>
<td>144</td>
<td>272</td>
</tr>
<tr>
<td>Small slabs</td>
<td>12.5</td>
<td>18</td>
<td>35</td>
</tr>
<tr>
<td>w/c=0.38, 2 kg/m³ polypropylene fibres</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large slabs</td>
<td>2.9</td>
<td>16</td>
<td>40</td>
</tr>
<tr>
<td>Small slabs</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>w/c=0.38, 25 kg/m³ silica</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large slabs</td>
<td>9.0</td>
<td>56</td>
<td>80</td>
</tr>
<tr>
<td>Small slabs</td>
<td>9.4</td>
<td>13</td>
<td>23</td>
</tr>
<tr>
<td>w/c=0.38, 25 kg/m³ silica, 2 kg/m³ polypropylene fibres</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large slabs</td>
<td>0.3</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Small slabs</td>
<td>1.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>w/c=0.38, 100 kg/m³ limestone filler</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large slabs</td>
<td>18.2</td>
<td>132</td>
<td>244</td>
</tr>
<tr>
<td>Small slabs</td>
<td>16.6</td>
<td>24</td>
<td>40</td>
</tr>
<tr>
<td>w/c=0.38, 100 kg/m³ limestone filler, 2 kg/m³ polypropylene fibres</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large slabs</td>
<td>5.9</td>
<td>36</td>
<td>64</td>
</tr>
<tr>
<td>Small slabs</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4. Effect of specimen size on the mean spalling depth.

<table>
<thead>
<tr>
<th>Recipe</th>
<th>Cement</th>
<th>w/c</th>
<th>Limestone (kg/m³)</th>
<th>Fire curve</th>
<th>Mean spalling depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Large slabs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Unloaded</td>
</tr>
<tr>
<td>10</td>
<td>CEM II</td>
<td>0.65</td>
<td>105</td>
<td>Std</td>
<td>38</td>
</tr>
<tr>
<td>46</td>
<td>CEM II</td>
<td>0.52</td>
<td>120</td>
<td>Std</td>
<td>-</td>
</tr>
<tr>
<td>46</td>
<td>CEM II</td>
<td>0.52</td>
<td>120</td>
<td>HC</td>
<td>-</td>
</tr>
<tr>
<td>39</td>
<td>CEM I</td>
<td>0.40</td>
<td>140</td>
<td>Std</td>
<td>-</td>
</tr>
<tr>
<td>39</td>
<td>CEM I</td>
<td>0.40</td>
<td>140</td>
<td>HC</td>
<td>-</td>
</tr>
<tr>
<td>45</td>
<td>CEM I</td>
<td>0.40</td>
<td>-</td>
<td>HC</td>
<td>-</td>
</tr>
<tr>
<td>A</td>
<td>CEM I</td>
<td>0.40</td>
<td>-</td>
<td>Std</td>
<td>-</td>
</tr>
</tbody>
</table>

For all the concretes presented in Table 4, i.e. concrete that spalled during the fire test, the mean spalling depth was considerably larger on the large slabs. The large slabs had a mean spalling depth between 1.6 to 3.5 times deeper compared to the small slabs.

The conclusion from these results is that there is a large difference in the results which depends on the geometry of the test specimen. The large slab specimens with 400 mm thickness resulted in most spalling and small cubes and unloaded plates did not spall at all. Hence it is a wide scatter depending on geometry.
Effect of external loading

The loading has an important role on the spalling. It is not only the stress level applied but also how the load is applied that affects the results. Table 5 show the mean spalling depth measured on some different concretes tested with varying load level. The applied load was chosen to give a compressive stress of 0, 5 and 10 % of the compressive strength of the actual concrete. All tests were performed on small slab specimens with the dimensions 600 x 500 x 200 mm. The load was applied by post stressing bars going through the centre of the test specimen, except the tests made on aged specimens (specially marked in the table). These aged specimens were loaded with an externally mounted cradle.

The results presented in Table 5 show that there is a difference in spalling between unloaded specimens and specimens loaded in compression. This was also the case for cylindrical specimens, see Table 2. When increasing the stress level from 5 % of the compressive strength up to 10 % was there no significant change in the measured spalling depths. The tests were carried out with relative low compressive stresses, so it might well be that the spalling increases with higher compressive stresses.

When comparing the method of applying the load to the concrete specimens, see Figure 1, a remarkable difference was observed in the amount of spalling. When using an externally mounted cradle the spalling was more severe. An explanation could be that when using the post stressing bars in the centre of the specimen a different crack pattern is formed which may release water vapour and facilitate water transportation within the concrete sample.

The test results show that unloaded specimens spall less compared with loaded specimens. Hence it is not recommended to perform spalling tests on unloaded specimens, if not for a specific reason. Furthermore, and maybe even more important, the method of applying the load on the specimen have a great influence on the amount of spalling. If possible it is recommended that the load is applied as in practice. When applying the load through post stressing bars or pre stress bars/wires it is difficult to draw any conclusions on the spalling behaviour of the concrete since this type of loading affects the spalling. For instance, if pre stress wires are used the load is lost when the spalling has progressed to the wires and they are exposed to the fire.
Table 5. Effect of applied load on the mean spalling depth.

<table>
<thead>
<tr>
<th>Age (months)</th>
<th>Mean spalling depth (mm) at stress level of compressive strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 %</td>
</tr>
<tr>
<td>Recipe 39, CEM I, w/c=0.40, limestone=140 kg/m², HC fire</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Not tested</td>
</tr>
<tr>
<td>6</td>
<td>Not tested</td>
</tr>
<tr>
<td>12</td>
<td>Not tested</td>
</tr>
<tr>
<td>48</td>
<td>Not tested</td>
</tr>
<tr>
<td>Recipe 45, CEM I, w/c=0.40, limestone=0 kg/m², HC fire</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Not tested</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>Not tested</td>
</tr>
<tr>
<td>46</td>
<td>Not tested</td>
</tr>
<tr>
<td>Recipe 10, CEM II, w/c=0.65, limestone=105 kg/m², Std fire</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Not tested</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>Not tested</td>
</tr>
<tr>
<td>12</td>
<td>Not tested</td>
</tr>
<tr>
<td>63</td>
<td>Not tested</td>
</tr>
<tr>
<td>Recipe 46, CEM II, w/c=0.52, limestone=120 kg/m², Std fire</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Not tested</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>9</td>
<td>Not tested</td>
</tr>
<tr>
<td>12</td>
<td>Not tested</td>
</tr>
</tbody>
</table>

* Tested with load applied through an externally mounted cradle. The load was 4.8 MPa, i.e. slightly less than 10% of the compressive strength.

Effect of fire curve

There is often a debate on which fire curve shall be used when testing concrete. The general view found in the literature is that the fire curve has a major effect on the spalling, the more severe fire, the more severe spalling. These observations have mainly been observed when heating at very slow rates, e.g. when conditioning specimens for determination of strength at elevated temperatures. If the heating rate is too high the specimens may spall. The above case is generally far from the heating rates expected in fire scenarios. In Table 6 are results from tests performed with small slab specimens using different fire curves. Tables 7-8 show the results obtained with large slab specimens. These results indicate that there is no significant influence on the amount of spalling due to the heating gradient, nor the maximum temperature used in the experiments. There is, however, a large difference when looking on the time when the spalling starts. In a fast heating, e.g. the hydrocarbon fire, the spalling starts after 1-2 minutes. In a slow heating, e.g. by using a temperature ramp of 10 K per minute, the spalling starts after 45-60 minutes. In all tests the furnace temperature is between 500-700 °C when the spalling commences.
Table 6. Results from small scale tests on self-compacting concrete.

<table>
<thead>
<tr>
<th>Max spalling (mm)</th>
<th>Mean spalling (mm)</th>
<th>Spalling time (min)</th>
<th>Fire curve*</th>
<th>Appl. stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building concrete, CEM II, w/c=0.52, limestone=120 kg/m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>29</td>
<td>4,0</td>
<td>HC</td>
<td>5,7</td>
</tr>
<tr>
<td>43</td>
<td>25</td>
<td>3,0</td>
<td>HC</td>
<td>5,7</td>
</tr>
<tr>
<td>58</td>
<td>36</td>
<td>3,4</td>
<td>HC</td>
<td>5,7</td>
</tr>
<tr>
<td>67</td>
<td>42</td>
<td>9,5</td>
<td>Std</td>
<td>5,8</td>
</tr>
<tr>
<td>46</td>
<td>26</td>
<td>11,3</td>
<td>Std</td>
<td>5,7</td>
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<tr>
<td>77</td>
<td>48</td>
<td>28,8</td>
<td>Slow</td>
<td>6,0</td>
</tr>
<tr>
<td>84</td>
<td>44</td>
<td>28,5</td>
<td>Slow</td>
<td>5,6</td>
</tr>
<tr>
<td>Tunnel concrete, CEM I, w/c=0.40, limestone=140 kg/m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>age=6 months</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>59</td>
<td>42</td>
<td>53,4</td>
<td>10 K/min</td>
<td>9,2</td>
</tr>
<tr>
<td>64</td>
<td>35</td>
<td>31,9</td>
<td>Slow</td>
<td>8,8</td>
</tr>
<tr>
<td>71</td>
<td>38</td>
<td>30,0</td>
<td>Slow</td>
<td>9,2</td>
</tr>
<tr>
<td>55</td>
<td>22</td>
<td>10,0</td>
<td>Std</td>
<td>9,2</td>
</tr>
<tr>
<td>67</td>
<td>41</td>
<td>11,0</td>
<td>Std</td>
<td>9,2</td>
</tr>
<tr>
<td>48</td>
<td>25</td>
<td>3,0</td>
<td>HC</td>
<td>9,5</td>
</tr>
<tr>
<td>64</td>
<td>29</td>
<td>3,0</td>
<td>HC</td>
<td>9,3</td>
</tr>
<tr>
<td>Tunnel concrete, CEM I, w/c=0.40, limestone=140 kg/m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>age=9 months</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>23</td>
<td>13,0</td>
<td>Std</td>
<td>4,4</td>
</tr>
<tr>
<td>59</td>
<td>28</td>
<td>13,0</td>
<td>Std</td>
<td>4,4</td>
</tr>
<tr>
<td>47</td>
<td>22</td>
<td>2,5</td>
<td>HC</td>
<td>9,1</td>
</tr>
<tr>
<td>64</td>
<td>34</td>
<td>2,7</td>
<td>HC</td>
<td>8,7</td>
</tr>
</tbody>
</table>

HC = hydro carbon curve, Std = standard fire curve, Slow = slow heating curve, 10 K/min = ramp heating rate with 10 K per minute

Table 7. Results from large test specimens of self-compacting concrete.

<table>
<thead>
<tr>
<th>Max spalling (mm)</th>
<th>Mean spalling (mm)</th>
<th>Spalling time (min)</th>
<th>Fire curve*</th>
<th>Appl. stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building concrete, CEM II, w/c=0.65, limestone=105 kg/m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>117</td>
<td>55</td>
<td>9,5</td>
<td>Std</td>
<td>3,9</td>
</tr>
<tr>
<td>87</td>
<td>41</td>
<td>10,1</td>
<td>Std</td>
<td>3,9</td>
</tr>
<tr>
<td>84</td>
<td>34</td>
<td>8,9</td>
<td>Std</td>
<td>3,8</td>
</tr>
<tr>
<td>93</td>
<td>39</td>
<td>1,3</td>
<td>HC</td>
<td>3,8</td>
</tr>
<tr>
<td>Building concrete, CEM II, w/c=0.52, limestone=120 kg/m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>156</td>
<td>102</td>
<td>6,1</td>
<td>Std</td>
<td>3,8</td>
</tr>
<tr>
<td>200</td>
<td>106</td>
<td>2,5</td>
<td>HC</td>
<td>3,8</td>
</tr>
<tr>
<td>Tunnel concrete, CEM I, w/c=0.40, limestone=140 kg/m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>83</td>
<td>11,7</td>
<td>Std</td>
<td>6,4</td>
</tr>
<tr>
<td>159</td>
<td>83</td>
<td>1,3</td>
<td>HC</td>
<td>7,7</td>
</tr>
<tr>
<td>179</td>
<td>71</td>
<td>1,3</td>
<td>HC</td>
<td>7,7</td>
</tr>
<tr>
<td>Tunnel concrete, CEM I, w/c=0.40, limestone=0 kg/m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>28</td>
<td>10,0</td>
<td>Std</td>
<td>6,8</td>
</tr>
<tr>
<td>47</td>
<td>28</td>
<td>2,0</td>
<td>HC</td>
<td>6,8</td>
</tr>
<tr>
<td>47</td>
<td>30</td>
<td>2,0</td>
<td>HC</td>
<td>6,8</td>
</tr>
</tbody>
</table>
Table 8. Results from large test specimens of tunnel concrete.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Max spalling (mm)</th>
<th>Mean spalling (mm)</th>
<th>Spalling start (min)</th>
<th>Fire curve (-)</th>
<th>Appl. stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>89</td>
<td>40</td>
<td>2,0</td>
<td>RWS</td>
<td>7,1</td>
</tr>
<tr>
<td>A2</td>
<td>140</td>
<td>97</td>
<td>8,0</td>
<td>Std</td>
<td>7,0</td>
</tr>
<tr>
<td>F1</td>
<td>45</td>
<td>16</td>
<td>4,0</td>
<td>RWS</td>
<td>7,0</td>
</tr>
<tr>
<td>F2</td>
<td>40</td>
<td>19</td>
<td>12,0</td>
<td>Std</td>
<td>8,2</td>
</tr>
<tr>
<td>I1</td>
<td>32</td>
<td>8</td>
<td>4,8</td>
<td>RWS</td>
<td>7,9</td>
</tr>
<tr>
<td>I2</td>
<td>20</td>
<td>0</td>
<td>13,5</td>
<td>Std</td>
<td>8,2</td>
</tr>
<tr>
<td>M1</td>
<td>31</td>
<td>3</td>
<td>4,8</td>
<td>RWS</td>
<td>8,0</td>
</tr>
<tr>
<td>M2</td>
<td>25</td>
<td>1</td>
<td>16,1</td>
<td>Std</td>
<td>8,0</td>
</tr>
<tr>
<td>N1</td>
<td>27</td>
<td>9</td>
<td>4,8</td>
<td>RWS</td>
<td>8,0</td>
</tr>
<tr>
<td>N2</td>
<td>37</td>
<td>2</td>
<td>19,0</td>
<td>Std</td>
<td>8,0</td>
</tr>
</tbody>
</table>

The conclusion of the study on effect of fire curve on spalling is that for the concretes tested, and the methods used, it does not influence on the amount of spalling. The results point more towards more severe spalling for the fire curves with a lower heating gradient. A pronounced effect on the time when the spalling starts can be observed. The studied fire curves cover a reasonable region of heating regimes that can be expected for concrete directly exposed to fires. There are some contradictory results found in the literature on this issue. During a study on spalling of slabs with the dimensions 1450 x 640 x 80 mm heated from three sides made of ordinary concrete with strength 22.5 MPa and 45 MPa it was found that during faster heating than the standard fire curve 5-10 mm spalled away whereas during exposure to the standard fire curve none or minor surface spalling occurred [12]. Also on tests on thin loaded slabs, thickness 30 mm, it was found that increasing the heating rate reduced the load level were spalling occurred [13].

Measurement of spalling

The spalling can be measured using different techniques. The most frequent methods used are by visual inspection during the test, by weighting and by measuring the spalling depth after the fire exposure. With visual inspection it is possible to define when the spalling starts, and to get a rough measure on the amount of spalling. It is a very simple method and the result is reliable as long as the amount and severity of spalling is of no interest. The advantage with measuring the weight loss is that the amount of spalling can be measured during the test, i.e. it is possible to determine the weight loss as a function of time, and it is a simple method. The disadvantage is that it is difficult to separate the weight loss due to spalling and the loss due to evaporation and loss of water. This can lead to significant errors if not handled correctly. The measurement of the actual spalling depth after the fire test gives a correct measure on the amount of spalling. The disadvantage with the method is that it only shows the result after a complete fire test and it can be quite time consuming, especially of a large area shall be mapped with a course mesh. Depending on the shape of the surface it may also be important to measure the shape before the fire test to establish the initial state of the surface. This is often the case when testing shotcrete, where the surface is very uneven.

Conditioning of test specimens

Concrete is a hygroscopic material containing a substantial amount of water after casting (150-300 kg/m³). If the concrete is kept indoors for a long time, and is in equilibrium with 60 % relative humidity, the amount of free water decreases to around 50 kg/m³. The moisture content has most certainly a significant role on the spalling behaviour. Therefore it is of great importance to know the amount of water in the tested concrete samples.

The drying process is very slow, and it may take many years before the concrete reaches a state of equilibrium with the surrounding climate, especially for dense concretes such as self compacting concrete and high strength concrete. Furthermore, due to the slow drying process the moisture content
will be different within the concrete. The surface dries fast while it takes long time for the central parts of the element to reach equilibrium.

A question is thus whether the concrete shall be tested at a young age, i.e. with high moisture content, or when it has reached its final conditions, i.e. in some cases after several years.

**Other important issues**

Concrete is a broad family of materials, consisting of cement, water, aggregates and additives. These constituents can be mixed with different proportions and the constituents can be different. The type of cement used varies considerable, especially between different countries, as well as the type of aggregates. Therefore is it of great importance that the material that is tested is well prescribed in the test report or scientific article, i.e. that the mix proportion s of the different constituents are presented as well as what kind of cement, type and size of aggregates and additives that have been used.

**DISCUSSION AND CONCLUSIONS**

It is well known, and the results presented here further proves, that the test method used when determining the spalling behaviour of concrete exposed to fire can have a dramatic effect on the results. When reading the literature on experimental studies of fire spalling of concrete it shows clearly the very wide spread of methods used, ranging from very small test specimens up to full size concrete elements, and with fire exposure from small radiant panels up to almost explosions. Furthermore, the concretes tested are made of raw materials from different parts of the world and the recipes are quite different. When putting these facts together it is quite clear that it is impossible to compare test results between different studies.

In the present study have a number of different samples and techniques been used to determine the spalling behaviour of concrete. The study clearly shows large differences between different methods. Small scale tests are often used, due to simplicity and cost, but the ability of these methods to show the spalling behaviour is questionable. Generally the small scale test methods result in much less spalling compared to tests with large elements. Although, it may well be that small scale tests can be used to determine whether a type of concrete spalls or not. According to the test results within the present study, whit the range of concretes used, the small loaded slab specimens detected well if the concrete spalls or not.

The load applied during fire tests as well as how the load is applied affects the results to a large degree. Unloaded specimens (or specimens loaded in tension) spall less compared to specimens loaded in compression. Within the load levels used in these tests it was no significant difference in the spalling behaviour, it was only the unloaded specimens that spalled less. A substantial effect was observed on how the load was applied to the test specimens. Two different systems were used, one where tubes were casted into the slab specimens where post-stressing bars were mounted, and one where the load was applied externally with a cradle. The experiments made with the externally cradle spalled much more compared to the system with the centrally mounted post-stress bars.

The fire curve or heating rate used in experiments is often discussed. The general view is that the higher heating rate, the severer spalling occurs. This may be correct for certain concrete qualities, and at very slow heating rates. In the present study heating rates that are expected in fires were examined and for a relatively large span of concrete qualities no significant effect on the amount and severity of spalling was observed. The difference is the time when the spalling starts. In rapid heating the spalling starts sooner compared to a slow heating.

A general conclusion from the study is that experimental study of concrete spalling is very difficult. There are many parameters within the test methodology that affects the result. It is therefore important that before starting an experimental study the objectives are clearly stated, and that a test methodology is chosen which eliminates possible errors.
REFERENCES

Assessing the fire resistance in existing tunnels

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ABSTRACT

In this paper the assessment of the fire resistance of an existing tunnel using a combination of experiments and computer simulations is described. The tunnel has been built over half a century ago and some decades ago a passive fire protection product has been sprayed against the tunnel roof. Unknowns in this specific case are the adhesion and performance of the mortar, the susceptibility to spalling of the concrete mixture and the exact reinforcement details. By means of laboratory fire tests on test specimens removed from the tunnel and limited scale on-site fire tests, complemented with computer modelling, the current fire resistance of the immersed tunnel is determined.

KEYWORDS: fire resistance, existing tunnel linings, passive fire protection

INTRODUCTION

The results of the large European research programmes on tunnel fires of the last decade, like UPTUN, FIT and DARTS, are slowly converted into legislation. Largely based on the European tunnel directive, tunnel fire safety requirements are introduced or modified in the National Codes of the member states of the European Union.

In some cases existing tunnels have to be upgraded within the foreseeable future to meet the contemporary requirements. In addition, existing tunnels reach the age they were initially designed for and are awaiting large renovations. In case of an upgrade or renovation all fire safety aspects are assessed and depending on the type and usage of the tunnel, some aspects are more important than others.

For immerged tube tunnels the fire resistance of the tunnel structure is important to prevent collapse and serious damage in case of fire [1]. In existing tunnels of an advanced age, the construction details of the tunnel structure are uncertain or even unknown. In addition, for passive fire protection products, the performance or adhesion might have been degraded in the course of time. So, when establishing plans for upgrading or renovating an existing tunnel often a 'reverse engineering' process will be started to find out what the current state of the tunnel is.

FIRE RESISTANCE

The fire resistance of a tunnel lining is important to prevent or limit damage to a tunnel in case of fire. Possible considerations on the required level of fire resistance are the prevailing law and the acceptable damage level for the owner or concessionaire of the structure. The acceptable damage level is of course related to the corresponding closure time of the tunnel and the economic importance of the infrastructure.

In general the fire resistance requirements of the owner are expected to be higher than the
requirements in the legislation, because for the owner additional aspects are important. In general the
focus of the legislator will be on victims and damage to third parties, while the focus of the owner will
also be on the reparability of the tunnel structure itself.

For the fire resistance of a concrete tunnel with fire protection the following aspects are important:

- The relevant fire scenario and accompanying thermal load on the structure;
- Acceptance criteria (critical temperatures of reinforcement and concrete), in the view of
  reparability or collapse;
- The thermal insulation of the present passive fire protection (and resulting concrete and
  reinforcement temperatures);
- The fixing/bounding of the passive fire protection on the concrete, under fire conditions;
- The susceptibality of the concrete mixture to spalling of concrete for the relevant fire curve.

In case of unprotected linings the following aspects are important:

- The relevant fire scenario and thermal load on the structure;
- Acceptance criteria (critical temperatures of reinforcement and concrete) in the view of
  reparability or collapse;
- The heat penetration into the structure and temperature development of concrete and
  reinforcement;
- The susceptibility of the concrete mixture to spalling of concrete for the relevant fire curve.

In the next sections the tools and possibilities to assess the aspects above are described in the
framework of a study carried out for an existing immersed tunnel, protected with passive fire
protection. Aspects of the study apply also for unprotected concrete tunnels, where spalling of
concrete is expected to be a major damage mechanism.

**FIRE SCENARIO AND THERMAL LOAD**

The relevant fire scenario or fire curve can be the subject of a separate study depending on the use of
the tunnel and the equipment present in de tunnel. In this paper, the Rijkswaterstaat or RWS fire curve
as specified in Efctis/RWS tunnel test procedure [2] is used without further analysis. The
Rijkswaterstaat fire curve is commonly used in the world and referred to in international standards
like the NFPA 502 [3].

![Figure 1: The Rijkswaterstaat fire curve.](image-url)
ACCEPANCE CRITERIA

The acceptance criteria as used in the Efectis/RWS tunnel test procedure and NFPA 502 are based on the Dutch Safety guidelines [4] and intended to prevent damage to the tunnel structure that can not be repaired. The limiting temperatures for concrete and reinforcement steel after 2 hours heating according to the Rijkswaterstaat fire curve are:

- Maximum temperature of concrete: 380°C;
- Maximum temperature of the reinforcement steel: 250°C.

These criteria are lower than the generally accepted values where the construction materials start to loose strength (400°C – 450°C). However, in these criteria is taken into account that due to thermal inertia higher temperatures will appear after the two hours of heating (time effect). Additionally, for reinforcement steel it is also taken into account that thermal elongation of the steel will occur already at lower temperatures which might cause permanent sagging of the structure.

ASSESSMENT OF THERMAL INSULATION OF PASSIVE FIRE PROTECTION

When a passive fire protection has been applied in a tunnel in the past, questions arise on its performance nowadays. In the tunnel under investigation, passive fire protection has been applied decades ago and the applied thickness of fire protection was verified by the results of fire tests, performed shortly after the application of the sprayed thermal insulation. Therefore the main questions are:

- Are the fire tests that were carried out in the past still in agreement with the current practice?
- What is the applied thickness?
- Are the applied thickness and the expected temperature development, based on the old fire tests, still in agreement with the current practice?
- Is the thermal insulation of the passive fire protection still acceptable, after this many years?

In order to answer these questions, the applied thickness has been determined and multiple concrete cores have been drilled from the existing submerged tunnel including the layer of passive fire protection, in this case a spray mortar. The concrete cores have been fully instrumented with multiple thermocouples per test specimen at different positions to record the temperature development in the concrete core during the fire test.

![Figure 2: Drilled concrete core prior to instrumentation.](image)

In order to carry out a fire test on the instrumented concrete cores, multiple cores have been casted within a concrete slab in such a way that one dimensional heat penetration is ensured through the concrete cores. Figure 3 shows the concrete cores prior to casting and figure 4 shows the test specimen just before the fire test.
The fire test has been carried out on the small furnace at the laboratory of Efectis Nederland in Rijswijk. The test specimen has been exposed to the Rijkswaterstaat fire curve for two hours and the resulting temperatures of three of the concrete cores are shown in figure 5. The three test specimens are labeled A, B and C and the position relative to the interface between insulation and concrete is added in the legend. It can be clearly seen that the critical concrete temperature of 380°C is not reached and therefore the thermal insulation of these protected samples is sufficient. The critical steel temperature of 250 °C is only reached in the interface; the steel temperatures stay well below that value (150-200 °C at a depth of ~30 mm).
ASSESSMENT OF SPALLING RISK OF CONCRETE

The spalling risk of an existing concrete structure (which might be protected or unprotected) can only be determined by fire tests on representative test specimens. This means the test specimen should be large enough to account for the thermal restraint present in the existing tunnel. Therefore it is extremely difficult or even impossible to carry out a fire test on a small scale test sample from the tunnel that gives representative results on the spalling risk. I.e. the drilled concrete cores are absolutely not suitable to determine spalling risk of an existing concrete structure!

The appropriate solution is an on-site fire test carried out using a mobile furnace in the existing tunnel to assess the spalling risk in a representative way [5][6]. This method is not discussed in detail in this paper, but here is referred to [6].

CONCLUSION

The fire resistance of existing tunnels is an important parameter for to ensure that the damage level after a fire is acceptable. In this paper a method is described how the fire resistance level can be determined, based on a study carried out for an existing immersed tunnel.

Important issues before starting to determine the fire resistance are the relevant fire scenario or fire curve to account for and the required acceptance criteria. After the scenario and criteria are set the fire resistance of the existing structure can be assessed by evaluating the thermal insulation of the structural concrete and reinforcement and the susceptibility of the concrete mixture to spalling. Both the thermal insulation and the susceptibility can only be assessed by means of representative fire tests. Therefore a custom fire test has been set up to determine the thermal insulation of passive fire protection in a representative way by means of drilled concrete cores. For the assessment of the susceptibility of the concrete mixture to spalling an in-situ test with a mobile furnace is appropriate.
REFERENCES

INTRODUCTION

Water leakage in rock tunnels can create severe problems such as formation of icicles during winter. In cases where injection is not enough in order to fulfill the requirements on water leakage other measures must be taken, i.e. the water must be conveyed away from roof and walls down to the drainage system of the road or railway. This is traditionally done by jointing boards of extruded polyethene cellular plastic to the rock by bolts.

The amount of combustible material shall of safety reasons be minimised in tunnels. During the building phase is the storage of the cellular plastic a potential fire hazard, and also when they have been mounted and not yet protected they form a risk factor. Furthermore, the traditional drainage system requires a relatively large space. About 6-10 m³ extra shaft pit per meter tunnel is needed for the traditional drainage which gives a higher environmental load and higher costs.

Rockdrain is a channel system that is mounted directly to the rock reinforcement. The channel system is protected by a special concrete with good fire resistance and thermal insulation. There are many advantages with the Rockdrain system compared with traditional drain.

The present project has the objectives to study the function of the Rockdrain system in a real installation, a railway tunnel, as well as doing detailed studies of different properties in laboratory.

ROCKDRAIN

Rockdrain is a system for water drainage as well as fire and frost insulation, specially designed for underground facilities such as traffic tunnels and more. The concept is based on a draining pipe mesh, covered by an insulating, waterproof and fire resistant shotcrete, Solbruk T, see figure 1. The draining pipe mesh cannot be mounted directly on the rock surface since the fastening, with drilled holes and plugs would be too cumbersome. Recommendation is that the surface is first shotcreted with approximately 30 mm concrete for the nails to be easily attached. If the surface first is permanently reinforced with shotcrete this is obviously good enough. Although the draining pipe mesh is soft and malleable there is a limit depending on the roughness of the substrate, where it no longer can be mounted. The limit can be said to be where the tunnel contour does not comply with the tolerance requirements, for drilling and blasting, which are for traffic tunnels, or where the rock properties provides very rough edges. This could be handled by shotcrete modeling.

During 2011, the Rockdrain system has been installed in two phases in a doubletrack tunnel under construction. Phase 1 was conducted in a full tunnel section for a length of 40 m and some 20 m in the wall, situated about 100 m from the northern tunnel entrance. Phase 2 was conducted in a full tunnel section for a length of 20 m about 500 m further into the tunnel. Mapping of geology and in leaking water had previously been done associated with the excavation of the tunnel. Mapping of the location and intensity of in leaking water in the two phases have been done continuously. In phase 1 no leaks are longer observed. In phase 2 some single leaks remains, the tendency is that leakage decreases with
time. During the following winter and spring further mapping will be performed.

![Illustrated cross section of the Rockdrain system. (1) Shotcrete min 30 mm, (2) Draining pipe mesh, (3) Covering shotcrete, (4) Solbruk T, (5) Flushing unit](image)

**TEST PROGRAM**

**Material tests**

The results from the first material tests on compressive strength, density and thermal properties, showed a large scatter. When investigating these variations it was concluded that the type of pump used affects the material properties. The type of pump also affects how well the Solbruk can be applied in practice. Piston pumps are not suitable for Solbruk so it is recommended that screw pumps are used.

**Water drainage function**

The water drainage has been testing on small samples (1.2 x 0.8 m²) with the complete system, for five mounting tolerances. The channel net was mounted with the distances; 0, 5, 10, 15 and 20 mm. For distance 0 and 5 mm there is no problem for the water to go through the channel net. There were more or less problems for the water to get through with distance 10 and 15 mm. With distance on 20 mm there was no water through the system. It is thus recommended that the net should not be mounted more than 10 mm from the surface. Although, if the distance is larger in some points, it would not affect the drainage since the water can chose other paths within the channel net.

**Fire resistance**

The fire resistance of the system has been tested using the hydrocarbon fire curve on 1.5 x 1.2 m² specimens. In the tests were the type of application of the Solbruk T examined, wet or dry sprayed, as well as the effect of adding polypropylene fibres into the Solbruk T. Four fibre contents were studies, no fibres, 0.3, 0.6 and 1.2 kg/m³ fibres. The tests showed that severe spalling occurred on all specimens using dry spraying. This was also the case for the wet sprayed specimens without fibres. The wet sprayed specimens with 0.6 and 1.2 kg/m³ polypropylene fibres did not spall at all. With 0.3 kg/m³ fibres there was some spalling on the wet sprayed specimens.
Crossrail Fire Safety Designs

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KEYWORDS: Fire strategies, Smoke control, Tunnel Ventilation, Design Fire Size, Rolling Stock, Open-Wide Gangways, Fire safety systems

INTRODUCTION
This poster paper will give an overview of the fire safety designs for the Crossrail project, and highlights several of the more complicated and difficult challenges faced by the design team. The Crossrail project in London, UK is currently the largest active sub-surface infrastructure project in Europe. It consists of a new heavy rail line spanning London from west to east, and incorporates 22km of new tunnels beneath central London with eight new sub-surface stations. Five of the stations will be mined with individual platforms connected via cross-passages, and three will be cut-and-cover box-type with island platforms. Ultimately the line will run a metro-like service, with a peak service of 24 trains per hour when the system is fully operational. Mott MacDonald (MM) has been heavily involved in the project from its inception in the 1990s right through to the current detailed design stage. Construction has now commenced on a number of sites across London. MM's most recent responsibilities in the fire engineering area have included the system-wide fire strategy for all of the tunnels, fire strategy for one of the major interchange stations at Liverpool Street, design of smoke-control systems for the tunnel and all station platforms, design of fire-fighting systems for the tunnels, the design fire size and fire safety of the proposed Open-Wide Gangway (OWG) rolling stock for the project, and the design of the fire safety systems at Liverpool Street Station.

ROLLING STOCK - DESIGN
The rolling stock for the project will consist of five-car sets in a ten-car train, with OWG in each of the five-car sets. The fire safety standard for the rolling stock will be BS6853 Category 1a. The design fire size for the project was developed and reviewed extensively over the life of the project, before settling on the current specification. It was further reviewed following the project decision to employ OWG rolling stock. MM modelled the spread of fire within the train to establish the validity of the design fire, as well as to estimate the life safety of the rolling stock prior to detrainment. The methodology was validated against published tests of carriage fires and project-commissioned tests of luggage fires to give confidence to the results. MM also carried out simulations of evacuation from the rolling stock to estimate egress times.

TUNNELS - FIRE STRATEGY
The tunnels for Crossrail consist of two new tunnels, totalling 22km of tunnelling, plus a major refurbishment of a 550m existing disused tunnel. The tunnels provide distinct challenges in terms of fire safety. The longest new-build tunnel is 14km in length, with a single western portal but the line splits via a Y-junction east of Whitechapel, and so has two eastern portals. There is also a split crossover within the main tunnel. Intermediate shafts and cross-passages are employed to provide emergency egress (including that of Persons of Restricted Mobility - PRM) and intervention facilities. A separate new-build tunnel takes the line under the Thames. A third tunnel dates from the 19th Century and required to be completely refurbished to be made suitable for use by Crossrail. The fire strategy was developed to minimise the risks from fire to both life safety and asset protection, and also to minimise the impacts on operational continuity. Stakeholder Approval was required for all the tunnel fire strategies, achieved via usage of the BS7974 process. The major Stakeholders on the project include Crossrail Limited (Project & Train Operator), London Underground (Station Infrastructure...
Manager), Network Rail (Railway Infrastructure Manager), and London Fire Brigade (Fire & Rescue Service), plus other site-specific Stakeholders.

TUNNELS - DESIGN
The smoke control systems for the tunnels are required to provide safe egress routes and intervention routes in event of a fire incident with the tunnel. They are also required, in conjunction with station systems, to provide the same in event of a fire at a station platform, either on the train or on the platform. Full-height Platform-Screen Doors (PSDs) will be employed at all eight of the sub-surface stations, which provides some complications in the design of the smoke-control systems for the tunnels, as well as for the stations (both mined and box stations), specifically the split in smoke-extraction capabilities between the longitudinal tunnel ventilation system (TVS) and the station platform extract systems.

The tunnel fire-fighting systems for such a large tunnel system are complex, due to the length of the tunnels and the vertical alignment. A large number of various types of tunnels already exist underneath London, and the geology of the London clay further complicates the tunnel alignment requirements. Furthermore, energy usage optimisation requirements for the rolling stock adds more constraints upon the vertical alignment. The consequences are that the Crossrail tunnel vertical alignment has significant gradients, both upwards and downwards. There is a supply main located at each surface access point (one at each end of a station, plus at every intermediate shaft and portal), and independent supplies for each bore. The detailed design of the system was required to maintain flowrate and supply pressure to fire service requirements at all locations within this complex system with over 44km of fire mains in total.

STATIONS - FIRE STRATEGY
Liverpool Street Station is a main station interchange for the Crossrail project. It links with two London Underground metro stations as well as the heavy-rail Liverpool Street main line terminus. Accordingly, there were numerous challenges in integrating the Crossrail station operations and fire safety provisions with those of the existing infrastructure, without compromising the safety cases for the existing stations. The fire strategy was developed to minimise the risks from fire to both life safety and asset protection, and also to minimise the impacts on operational continuity. As part of the fire strategy, risk assessments were undertaken to determine the requirements for fire suppression systems in the station. Stakeholder Approval was required for the station fire strategy, achieved via usage of the BS7974 process.

STATIONS - DESIGN
The fire safety measures for the station include provision of means of controlling smoke and allowing persons, including PRM, to evacuate safely from the station, intervention routes for the fire services, fire & smoke detection and alarms, fire suppression systems where deemed necessary by the fire strategy, fixed fire-fighting systems, including provisions for the fire services to attend and use the systems, and passive fire protection via compartmentation and materials.

FUTURE PLANS
The project has recently completed design to RIBA Stage E. Enabling works have commenced and the next major stage will be developing the designs to RIBA F and beyond, and selection of Contractors to design-and-build contracts. Project completion is scheduled for 2018.
Automatic Fire Suppression in Tunnels with Stationary Compressed Air Foam Extinguishing Systems (CAFS)

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KEYWORDS: Fire suppression, stationary, automatic extinguishing system, compressed air foam, One Seven CAFS

INTRODUCTION
Catastrophes in road tunnel constantly remind us of the importance of security issues. A comprehensive security concept for tunnel is crucial, not only in order to save lives, but also to protect the structure and serviceability of the tunnel itself. Especially cases of fire constitute an immense threat to life and property.

COMPRESSED AIR FOAM
Compressed air foam systems, also known as “CAFS”, are used in fire fighting by fire departments worldwide. Usually fire trucks are equipped with CAF systems. The company One Seven of Germany initiated the use of compressed air foam in automatic fire suppression systems.

The technology used for the stationary applications is the same as for the use in mobile. Compared to conventional foam extinguishing systems, where a water-foaming agent solution will be foamed at the discharge device, CAF systems generate foam in a mixing chamber where a water-foaming agent solution is mixed with compressed air. With foam instead of water being transported through pipes towards the discharge devices it is possible to reach heights of more than 400 meters and horizontal distances of more than 2,000 meters.

The One Seven system defines a reproducible extinguishing agent with monitored and controlled flows and pressure of water and air which results in a highly effective fire fighting system with extremely low proportioning rates for foaming agent of 0.3% for class A and 0.5% for class B fires. The One Seven System uses an environmentally sound, flour-surfactant-free foaming agent. This agent replaces perfluorinated surfactants (PFS) with new polyfluorinated surfactants, and thereby stands up to the latest challenges posed by science and legislation.

Therefore, an integrated foam concentrate tank of 500 liters is sufficient for a fire time of up to 100 minutes. An obvious reduction of the amount of water required compared to other conventional extinguishing systems results from the high efficiency of One Seven compressed air foam, which minimizes the necessary supply of extinguishing water.

FIRE TESTS AT RUNEHAMAR
At full-scale-tests in the Runehamar test tunnel in Norway the One Seven system proved its capabilities under attendance and supervision by SINTEF. Two test series were carried out to demonstrate different scenarios and hazards of fires in tunnels.

A truck was displayed, loaded with 720 pallets, of which 80% were wooden and 20% were plastic pallets. That way a heat release rate of 160 MW and temperatures higher than 1000 °C were reached during the pre-burning phase. This fire was able to be controlled within 6 minutes and to be extinguished in the following 16 minutes without the help of firehoses, despite wind speeds of up to 5 m/s.

Furthermore 5,000 liters of Diesel fuel were ignited in a fire pan with a surface of 100 m². This fire was fully extinguished with One Seven compressed air foam after only 2 minutes.

THE PÖRZBERG TUNNEL, GERMANY
An automatic One Seven compressed air foam fire suppression system has been installed in the Pörzberg-Tunnel in Germany. A pressure station provides each of the system’s two foaming modules with 1,700 liters of firewater per minute from a water pool with a volume of 72 m³. The extinguishing system is located in a building outside the tunnel itself, thereby securing a maximum of accessibility and control. The extinguishing foam is produced here and transported by a main pipe and sub-lines to the extinguishing areas. One Seven foam rotors will effectively distribute the extinguishing agent in the afflicted areas. The fire detection system activates the stationary system automatically in cases of fire and allocates the endangered extinguishing area. The fire suppression system can be activated and operated automatically, semi-automatically or manually. The entire system is monitored and controlled by the extinguishing system control unit, which at the same time has a permanent connection to a remote operation control center.

FIRE TESTS AT PÖRZBERG
For the final approval of the automatic fire suppression system several fire tests were conducted in November 2010. The test were prepared, conducted and recorded by an independent engineering company.

Test 1: Fire Test according to RABT 2006 testing the automatic fire detection system
Fire detection occurred after 25 seconds. After the automated detection, the jet fans shut down and smoke-suction occurred by means of the controllable suction-openings through the intermediate ceiling and into the aeration outlets. The stationary extinguishing system was activated after fire detection and the foam pipe was filled. In order to test for foam quality, the last extinguishing area was activated. Foam quality was judged to be excellent.

Test 2: Fire Test with heptane to test allocation of extinguishing area and efficacy of the stationary fire system in fire classification B
The second test concerned the confirmation of the faultless, automatic functioning of the stationary extinguishing system and the accurate allocation of extinguishing areas. Further, foam quality and extinguishing success were assessed. Twenty liters heptane were chosen as fire agent and ignited in an area of 2 m². The maximal heat release rate was 6.4 MW. The airflow rate, produced by using jet fans, was 2.5 m/s westward. The fire was extinguished after approximately one minute. During the test, temperature developments were measured. It was observed that, due to the short duration of fire, temperatures rose to 90 °C very shortly and decreased rapidly due to fast extinguishing. Test results were convincing: Short duration of fire and little smoke development. Foam quality was found excellent.

Test 3: Vehicle fire to test allocation of extinguishing area and efficacy of the fire suppression system in fire classification A.
This test occurred under realistic circumstances in order to judge faultless functioning, extinguishing capacity and extinguishing success. A fire was ignited in the glove compartment of a small vehicle. Automatic fire detection occurred around 6 minutes after ignition. Around five minutes after fire detection, the foam pipes were filled and the system ready to begin the extinguishing operation. The automatic system was able to contain the fire within one minute. The fire department extinguished the remaining fire in the vehicle’s interior and the engine-bay with a mobile One Seven system installed in the tunnel fire truck.

SECURITY THROUGH TECHNOLOGY
Fire security in tunnel is and will be one of the main challenges for operators and engineers worldwide. Compressed air foam is, like any other extinguishing method, certainly not a cure-all solution. For applications where the possible appearance of hazards through class B fires has to be faced, compressed air foam can not any longer be ignored as an alternative possibility to conventional extinguishing systems to protect humans, material values and structure.
Concept of Cost Effective Modernization of Old Single-tube Road Tunnels
Case Study: Učka Tunnel

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KEYWORDS: Road tunnel, modernization, tunnel safety systems, ventilation control

INTRODUCTION

Practically whole Croatian modern motorway network was built during the past 12 years. Starting with construction relatively late, in compare to most Western Europe and other developed world countries, gave the opportunity to apply most advanced design and technological solutions to motorway construction and what is of special interest in this article, to road tunnels.

Despite the fact that the most of the new Croatian tunnels are highly ranked regarding the safety issues tested by Euro TAP (European Tunnel Assessment Programme), there are some older tunnels, all of them single-tube with bi-directional traffic, whose state of equipment and design solutions are not strictly in accordance with today regulations and standards accepted in EU. Some of those tunnels are on the road sections which are foreseen to be upgraded to full motorway profile in the future, as twin tube tunnels. In the meantime, their safety level could remain inappropriate, especially in terms of increasing traffic rate during years and high seasonal peaks.

UČKA TUNNEL – CASE STUDY

Tunnel Učka is a typical example described previously. It is a tunnel built in 1981, as a single-tube, bi-directional tunnel, located on largest Croatian peninsula Istria. With a length of 5062 m it was the longest tunnel in Croatia at that time. In 2006 it was decided to start extensive modernization of the tunnel in order to raise the safety level, especially in terms of fire safety and evacuation possibilities. Modernization was planed in two phases.

The requirements of the first phase were mainly focused on implementation of modern active fire protection systems, video detection, procedures and appropriate software, without any big changes in civil engineering part of the tunnel or major technical systems, like ventilation or power supply. The second phase of modernization foresees upgrading the tunnel to full profile (two tubes), and include improvements in major tunnel systems, which will significantly raise the evacuation possibilities, quality of fire brigade intervention and safety level in general.

On the poster exhibited in Poster Session a cost-effective concept of raising tunnel safety level with afore-mentioned limitation is presented. It can be generally applied on tunnels like Učka tunnel, as intermediate solution to full profile upgrade, or as a long term solution in old tunnels which are planed to remain as single-tube tunnels, with lower traffic intensity and possible restrictions in HGV and dangerous goods transports.

Governing criteria to evaluate safety level for Učka tunnel was taken from Austrian RVS guidelines for road tunnels. Main idea was that desired safety level can be achieved by combining different construction, technical and organizational measures. Final decision of the ventilation system configuration for the twin tube tunnel (the second phase) is evaluated by using quantitative risk analyse (QRA).
As mentioned before, bigger construction works were not part of the brief for the first phase of Učka tunnel modernization. Initial state of the tunnel before modernization was evaluated, regarding ventilation system at first place, remote control system, fire detection system, video surveillance and air sensor system. According to desired upgrade in safety level and dynamic of investments it was decided which technical systems and corresponding modernization schedule would be applied.

The biggest changes were done on ventilation control and fire detection system. Fire detection system was entirely replaced with a modern system based on linear fiber-optic sensor cable, supported with the temperature profile measuring software. In combination with the new AID (Automatic Incident Detection) system, fire detection possibilities are highly improved. The new active control of existing ventilation system enables control of longitudinal velocity in order to obtain the best suitable smoke propagation forms which create optimum conditions for all phases of passengers’ evacuation and fire fighters activities as well. Ventilation control software was successfully tested both on virtual tunnel physical model of ventilation and during the extended on-site “pool” fire tests.

CONCLUSION

Synergy of all described technical systems, modern software solutions and organizational measures, as the result of the tunnel modernization, can successfully overcome disadvantages of single tube tunnel in the certain period till the full profile upgrading. In the case that modernized single tube tunnel is planned as the long time solution, some reasonable restrictions in HGV and DG transports should be analysed.
Carmel Tunnels – Case Study and project profile
Fire alarm & voice evacuation system

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In General
The technology of safety systems has been developed, and, still developing in the world, particularly in Europe in terms of mass transit in tunnels - a technology that is supposed to address a mass evacuation during a tragic event, along with written standards, instructions and recommendations in accordance with technological development and based on the experience of tragic events that happened in tunnels in the past.

Carmel Road Tunnels
Carmel tunnel is the largest transportation infrastructure project in Israel carried out so far. The tunnels cross the Carmel mount from west to east.
The tunnels have couple of two pair tunnels, the western tunnels have a pair of 2-lane 3280 m each & the Eastern tunnels have a pair of 2-lane 1720 m each (Total of 10Km).

Safety system design began in 2007, the system installation began in early 2009 and tunnel opening was at Nov. 2010,
The performance was BOT and initial planning was undertaken by the electricity and safety consultants based on the accumulated knowledge of similar systems worldwide.
As the fire detection systems in road tunnels are an important part of fire safety, which is a critical system that activates (triggers) all other safety system in case of fire or emergency events, it must be more than a sophisticated system that can survive in a harsh environment, detect real alarm, prevent unwanted alarm & require minimum maintenance.
Therefore the importance of the fire detection systems is critical to carry out the evacuation quickly and efficiently in order to reduce loss of life to a minimum.
The goal is to provide the latest information (visual and audio) to the public passengers during an event, that will enable them to evacuate quickly and safely to the protected areas while allowing operators and security personnel, to enable all means and tools for rapid handling in the event .

Engineering requirements for safety systems in the tunnel:

- High survivability systems suitable for difficult environmental conditions
- Minimum maintenance - to prevent closure of main traffic routes
- Out-door equipment, IP-65 waterproof
- Quick response of fire detection with exact location
- Distributed systems (number of network systems) on fiber optic infrastructure integrated with an emergency voice evacuation system.
- Control from two different locations (primary and secondary)
- Firefighter's Control and command from every tunnel's entrance.
  - Transfer of information to traffic and ventilation control systems in two different channels (Main channel and a backup channel).
  - Intelligible emergency messages
Project description
The system planning was based on a high survival level, when several (10) of fire control panel (see sketch below) integrated with emergency voice evacuation connected by network infrastructure on a different route. All fire detection, firefighter telephone and voice speakers connected in a closed ring. The fire detection at the tunnels based on linear heat detection systems (DTS) using optical fiber sensor (new technology) deployed along the tunnel. Heat detection in the tunnel is done by pre-defined heat areas according to the operation definitions of the ventilation system (in total 102 sections).

A video smoke detection system installed as a Backup for the linear heat detection system using cameras scattered along the tunnel, the information is also given to the control systems and activates the emergency systems to predetermined conditions.

Emergency audio system in the tunnel supports different areas, each section between the escape getaways is considered as an area including all escape passages accordingly. Each area is supported by its own digital amplifier and includes a backup amplifier just in case. There is a different message at the event area and at the protected area at the same time.

The voice alarm system includes high watts speakers & intensity, give high intelligible messages. Fire fighters telephone are scattered along the tunnel (Anti Vandal) every 90 meters, communication is controlled from the control room where each fire fighters telephone is identified by its exact location in the tunnels.

In addition to the fire fighters telephones, emergency public telephones are scattered in the tunnels for the use of reporting hazards and messages to the control center.

Fire strobes & directional lights installed along the sides wall of the tunnels operates with special synchronized signal from the fire alarm control panels.

A fire scenario in the tunnels:

- During a fire event in the tunnel, and, after a full recognition of a real fire event by the safety systems.
- Automatic evacuation messages are being activated as well in the relevant tunnel and the escape crossings.
- Emergency lights and directional signs are being activated to indicate the relevant exit for passengers.
- During the fire scenario there is always the ability to manually control the event by the authorized and suitable personnel.
- Transfer of information to traffic management system (TMS) and facility management system (FMS) in different route.
Analysis of tunnel fires over twenty years

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ABSTRACT:

More than 1500 kilometers of road tunnels have been equipped in the last twenty years with the automatic fire detection system LIST. In this time, a remarkable number of fires have been recorded. A new report gives an overview about the known fires in „LIST-tunnels“, gives details about extraordinary events and an analysis about the fire reasons, response of technique and the behavior of concerned persons.
CONTENT:
The report is based on information and data given by the operators of road tunnels in Europe and outside. It lists the relevant tunnel specifications like dimensions, year of opening and traffic volume.
The reason for the fires are analyzed, e.g. technical defects, car accidents, dangerous load, and the course of events.

Important is the serious assessment of the detection and recognition of each fire, by automatic detectors, whereas several technical possibilities are given in modern tunnels, and through human reaction of drivers or operators in the control room.

The behavior of the persons, directly and indirectly involved in the fire event, is a further aspect of this work.
A last issue of the report is the consideration of measures for the future, to improve the tunnel safety concerning rapid and reliable fire detection concerning technical aspects, but also with regard to human behavior.

KEYWORDS: LISTcable, real fires, tunnel fires, linear heat detector, fire detection
FFFS for Flammable Liquid Fires in Road Tunnels

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ABSTRACT

The benefits of fixed fire fighting systems (FFFS) have been demonstrated for heavy goods vehicle (HGV) fires both in test programs and in actual tunnel fire events. In most of these studies the bulk transport of flammable liquids has not been addressed. In many road tunnels passage of flammable liquids is restricted or banned. Unfortunately practical alternative routes are often not available resulting in long detours that can be equally dangerous and costly to the communities served. As such, there has been recent consideration to allow flammable liquid tankers (FLT) through some of the tunnels where they were previously restricted and in new tunnels. This is occurring for a number of reasons including an assessment that the tunnel route is safer and by allowing the tanker traffic, overall safety may be improved.

BACKGROUND AND HISTORY

Tunnel operators are faced with two choices for FFFS. One is to provide a separate system for it such as foam. In many cases this can be integrated with the water system, but there are complexities in both operation and maintenance that reduce its apparent benefits. The other choice is to determine the effectiveness of water droplets alone in mitigating fire effects, thus having a single system reducing operational complexity.

If the fire can be confined to the initial incident, the damage, especially to the facility, can be minimized. This objective can be described as prevention of spread. Prevention of spread is a strategy of offensively attacking the fire if possible, but if not, still preventing the fire from moving to adjacent fuel piles. Such a strategy can prevent an initial low single digit number of vehicles from becoming a double digit vehicle incident. In order to figure out if an FFFS can implement this strategy, it must be defined so that a determination of success can be made.

DOES WATER SPRAY SUPPRESS FLAMMABLE LIQUID FIRES?

Lemaire (1) reported on a series of tests carried out in 2007 on liquid pool fires in the Runehamar Tunnel in Norway. The results of these tests showed that water mist sprays could extinguish a diesel pool fire. What was also significant was that the ability of the spray to extinguish the fire was relatively unaffected by the addition of an AFFF additive.

Numerous tests and studies have been done that show water spray does suppress flammable liquid fires. The application of spray however does have to meet certain conditions, particularly with regard to droplet size. Rasbash and Rogowski (2) conducted a series of tests in 300 mm diameter open vessels with flammable and combustible liquids of 50-60 mm thickness. Of significance in road tunnel applications is the approximately 50% drop in temperature within 15 seconds after activation.

The correlation of the critical parameters was established in Equation 1.

\[ t = 34,000 \times \left( \frac{D}{M} \right) \left( \frac{y}{\Delta T^{1.75}} \right) \] (1)
The terms are defined below:

- **t** Time to extinction (seconds)
- **D** Median drop size (mm)
- **M** Flow rate grams/cm² min
- **ΔT** Ambient temp-fire point temperature (C)
- **Y** Preburn time (min)

One of the difficulties with this method is that it requires the difference between ambient temperature and the fire point. For Class I flammable liquids such as gasoline, the fire point is below ambient temperature.

Rasbash, Rogowski and Stark (3) conducted tests of additional liquids including alcohols and gasoline. Since gasoline is the most common liquid transported, attention will be focused on that. The tests were similar with 50-60 cm thick pools involved. Equation 2 for gasoline was developed from regression analysis of the various tests and can be used to establish estimated extinguishment times for a range of water application rates.

\[ t = 6.1 \times 10^{12} \times \left( \frac{D^{4.5}}{M^{2.1}A^{3.0}} \right) \]  

(2)

The additional term is defined below

- **A** Entrained air velocity (cm/second)

The context of this previous work has been to extinguish flammable liquid fires quickly, typically in less than one minute. However, a strategy that prevents spread from the initial incident allows for longer burn durations. Arvidson (5) showed a plot of fire heat release rates of shielded fires under different spray application rates. Detection systems are capable of identifying fires of 5 MW heat release rate. Taking this 5 MW fire heat release rate as being one that could be considered under control, the duration when the fire heat release rate exceeds this value is about five minutes. If this is considered acceptable, water application rate of 6 mm/min accomplishes this objective.

**SUMMARY AND CONCLUSION**

HGV fires continue to carry the highest probability of causing a major tunnel fire and many operators are installing fixed fire fighting systems to mitigate the damage from these fires. While FLT are restricted or prohibited from many road tunnels, others are faced with the very real situation of having to deal with them. Traditionally, water spray systems alone have not been used for this purpose. However, by understanding their abilities and limitations, a realistic assessment of their ability to mitigate the fire effects may be made.

1. Standard drop deluge sprays can suppress flammable liquid fires. Their effectiveness is principally a combination of the drop size and water application rate.
2. As with most suppression systems, operation should be as early as possible. Road tunnels have incident detection systems that may be used to determine if an incident has occurred that could eventually be a fire.
3. For road tunnels, using standard-drop deluge sprays may be a cost-effective option that if properly designed can mitigate both the more common HGV fire and the less common but faster growing FLT fire.
4. Having only one suppression system may result in simpler operation and more likelihood of optimizing its effectiveness.

**KEY WORDS:** fixed fire fighting systems, flammable liquid fires, tunnel operation
Commissioning of Performance Based Fire Systems

Charles Kilfoil

Performance Based Systems Commissioning is a complete building process. The challenge of Commissioning Performance Based Designs is beyond testing and start up at the end of the Construction Phase. Commissioning of Performance Based Systems is considered from the very beginnings of the project and follows through the life of the facility.

Commissioning of the passive and active Performance Based Life Safety Systems is to ensure the Owners needs for a useable system are met.

Commissioning of these systems from an Authority Having Jurisdiction’s perspective brings together the integrated testing of the systems not accounted for under individual acceptance testing.

Application of Commissioning of Performance Based Systems as a flow down of requirements from upper tier documents to be integrated into the building design.

- Commissioning Plan-The living document specific to the Owners Building.
- Design Methodology-How Commissioning is integrated into Design.
- Construction-How Commissioning is integrated into Construction.
- Testing Criteria-How the Integrated Testing is to occur.
- Occupancy Phase-Commissioning during the life cycle of the building.

The author, Charles Kilfoil, is a Professional Member of the Society of Fire Protection Engineers. He has over twenty years of experience in the Design and Installation of Fire and Life Safety Systems. He is a member of NFPA and is a Principle Member of the initial NFPA 3-Commissioning and Integrated Testing of Fire and Life Safety Systems-Technical Committee.
Prediction of the temperature evolution in a tunnel construction in case of fire, by coupling the temperature-dependent heat transfer mechanisms inside the structural components and at their surface

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KEYWORDS: fire, high temperature fire loads, component temperatures, wall temperatures, concrete, high temperature behavior, thermal properties, Computational Fluid Dynamics, CFD

INTRODUCTION
The thermal and mechanical behavior of structural components exposed to fire depends essentially on the time evolution of component temperature, the characteristic course of the fire incident and the duration of exposure to fire. The design of the components is usually based on standardized or project-based temperature-time curves.

Based on experience, analysis and experimental investigations, numerous temperature-time curves have been developed nationally and internationally for the simulation of fires. Currently, there are no uniform standardized fire curves available for the design of tunnel components [1]. The different assumptions made for the temperature-time curve in each country lead inevitably to different designs of components. Only at a national level, if any, it is regulated which temperature-time curves are to be applied for the different fire incidents and tunnel types (e.g. in Switzerland).

For special projects that are not covered by national standards, it is a difficult task for the project designers to develop a suitable fire curve that enables the dimensioning of components ensuring both security and economic feasibility. Since at the moment there are no common European regulations in this respect, it can be even more problematic for the project designers if a tunnel project involves the security interests of different countries.

Based on Computational Fluid Dynamics (CFD) methods, now it is possible for scientists and researchers to develop appropriate fire curves and to make them available for the project planners. Numerical and experimental methods can be used for investigations in fluid mechanics and structural analysis to predict the component behavior under fire exposure (fire resistance, spalling etc.).

Current technology allows the coupling of the heat transfer mechanisms in case of fire within the structural components and at their surface by means of CFD. For a given fire scenario (e.g. fire load, smoke exhaust systems, ventilation conditions) and tunnel design, not only safety parameters such as smoke layer height and visibility but also the influences of heat storage in the component layers of the tunnel structure can be predicted taking into account the temperature dependent material properties in the course of time. As a result, it is possible to provide the structural project designers with useful information about the temperature-time characteristics of the structure.

PROCEDURE
Some preliminary numerical and experimental investigations on component behavior in fires [2], [3], [4] and fire simulation in buildings [5] have already been carried out at BAM. In this paper, the example of a tunnel fire caused by a truck with a heat release of 100 MW will be analyzed numerically using FLUENT [6]. Due to good ventilation conditions, the fire shall be assumed to be fire-load controlled. The figure 1 shows the modeled tunnel in cross section with its main dimensions. The Tunnel is 400 m long.
The heat storage and the temperature distribution in the components are examined with respect to thermal material properties, which are temperature-dependent. The temperature distribution caused by the heat release from fire (part 1) is predicted numerically for the proposed construction of the tunnel.

In November 2011 a tunnel-lining-test facility was built at BAM, as depicted in figure 2. Tests on tunnel lining components shall be carried out in 2012. Preliminary numerical simulations were performed using FLUENT in order to predict the temperature behavior of the lining component in the tunnel-lining-test facility (part 2). The thermal load of the component is based on the temperature-time curve shown in figure 3.
Figure 3  Temperature-time curve, RABT. German Tunnel fire curve. Guideline for the equipment and operation of road tunnels 2006. Research Association for Roads and Transportation. Working Group Traffic Management and Road Safety.

MODEL FUNDAMENTALS
The numerical simulation of turbulent fluid flows as well as the heat and mass transfer and chemical reactions are based on the solution of conservation equations for mass, momentum, concentration and energy [7], [8], [9].

The calculation of the turbulent flow is carried out with the k-ε turbulence model and the radiation with the discrete ordinates approximation model [6], [9], [10].

The spatial discretization is done with a second-order finite volume method (FVM), and the temporal discretization with an implicit method, also of second order. The combustion is modeled using a heat and species source for the smoke gas. The unsteady heat conduction in the structural component is modeled by using the Fourier heat equation.

DISCUSSION
The results of the temperature-time curve in the tunnel construction in case of fire will be presented and discussed. The analysis of the results predicted by simulation (part1, part2) shows that the predicted results from the tunnel-lining-test facility are transferable to the temperature behavior of proposed construction. Our future investigations will show whether the experimental research does confirm this temperature behavior.

LITERATURE
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Active Open-Area Smoke Imaging Detection

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ABSTRACT
A new smoke detection technology base incorporating the characteristics of active, remote sensing, multi-wavelength smoke-level measurement is presented.

A number of large-open spaces in the built environment present unique challenges to fire detection systems. Buildings such as stadiums, large atria, airports and rail stations, hotels and convention centers and warehouses demand a fire detection solution that is sensitive to diluted smoke but that is non-intrusive on the space. Existing path-loss type smoke detection systems such as optical projected beam smoke detectors solve this problem by placement of the sensor elements at either side of the protected space. However, many of these technologies have issues with optical alignment during commissioning and operation, somewhat overcome with automated alignment techniques. These systems continue to be complex to install and commission but cause most concern in their inability to distinguish dust or obstructions from smoke. Beam detectors are thus known for causing a higher rate of false alarms.

KEYWORDS: smoke detection, smoke imaging technology, projected beam smoke detection, path-loss detector, dual wavelength beam smoke detection

A NEW CONCEPT/TECHNOLOGY
Xtralis has developed a new type of path-loss detector that provides enhanced sensitivity compared with beam type detectors, excellent discrimination of particle size and obstructions and simplified commissioning.

In its simplest configuration, the system uses an imager unit with a selected field of view that is mounted at one side of the area to be protected and one or many emitters on the other side of the area. The emitters use wide beam Infra-Red and Ultra-Violet LEDs. Sophisticated software locates the pixels on the imager illuminated by the emitter as it flashes. The strengths of received IR and UV are compared to detect smoke.

The use of many emitters allows a planar coverage over an area. The emitters can also be placed at different elevations to provide a three-dimensional mesh.

The novel use of two wavelengths allows the system to discriminate between the sizes of particles causing the path loss. This is because smoke reduces UV light more than IR, whereas dust & solid
objects affect both equally. This feature results in significant benefits to the lifetime costs of ownership of such a system.

Simplified commissioning is achieved because only a very rough manual alignment is required for the imager unit to locate and lock-in each emitter in its field of view. Low cost of maintenance over the life of the system is made possible because the imager unit is able to track any building movement. The system’s ability to distinguish solid objects (such as ladders, steam, insects or birds) reduces the incidence of nuisance alarms.

Discussion is drawn to the benefits of a quantifiable, easily testable and active detection system for train and metro tunnels, landings, large open spaces, high-ceiling areas, and applications with limited access. This new technology outperforms traditional beam detection and its performance in beam length and area coverage is currently limited by the existing standards based on single IR wavelength detectors limitations.

Recently installed products have successfully demonstrated the robustness of the system to risks such as building movement, vibration, bright sunlight, object intrusion and dust rejection. Systems are currently being installed in metro stations and tunnels. These applications will be highlighted in the poster presentation. Integration with a variety of fire alarm panels is planned and the product is UL/ULC/FM/CPD/CSIRO listed and compliance to other standards is proceeding.

REFERENCES

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1. Open-Area Smoke Imaging Detection (OSID) 14th Suppression, Detection and Signalling Research and Applications (SUPDET) Conference February 2010
ABSTRACT

The Existing Elizabeth River Midtown Tunnel, as a section of U.S. Highway 58, serves bi-directional traffic between the City of Norfolk and the City of Portsmouth in the State of Virginia. A new 1280 m long two-lane tunnel will be constructed parallel to the existing tunnel and serve uni-directional traffic.

The final tunnel design incorporates an emergency egress corridor extending the full length of tunnel. An emergency egress corridor constitutes an important egress element for tunnel evacuation. Properly pressurized it acts as a safety refuge for evacuating motorists from a fire or other hazardous event. Thus an evacuation route (smoke-free environment) is provided to the tunnel occupants completely isolated and protected from the fire incident roadway section. The emergency egress corridor must be properly sized to prevent queuing at access doors due to an overcrowded egress corridor. In a fire incident, it is assumed that the tunnel motorists in the zone immediate to the fire zone evacuate to the nearest available door with minimum evacuation pre-action time. This evacuation activity is continued by the tunnel motorist stranded in different zones upstream of the fire incident zone at an increasing rate of pre-action time resulting in crowding of the egress corridor. Based on two fire evacuation scenarios simulated, fire at the portal entrance and at the center of the tunnel, access doors every 91 m and an egress corridor width of 1.7 m provide adequate capacity for the tunnel occupants to reach the portal buildings. In the new two-pane tunnel, each lane is 3.7 m (12 ft) wide with a 0.61 m (2 ft) shoulder on either side. The egress corridor connecting the shoulder on one side is at the same elevation as the roadway surface.

This poster presents the evacuation results as determined during analysis of the proposed Elizabeth River Midtown Tunnel Emergency Egress Corridor using the SIMULEX exiting program. The results show the capacity of the emergency egress passageway during a tunnel evacuation scenario and the time required by tunnel occupants to evacuate the roadway section and reach a point of safety. A point of safety is defined as the emergency egress corridor due to the two hour fire rated concrete wall dividing the roadway from the egress corridor or outside the tunnel portal. The emergency egress corridor is provided with a stairway at each portal. The stairway entrance and the Norfolk Portal are 26m (85 ft) apart. The egress stairway entrance on the Portsmouth side is 50 m (165 ft) from the Portsmouth Portal. This stairway entrance connects the tunnel roadway to the Tunnel Support Main Building allowing people to evacuate to the main building level and out to the surface.

SIMULEX simulates the emergency evacuation activity of people to a point of safety. The computer program is well validated and has been used to model emergency evacuation from tunnel roadway environment. The following assumptions have been used in the emergency exiting simulations:

a. The tunnel occupants consist of approximately 60% adult males and 40% adult females.

b. The tunnel occupant load has been assumed to be 6 people per 30 lane-m based on previous project experience. Hence for a 610 m (2,000 ft), two-lane section of tunnel, 240 evacuees were
simulated. In addition, one coach bus having 50 passengers was included in the simulations. The total number of occupants for a 610 m (2,000 ft) long tunnel egress zone is therefore 290.

c. The average walking speeds assigned for the male and female occupants are 1.0 m/s (200) and 0.81 m/s (160 fpm), respectively. The effect of tunnel grade on the walking speed of the occupant was insignificant and was not modeled. The passengers in each zone do not have to walk more than 200 ft on tunnel roadway section and hence grade will not have any significant effect on the crowding at the doors.

In the first scenario, the fire is located about 50 m (165 ft) from the Portsmouth portal and the access door adjacent to the fire is not available for evacuation. The traffic direction modeled is eastbound towards the City of Norfolk while the egress direction of tunnel occupants is towards the Portsmouth Portal. The traffic consists of 19 cars and a single bus resulting in a total tunnel occupant load of 70 persons (50 in bus, 20 in cars). The eastbound traffic upstream of the fire location has stopped before the start of evacuation activity. The time taken by the car occupants, 20 passengers, to reach the point of safety is 55 seconds. The time taken by the 50 passengers to evacuate the bus is approximately 67 seconds. The total egress time is 140 seconds. No queuing is observed at any point except at the bus exit.

In the second scenario, the fire is located at the middle of the tunnel such that 614 m (2,015 ft) of the roadway section is occupied by vehicles. The egress direction is toward the Norfolk Portal while the traffic direction is westbound. The emergency egress corridor is the primary means of evacuation, but the Norfolk Portal is also used. The roadway section is divided in seven zones such that each zone is served by an access door to the egress corridor. The last Access door (#7), which is farthest from fire scenario, is 24 m (80 ft) away from the Norfolk Portal and the other access doors (#6 through #1) are 91 m (300 ft) apart. The first zone (zone 1a), 59 m (195 ft) long, is closest to the fire location; while, the last zone (zone 7) is closest to the Norfolk Portal. The tunnel occupants in each zone will evacuate to the emergency egress corridor through an access door with the exception of zone 7 which use the Norfolk Portal. The pre-reaction time for zone 1a is 15 seconds and increases for subsequent zones. The change in pre-action time is designed to maximize the number of evacuees in the egress corridor at the time evacuees are trying to enter the egress corridor from the roadway. Traffic consists of 188 cars and a single bus containing a total tunnel occupant load of 290 persons (50 in bus, 240 in cars). The tunnel occupant load for zone 7 is only 4 passengers due to a short roadway length of 12 m. The rest of the zones, 1b through 6 are approximately 91 m long with occupant load varying between 30 and 38 persons. The occupant load for zone 1a is 78 passengers due to the presence of the bus. The time taken by 78 passengers in zone 1a has passed through the access door at 125 seconds after the start of evacuation activity. There was no indication of persons queuing at the access door in zone 1a. The total predicted evacuation times to reach a point of safety for zones 2, 3, 4, 5 and 6 was 112, 113, 109, 105 and 110 seconds. Queuing of tunnel occupants is predicted to occur only at the access doors on the tunnel roadway section. Some queuing was observed at access doors (#2 through #6) with the maximum wait time being less than 30 seconds (i.e., tunnel occupants did not have to wait more than 30 seconds to enter the emergency egress corridor).

Based on the two scenarios studied, proposed design for the emergency egress corridor having a width of 1.7 m and 1.1 m wide access doors from the tunnel roadway at a spacing of 91 m has adequate capacity to evacuate the tunnel occupants in the event of a tunnel fire incident. In the case of a fire incident occurring near the midpoint of the tunnel when one half of tunnel is filled with vehicles, the predicted maximum time for all tunnel occupants to reach a point of safety (i.e., enter the egress corridor or exit through a tunnel portal) is 125 seconds. In the case of a fire incident occurring in the cut-and-cover sections of the tunnel where evacuation would be through the nearby portal only, the predicted maximum time for all tunnel occupants to reach a point of safety (i.e., exit the nearby portal) is 140 seconds toward the Portsmouth Portal.

KEYWORDS: Egress Modelling, Emergency Egress corridor, Emergency Egress Evacuation
Continuous Emergency Egress Corridor Pressurization Along a Tunnel Ventilated by Jet Fans

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INTRODUCTION

The new Midtown Tunnel will be a two-lane, unidirectional, immersed tube tunnel approximately 1,280 meters long connecting the cities of Portsmouth and Norfolk in the state of Virginia, USA. A continuous emergency egress corridor is being provided to facilitate the evacuation of motorists in the case of a fire emergency. The emergency egress corridor will be accessible from the roadway via sliding access doors every 100 meters. To maintain tenability in the egress corridor, the corridor must be pressurized to prevent smoke and heat from entering the corridor with as many as three doors open, while simultaneously not becoming over pressurized such that evacuating motorists cannot operate the access doors or generate air velocities in the doorway that prevent motorists from entering the egress corridor.

The roadway area of the tunnel is ventilated by a series of jet fans spaced every 100 meters apart as shown in Figure 1. The pressure signature the jet fans generate along the roadway varies as a function of the location of the fire. This complicates the corridor pressurization design. The pressure signature itself and the variation of the pressure signature along the roadway influenced the location of the egress corridor doors in relation to the jet fans and the design of the egress corridor ventilation system. The range of pressure variation in the tunnel is about 140 Pa.

CRITERIA

To maintain a tenable environment in the egress corridor the ventilation system for the egress corridor has to be designed to meet the following requirements as defined in National Fire Protection Association (NFPA) 92A (2009).

- Positively pressurize the egress corridor to a minimum of 12.5 Pa relative to the tunnel across closed doors to prevent smoke infiltration through closed doors.
- Maximum pressure difference across egress corridor door so that it can be opened with a maximum of 133.4 N of force is 200 Pa, as specified by the egress door manufacturer.
Additionally, NFPA 502 (2010) specifies maximum air velocities that motorists can safely tolerate:

- Maximum air velocity through an open egress corridor door not to exceed 11 m/s.

**METHOD**

The tunnel and egress corridor system was modelled with the Subway Environment Simulation program, a 1 dimensional network model that can predict airflow patterns and pressures. Jet fans with a thrust of 1557 N were placed every 100m along the tunnel. The egress corridor was ventilated using a single 18.8 m³/s axial flow fan at each end of the corridor at the portals. An opening to the outside ambient condition was modelled at the midpoint of the egress corridor to simulate a backdraft damper. Simulations were performed to determine the pressure difference between the tunnel and the egress corridor for scenarios ranging from 0 egress doors open to a maximum of 3 egress doors open. The backdraft relief damper with an area to match that of an open egress door of 2.4m² was modelled open when the simulation showed pressure differences greater than 200 Pa between the egress corridor and the tunnel. All of the pressure data was then recorded and plotted.

**RESULTS**

The pressure difference between the egress corridor and the tunnel are measured at each egress corridor door and the data is plotted as a function of tunnel length. A number of simulations have been performed for fire locations throughout the tunnel. The worst case pressure differences are presented here, see Figure 2. The pressure plots for 3 door open shows a maximum pressure difference of 170 Pa using 18.8 m³/s egress corridor ventilation fans. The minimum pressure occurs at the doors that are open to the tunnel where people can evacuate though. The maximum pressure difference occurs at the door closest to the portal upstream of the fire. This pressure difference can be mitigated by locating the door directly opposite the jet fan to mitigate the large pressure variances at the inlet and outlet of the jet fans.

![Figure 2 - Pressure difference between the Egress Corridor and Tunnel at each Egress Door](image)

**CONCLUSIONS**

Tunnel smoke management is unique due to the varying pressure signature along the length of the tunnel. The longitudinal tunnel ventilation system and the location of the fire relative to grade as well as the thermal effects of the design fire itself contribute to the variability of the pressure signature. The design of an emergency egress corridor system requires an egress corridor ventilation system that can overcome the tunnel pressure signature while maintaining acceptable maximum pressure differences to allow motorists to use the egress corridor. This can be achieved by designing the egress corridor ventilation system to meet the minimum pressure differentials with the design number of egress doors open, then alleviate overpressure conditions when all egress doors are closed by designing backdraft air pressure relief dampers to simulate open egress doors.

**KEYWORDS:** pressurization, jet fans, egress corridor, variable pressure
Design Loads and Methods for Prestressed Open Cut Tunnels under Severe Accidental and Malicious Threats – Fire

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SUMMARY
The damage or failure of important built infrastructures like tunnels due to severe accidental and malicious threats (extreme fires and explosions) potentially has further disproportionate consequences for the traffic net and society. Hence a close-to-reality simulation of the structural behavior in such incidents plays an important role in current and future tunnel safety and security risk assessment (q. v.: Design Loads and Methods for Prestressed Open Cut Tunnels under Severe Accidental and Malicious Threats – Explosions). To obtain such a close-to-reality simulation of structures under fire loads, thermal and mechanical nonlinear numerical simulation are conducted. For standard tunnels the german guideline ZTV-ING [1] permits engineers to perform quite simplified calculations where a linear temperature gradient is used instead of a fire design curve. For exposed infrastructure which might cause a disproportionate consequence launched by a comparatively small, local fire incident or non-standard (prestressed) structures with large free-spans, a nonlinear simulation is obliged as several boundary conditions of the simplified approach are not met. The results of such numerical simulations are presented in a poster contribution.

KEYWORDS: Prestressed open cut tunnels, large spans, fire design curves, nonlinear thermal analysis, nonlinear mechanical analysis, derivation of simplified temperature gradient.

INTRODUCTION
In the consequence of the increasing traffic volume within city agglomerations and transit regions it is necessary to build wider traffic infrastructures which also absorb the noisiness of the vehicles. According to ZTV-ING [1] part 5 open cut road tunnels, it is proposed to consider fire incidents by using a simplified linear temperature gradient of 50 K if certain boundary conditions (thickness of the construction components: 0.80 to 1.60 m; maximum span length: 16.0 m) are met. If the construction deviates from the dimensions, a detailed analysis which considers the nonlinear heat transfer over the solid cross section and the changing of the structural stiffness during the fire is required. The following parts will discuss the derivation of linear temperature gradients in connection with several fire design curves, typical spans and components’ thicknesses.

FIRE DESIGN CURVES
Currently, two characteristic fire design curves in Germany are used for the calculation of built tunnel infrastructure. The first one [2] is characterized by a duration of 140 minutes with a temperature-time gradient of 240 K/min within the first five minutes (see figure 1 left). The second fire design curve, the so called EBA curve is usually applied to railway tunnels in Germany [3]. Current developments for the revised version of the ZTV-ING [1] provide the EBA curve for a higher level of security. The EBA curve is characterized by a longer fully developed fire phase of 55 minutes and the whole fire duration of 170 minutes. Nonlinear numerical calculations are conducted by taking account of the several fire design curves with the aim to calculate a simplified linear temperature gradient which covers the nonlinear calculated bending moments. Due to the larger span and the so associated less system rigidity compared to the boundary conditions of the ZTV-ING [1], a less linear temperature...
gradient than the 50 K is expected.

NONLINEAR THERMAL ANALYSIS

The first step of a detailed nonlinear fire design calculation consists of a nonlinear thermal analysis, which simulates the heat transmission over the solid cross section. As a result the nonlinear heating of the concrete cross section is obtained over the whole fire duration and the subsequent concrete cooling phase. The calculation of the temperature distribution in solids for the transient case is solved with the solution of the Fourier heat equation.

NONLINEAR MECHANICAL ANALYSIS

Based on the results obtained from the calculation of the temperature-time development in the reinforced concrete cross section, a physically nonlinear finite element analysis is conducted. Hereby the temperature depending nonlinear material properties are taken into account. A special focus is laid on the appropriate FE discretization over time and space.

PARAMETER STUDIES OF LARGE SPAN PRESTRESSED OPEN CUT TUNNEL SECTION

With the intention to calculate a simplified linear temperature gradient for a more elementary design of tunnel sections, it is necessary to vary the significant parameters which influence the process significantly (figure 1). Therefore, the tunnel section is analysed considering different span lengths (21.5 m till 28.5 m), thickness of the ceiling (1.2 m till 1.5 m) and prestressed levels with regard to the reinforced ratio. With respect to the pre stressing of the upper tunnel slab an additional structural-specific characteristic is the connection between the outer walls and the upper slab. A hinged and a fixed connection is analysed and compared with regard to the occurrence of plastic hinges, load redistribution capacity (ductility) and maximum fire bending resistance $M_{\text{rd,fi}}$.

RESULTS

Figure 1 compares the bending moments obtained by using a simplified linear temperature gradient of 41.5 K (hatched stacks) with the bending moments obtained by a nonlinear numerical simulation of the thermal transmission and the mechanical behavior of the structure. Due to the lower system rigidity a reduced linear temperature gradient (41.5K) compared to the 50 K of the ZTV-ING [1] is obtained. For significant points within the structure the linear elastic moments are conservative compared to the nonlinear Calculation. The graph shows an exemplary time history development of the bending moment for the fixed connection between the prestressed ceiling and the middle wall. The poster contains all important results of the parametric studies.

![Figure 1: Static system, linear (hatched stack) and nonlinear (white stack) bending moments, time history development of the bending moment at the fixed connection between inner wall and ceiling](image-url)
REFERENCES


Numerical predictions of blast waves caused by accidental or intentional detonations of gaseous and condensed explosives in 3D complex geometries.

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INTRODUCTION

The prediction of blast effects produced by either accidental or intentional detonation of explosive composition in 3D geometry is a complex task. It requires both a good understanding of: (1) the rapid expansion of the detonations products that creates a shock wave in the surrounding medium and (2) the interaction of this shock combined with its multiple reflections on the surrounding geometry. In this paper we present our numerical tools used to predict those two phenomena. The performance and the equation of state of any CHON explosive composition is predicted by the thermochemical code CARTE [1,2]. The detonation and the consecutive blast wave in arbitrary 1D/2D/3D geometries are then simulated with the massively parallel HERA hydrodynamic code using Adaptive Mesh Refinement techniques [3].

We compare our results with academic results in 1D and 2D dimensions and with the classical approaches [4-8] in 3D. We show that we can accurately predict the over pressure and the timing of the blast waves produced by a large range of explosives (from gaseous propane-oxygen to condensed TNT charges) in all the tested configurations. We then apply the same procedure to a realistic scenario. A charge is disposed at a tunnel entrance and we investigate the blast waves entering the tunnel, coming out at the exit on the opposite side and interacting with the outside waves. We think that such tools are very valuable for incident management, as well as threat and risk assessment.

TOOLS OVERVIEW

A predictive thermochemical code for CHON explosives: CARTE [1,2] provides thermodynamic properties and chemical compositions of CHON systems over a large range of temperature and pressure with a very small computational cost. To achieve this goal, the detonation products are split in one or two fluid phase(s), treated with the MCRSR or KLRR equation of state (EOS), and one condensed phase of carbon, modelled with a multiphase EOS which evolves with the chemical composition of the explosives. It provides us with an accurate multicomponent EOS usable in hydrodynamic codes that can model a wide range of explosive.

A hydrodynamic AMR platform for multi-physics simulations: The HERA [3] multi-physics platform covers a wide range of applications, from Laser-Plasma Interaction, to multi-temperature hydrodynamics, magneto-hydrodynamics, elastodynamics or detonics. One of the specificities of such a multifluid simulation platform is to support cell-by-cell Adaptive Mesh Refinement (AMR). The gains to be expected from AMR for the numerical simulation of detonations will be provided in both 2D and 3D. With the example of a realistic scenario of a charge disposed at a tunnel entrance, we need to model very different length scales: the short length scale of the detonation (~1 mm) and the dimensions of the tunnel (~100 m long, ~10 m wide). As will be seen, in 3D, very significant gains may be expected for such types of flow by using an appropriate AMR strategy.

A REALISTIC Scenario: A CHARGE DISPOSED AT A TUNNEL ENTRANCE

Assuming a realistic scenario, when dealing with threat and risk management, the time becomes of primary importance and it is difficult to rely on full scale experiments. Our proposal is to predict, within a feasible time, with the simulation chain validated against academic tests, the blast wave...
history to assess the risk and help designers and deciders in their decisions.

Figure 1 A charge disposed at a tunnel entrance: 3D geometric configuration.

In the final paper, the 3D prediction of the explosion of a charge disposed at a tunnel entrance will be presented. The overpressure of both the blast wave expending in free air and the blast wave entering the 50 m long tunnel and exiting at the other side are represented on Figure 1-(a) (respectively with negative and positive abscissa) along with the range of possible damages (in colour). On Figure 1-(b), we show the dramatic gains obtained with the AMR strategy (the cell number decreases from $440 \times 10^9$ without AMR to $268 \times 10^6$ with AMR). In the paper, the discussion will focus on the double interest: prediction of the explosive “source term” and blast wave propagation and interaction with the surrounding geometry.

REFERENCES


KEYWORDS: Blast waves, 3D propagation, detonations, explosive properties, complex geometries, hydrodynamic code
Model scale fire tests in a highly inclined tunnel

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KEYWORDS: Fire, tunnel, inclination, model scale tests

INTRODUCTION
In many underground constructions and mines ramp structures (inclined tunnel) occurs, i.e. a tunnel-like construction with one opening to the ground and a closed or partially open lower opening to the mine or the underground facility. Quite often the ramps have steeper slopes compared to traffic tunnels. There have been fires in tunnels with strong inclination. The fire in Kaprun is one example. In 2000 there was a fire in a cable car that developed very fast and caused a large number of causalities. But in a ramp due to the limited air supply the fire development will be different from a normal traffic tunnel.

FIRE TESTS
The question is how one lower partially closed opening in combination with a steep slope affects the fire development as well as the smoke development, which determines whether the evacuation can be done in a satisfactory manner or not. This will affect the evacuation possibilities and requirements for the fire protection systems such as the smoke ventilation system. To investigate this model tests will be performed. The model tunnel has the dimension 0.3 x 0.3 x 7.5 m. The slope and the lower opening will be varied and the fire source is small wood cribs. In the tests temperature and flow measurements will be performed at different locations in the model tunnel. One of the tunnel walls will consist of a glass panel so that fire and smoke spread can be observed. A fan will also be connected to the tunnel to simulate different smoke evacuation systems.

DISCUSSION
The purpose of the tests is to study fire and smoke development in a ramp with and without smoke evacuation systems in order to optimize the fire protection systems to secure an evacuation of people. The results will be applicable on tunnels during construction and are interesting for tunnel owners, tunnel builders and fire fighters.

The tests are sponsored by SKB (the Swedish Nuclear Fuel and Waste Management Company and) the results will be incorporated into the fire safety strategy for the potential repository for the final disposal of spent nuclear fuel. The tests will be performed in October 2011 at SP Technical Research Institute of Sweden.
Challenges and Consequences in Designing for Underground Station Fire Events in the Post 9/11 World

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ABSTRACT

Introduction

Following the events of 9/11 and the various arson initiated incidents around the world associated with modes of transportation such as road and rail, there is growing trend to design public infrastructure to manage such events. Current public infrastructure is not built to handle the most extreme fire scenarios, so future public infrastructure will need to be redesigned from the ground up to provide a tenable environment for extreme fire scenarios. Future public infrastructure could prove to be prohibitively expensive, so a risk based approach to design should be considered.

The design of the fire life safety systems for the proposed rail projects in Los Angeles has been updated to address such events. Scenarios of interest depict a train collision or derailment igniting a fire, an accelerant initiated fire, an undercar fire, and a platform fire. To provide a tenable environment for all of the listed scenarios, the infrastructure requires significant changes from traditional design methods.

Modeling Fire Growth Behavior

Conventional modeling approaches using Computational Fluid Dynamics (CFD) have adopted ‘t’ squared fire growth curves where the fire heat release rate increases as a square function of time where a constant coefficient determines the rate at which the fire heat release rate increases up to a maximum heat release rate. To accommodate the latest design scenarios, the heat release rate that was traditionally reached in 15 minutes is now reached in less than 2 minutes.

Other numerical approaches have considered the combustion of the vehicle components and the influence of ventilation and water to determine the variation of heat release rate and spread of heat and smoke over time modeled within a spatial and temporal framework. This modeling enables designers to understand the growth of individual fire sources rather than generalizing the spread of heat and smoke over time.

Understanding fire growth with the materials involved and oxygen availability allows designers to tailor emergency response systems to individual transit systems. Train set fire hardening has been improved recently, and in doing so, trains today are much less flammable than trains made in the past. Fire hardening of train sets must be taken into account when designing public infrastructure.

Owing to the uncertainties associated with numerical modeling, physical experiments are gaining in popularity, and a number of test programs are underway globally to address this.
Underground Transit Station Fire Life Safety Design

Underground stations have been perceived by a number of threat and vulnerability analyses to be targets for acts of terrorism and arson.

Many approaches have been proposed for the design of a fire life safety system that provides a tenable environment from a fire for egress. Some are listed below

- Creation of a smoke reservoir
- Prompt activation of emergency ventilation via rapid response detection
- Enclosed and pressurized stairwells and escalators
- Activation of a water based fire protection system

Each of these approaches has challenges and consequences, and this paper provides discussion of the approaches supported by numerical modeling.

The primary purpose of a smoke reservoir is to collect high temperature smoke in the first minutes of a fire. The smoke reservoir can be thought of as an upside-down swimming pool in the ceiling of a structure like an underground station. The buoyancy of hot smoke allows it to collect at a high level, which provides a tenable environment that lasts until the ventilation reaches full capacity and removes the smoke. The smoke reservoir is a good option for controlling smoke during a large fire, but it makes fire detection more complicated and makes the station much deeper which increases costs.

Prompt activation of the emergency ventilation system is a good way to help achieve a tenable environment in the early stages of a fire, but rapid response detection is under development and not fail safe. There is a high risk of false alarms and transportation system disruption. For the most extreme scenarios, it is unlikely that rapid response detection alone will provide a tenable environment for passengers.

Enclosed and pressurized stairwells and escalators reduce the amount of time required for evacuation of an underground station because the point of exit becomes the stairwell and escalator entrance rather than the station exit. This option is can contribute to the other mitigation methods, but it will not provide a tenable environment on its own.

Water based fire protection modeling is not reliable at this point because it has not been validated, but it has been shown that water based fire protection can help control a fire. Water based fire protection must be carefully integrated with the traction power system because of the electricity involved and conductivity of water. The Overhead Contact System (OCS) must be deactivated before the sprinklers are activated. False alarms could severely affect train operations by causing delays until power is restored. This option involves more maintenance than the other options.

KEYWORDS: arson fire, emergency ventilation, sprinklers, rapid detection, numerical modeling
Design, simulations and implementation of ventilation system for Metro Line 12 at Mexico D.F.

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KEYWORDS: metro system, critical control velocity, evacuation strategy, cross passages, anemometers.

INTRODUCTION
Line 12 of Mexico City was developed with 13 stations being one of the most important Metro systems. This tunnel system is one tube with 13 stations and a train deposit, up to the hill. Decisions about location of shafts, and ventilation and evacuation strategies have been achieved after SES simulations. Strategies of ventilation for stations have been designed. Line 12 is under construction, at present.

VENTILATION DESIGN
Several ventilation strategies for tunnel ventilation have been developed using SES simulations. Due to the big population of Mexico DF and people flux in stations, over 475,000 people, 200 meters long platforms have been designed.

GEOMETRIC MODEL
Tunnels and stations geometric model of Mexico’s subway have been developed for the ventilation system design, by simulations SES (Subway Environmental Simulation).

This tunnel has 10 stations and the trains depot, where the line ends. The system consists of one bi-directional tunnel with stations. The entire tunnel is characterized for the upward slope, from the initial station to the deposit, allowing the use of chimney effect, for smoke exhaust. The tunnel ventilation shafts are situated at each side of the station. Tunnel segments (division of tunnels) are 15 metres objective length (approximately a train car length)

VENTILATION SYSTEM
The following ventilation system is proposed for the system in study:

- The tunnel shafts will be situated at the extreme of each station, or in the initial point of each tunnel.
- There will be ventilation at the stations, including a supply shaft and another exhaust shaft.

TUNNEL VENTILATION SYSTEM
The tunnel shafts, are assigned at the ends of the stations, meaning, two shafts at each station end. These shafts have one fan same or similar to ZV-N 1800 @1500 rpm, at emergency regime.

Both in the normal mode as in the fire emergency mode, only at interstations of around 1 km or more there will be jet fans, to be situated at the beginning of the tunnels, at the 83, 240, 518 and 399 segments. These jet fans should be equivalent in thrust and flow to the JZVN-12.

STATION VENTILATION SYSTEM
The station ventilation system should have an exhaust system and a supply system, which allow to
introduce and to extract identical air volumes (the same exhaust and supply flow), in order to maintain the ventilation system of each station independent, respect to the ventilation system of the adjacent tunnels. 

A station ventilation has been designed where each one should include a supply shaft and a exhaust shaft. 

The corresponding volumes of station have been calculated and it has been considered to provide ventilation capable of performing 5 renewals/hour.

The fans wich have been included are the ZVN-1-12, or equivalent.

The ventilation system of the stations is the following one:
- Supply shaft : 2 fans equal or similar to ZVN 1200@1000 rpm.
- Exhaust shaft: 2 fans equal or similar to ZVN 1200@1000 rpm.

The Deposit ventilation system is the following one:
- Exhaust shaft: 2 fans equal or similar to ZVN 1200@1000 rpm.

**Normal exploitation**

Air velocity in the tunnel should reach at least 0,75 m/s, as it indicates the NFPA-130, in conditions of normal exploitation.

This is achieved thanks to the piston effect of trains and to the following strategy of ventilation:
- The equipments that have been used in the simulations have been exclusively those corresponding to the ventilation of stations, that will be always working (switched on).
- The fans in tunnel shafts tunnel will be always off.
- In interstations of more than one kilometer, ventilation will be helped by jet fans, wich will be situated at the beginning of the tunnels. These jet fans will always be working (both in confort as in emergency).
- The exhaust shaft of Deposit will always be working, both in comfort mode as in fire emergency mode.

**Emergency situation (passenger trains)**

Fire simulations have been done when passenger trains are stopped between two stations.

Strategies using extraction shafts close to stations and chimney effect, have proved being successful in order to achieve smoke extraction, according to SES simulations.

A car train fire has been simulated following the curve of Haukur Ingasson, for aluminum trains, with a maximum power of fire of 35 MW.

The tunnel shaft, corresponding to the station before the fire, will be in emergency operation, in supply mode.

The tunnel shaft, corresponding to the station following the fire, will be in emergency operation, at exhaust mode.

![Figure 1](Line 12 Metro of Mexico D.F.)
EVACUATION
Therefore, the tunnel section located upstream of the fire (respect to the ventilation) will be provided with the contribution of a flow of fresh air, that will turn into the route preferred for the evacuation. When not being able to use the route of preference of evacuation (interposition of the fire between the above mentioned route and the passengers), evacuation should be downstream the fire. The stratification of the smokes, will allow to use this way, provided to maintain a sustainable environment, 60 °C y 60 mg/m3 (visibility at 10 m).

STATIONS
In order to study completely the development of a fire in a tunnel, and in station, a CFD simulation has been done, showing the existing boundary conditions, to calculate the temperatures, smoke, and finally, the capacity of the ventilation system to clean the evacuation routes, in the stations. SES method is a one-dimensional analysis, specially oriented to the study of tunnels (Hardy-Cross Meshes).
CFD fire simulations have been done when passenger trains are stopped between two emergency galleries. And fire has been simulated in the particular situation of mid-wagon fire. An evacuation study has been performed to assure people achieve to arrive to emergency exits before the arrival of smoke.

VALIDATION TESTS
Validation test are being achieved to review the ventilation system is working correctly.

DISCUSSION
In the final paper a compilation of the results from the comfort situations and fire emergencies will be provided, as well as a discussion of people evacuation strategies.

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FIRE RESISTANCE OF SMOKE CONTROL AIR OUTLETS IN TUNNEL CONSTRUCTIONS

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A new method has been worked out to calculate the fireproof parameters and the dimensions of the fire curtain in air outlets of smoke control systems that are installed in transport tunnels. The method is based in numerical calculation of interconnected thermotechnical and static problems. It allows to estimate the real working conditions of smoke control air outlets in case of a fire.

Working conditions of air lines in a smoke exhaust system differ crucially from the conditions of their fire-response testing by the procedure of regulatory documents that act in the Russian Federation (National Standard of Russian Federation ГОСТ Р 53299-2009). Firstly, they differ by the presence of intensive internal heating of the walls caused by the combustion gases that pass inside of the air line. That is why the direct transferral of the results of air lines certification testing on location is not possible.

From the written above the importance and necessity of the new method becomes clear. Created by a group of authors to serve the mentioned above purpose it is meant to calculate air lines’ fire resistance and the required thickness of the fire curtain in smoke control system. The method allows registering the differences of the certification testing conditions from the working conditions of air lines in case of a real fire in a subsurface construction.

To calculate the fire curtain thickness which is needed to provide a required (standard) limit of fire resistance of any specific air line one needs to assume that

\[ P_a \geq P_{req} \]

where \( P_a \) is a true fire resistance limit of a fireproof air line; and \( P_{req} \) stands for required (standard) value of fire resistance limit.

Besides the characteristics of air lines’ ultimate behavior in case of a fire that are stated in effective documents regulating the fire safety in the Russian Federation and relate to the air outlets of the smoke exhaust system in tunnel construction, there have also been introduced the following characteristics. These new parameters allow one to specify and formalize figures to be used in the designed mathematical model of heat and mass transfer and stress strain behavior of air outlets:

- a) strength loss – maximum stress exceeds the limiting value that equals the wall’s yield point at this temperature;
- b) limpness – critical maximum deflection rate of the wall (the deflection rate of a duct wall equals the ratio of the deflection to the wall’s width) exceeds the limiting value that equals 0,05;
- c) reduction of area of the air line’s flow passage as a result of its walls deflection to the limiting state \( \left( \frac{F_{b,def} - F_{a,def}}{F_{b,def}} \right) = 0,05 \) (\( F_{b,def}, F_{a,def} \) stand for the values of the air line passage area before and after the deformation).

Generally, to define the required thickness of a chosen fireproof means of an air line one has to keep in mind the interdependent thermotechnical and statistical calculations provided that \( P_a \geq P_{req} \).
The results of making a thermotechnical calculation show the current distribution of the combustion gases temperature along the air line (the gases that flow inside of it) and the temperature pattern in the duct wall.

The results of making a statistical calculation show the movement of the air line walls as well as the stresses affecting them in relation to the time periods.

The general pattern of combustion gases’ movement and thermal transmission in smoke protection system is rendered in Figure 1. One can see that the gas environment of the emergency room (the part of the tunnel set on fire) which has a temperature of $T_f$, enters the inner compartment/cavity of the smoke exhaust air line through the smoke exhaust valves (3). In such case its temperature slightly decreases.

Combustion gases move along the smoke exhaust passage (5) towards the vent (7), exchanging heat with its sides. The direction of the heat flow depends on the correlation of the inside and outside gas temperatures. For example, in the area located in the adjoining room (2) the heat flow is directed outside, so the combustion gases cool down. At that, their cooling rate depends on the thermal insulating capacity of the air line side (in particular, it depends on the thickness of the fire-protection layer). The cooling degree in the area between the room entrance (2) and the vent depends on the length of the zone ($l_2$).

The required thickness of the air line’s fire-protection layer in the area with a length of $l_2$ is estimated on condition that the temperature of its outside surface increases (in Russia it should not exceed 356°F (180°F)) in time that equals the required fire resistance rating of the smoke protection system. Therefore, the higher the combustion gases temperature at the room entrance is (2), the thicker the fire curtain is and the less the cooling of the combustion gases is in the area, which length equals $l_2$. The length of such area is mostly determined by space-planning solutions of any particular construction; any possibility of its alteration is very much restricted.

Thus, there may be cases when the combustion gases temperature entering the vent exceeds the ultimate value. In such situations there appears a necessity in active heat protection of the smoke exhaust vent.

For mathematical description of heat and mass transfer processes one can use the well-known differential equation system. That is continuity equation, equation of gas environment motion, elements diffusion of gas mixture, that fills up the internal compartment (cavity) of the smoke exhaust passage (of air lines) and the emergency room; energy equation, and transient heat conduction in passage walls (of air lines) and in enclosing structures. For the closure of this system it is important to add to it the corresponding single-valuedness conditions, equations for the parameters of turbulent transfer (turbulence model) and integral differential equations of radiation transfer in gas environment.
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Towards 1D/3D coupling for fire and ventilation modelling in large underground infrastructures?

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Risks in underground infrastructures are commonly associated with fire that is the most frequent phenomena that occurs in such places. A lot of studies were carried out to provide better understanding of fire behaviour in tunnels, mainly after the huge fire in the Mont Blanc and Tauern tunnel in 1999. Those studies include experimental tests, from small [1] to large scale [2], and numerical simulation, from analytical model or 1D model [3] to highly complex CFD approach [4, 5]. Based on all studies that were achieved, great improvements have been made in terms of fire knowledge and safety design capability. Mainly, computation precision was highly increased using both physical model improvement and informatics possibilities.

However, even if current computer performances cannot be compared with the ones available ten years ago having the whole description of a complex underground infrastructure with a CFD model stays unrealistic. There was, during this last decade, several discussions relative to the ability of the CFD codes to predict real fire behaviour in tunnel [6] that have induce progress in such modelling. However, even with those improvements, two major issues still resist: the fire concerns the sub model used in the CFD code, the second concerns the time required in case of large infrastructure modelling. Of course, those two problems are closely linked considering that minimising the cell size, i.e. increasing the cell number, will induce a required time increase but also improve the quality of the results.

The second approach that can be used for evaluating fire impact in tunnel and designing ventilation is 1D models [7,8]. Those codes are based on the hypothesis of a homogeneous distribution of physical quantities in the tunnel section. This means that some information is loosed, such as thermal stratification for example. Those codes are however able to give a precise description of the pressure losses distribution, that makes those tools very useful for ventilation system design. As described above, both approaches have benefits and drawbacks. It then appears as a great interest on coupling those two modelling level. Such a coupling will enable to have both a precise description of the physical phenomena that occur close to the fire and a global description of the whole infrastructure. If this can appear complex for simple infrastructure as road tunnel, such a coupling is crucial to model events in subway station.

A coupling methodology was initiated using FDS, the well known fire code [9] and the INERIS 1D code VENDIS [8] for 1D modelling. The VENDIS code enable to compute pressure and flow rate equilibrium in highly complex network and can then be easily used for all underground infrastructures as tunnel, subway system but also mining network. As first evaluation test was made for a subway system with several stations as represented on Figure 1.
Figure 1: Schematic view of the first coupling test.

This example is used to demonstrate the possibility of an FDS-VENDIS coupling enable to reach the above mentioned objectives, this means local information on the fire behaviour and global overview of the whole infrastructure.

KEYWORDS: 1D/3D coupling, fire modelling, subway station

REFERENCE LIST

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