STAVANGER, NORWAY, APRIL 26-28, 2023

Proceedings from the Tenth International Symposium on Tunnel Safety and Security

Edited by

Ying Zhen Li
Anders Lönnermark
Jonatan Gehandler
Haukur Ingason
Abstract

This publication includes the Proceedings of the 10th International Symposium on Tunnel Safety and Security (ISTSS) held in Stavanger, Norway, April 26-28, 2023. The Proceedings include 45 papers and 16 posters. The papers were presented in 16 different sessions, i.e., Keynote sessions, Alternative Fuel Vehicle Safety, Risk Management & Explosion, Digitization, Explosion, Poster Corner, Ventilation 1&2, Fixed Fire Fighting Systems, Tenability and Evacuation, Emergency Management, Evacuation, Safety Management, Fire Dynamics and Resistance.

Each day was opened by invited Keynote Speakers (in total five) addressing broad topics of pressing interest. The Keynote Speakers, selected as leaders in their field, consisted of Ove Njå (University of Stavanger, Norway), Vladimir Molkov (Ulster University, UK), Ulf Lundström (Swedish Transport Administration, Sweden), Mirjam Nelisse (TNO, The Netherlands), and Gunnar Jenssen (SINTEF, Norway). We are grateful that the keynote speakers were able to share their knowledge and expertise with the participants of the symposium.

RISE Research Institutes of Sweden AB
Borås, Sweden
Preface

The proceedings include papers presented at the 10th International Symposium on Tunnel Safety and Security (ISTSS) held in Stavanger on 26-28 April 2023. The symposium is well established in the tunnel fire community and the success of ISTSS is a tribute to the pressing need for continued international research and dialogue on these issues. The proceedings provide state-of-the-art knowledge in the field of fire safety and security in tunnels and other underground structures.

ISTSS usually attracts over 200 delegates from all parts of the world and represents an arena for researchers and engineers to discuss safety and security issues associated with complex underground transportation systems. We clearly see that the fire and explosion hazards of alternative fuel vehicles have become a major area of concern. The airport car park fire in Stavanger 2020 involving alternative fuel vehicles is an example of the challenges ahead. Inside an underground construction such incidents would be more severe. The research on alternative fuel vehicle safety is in urgent need and it is becoming one of the most important research fields. Furthermore, tunnel digitization emerges as a new research area, while risk and engineering analysis continues to be a focused area of many papers. This year there are also specific focuses on fixed fire fighting systems and evacuation. Numerous renowned researchers and engineers have contributed to these and other topics at this symposium for which we are grateful.

We received 80 extended abstracts in response to our Call for Papers (not including our five invited Keynote Speakers) and believe that the quality of the accepted papers is a testament to the calibre of research that is on-going around the world. Of these, 40 extended abstracts were selected, based on their high scientific quality, for paper presentations. Besides, the poster session contains 16 posters to canvas interesting emerging research. The selections of paper presentations were made based on reviews conducted by the 14 members of the Scientific Committee. The Scientific Committee consists of many of the most well-known researchers in this field (a list can be found on the Symposium website, www.ri.se/en/istss/).

We are grateful for their contribution to making this symposium the leading one on fire and safety science in tunnels. ISTSS has long-term cooperation with Fire Safety Journal (FSJ) for publishing special issues on tunnel fire safety. Eight papers from the 9th ISTSS were selected as candidates, and after peer reviews the special issue containing seven papers has been published in FSJ. We hope to continue this process in the future to raise the level of the scientific part of the symposium. During the symposium there is also an exhibit where businesses present their expertise, products and services.

Finally, we would like to thank the other members of our organisation committee: Prof. Haukur Ingason (scientific advisor), Dr. Jonatan Gehandler (program co-ordinator), Kaisa Kaukoranta (symposium co-ordinator), and our colleagues Linnéa Hemmarö and Julia Burgén for their help. We would also like to thank our event partners Vital Infrastructure Arena (VIA), University of Stavanger and RISE Fire Research AS in Norway for their cooperation and help, and thank also our sponsors who contributed with their support and engagement.

Ying Zhen Li
Chair of Scientific Committee

Anders Lönnermark
Chair of Organisation Committee
# Table of contents

## Keynote speakers

<table>
<thead>
<tr>
<th>Title</th>
<th>Speaker</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why is the tunnel fire safety competence situation so fragmented? The need for a tunnel safety study program.</td>
<td>Ove Njå, University of Stavanger, Norway</td>
<td>11</td>
</tr>
<tr>
<td>Hydrogen vehicles safety in underground traffic infrastructure: overview of HyTunnel-CS findings</td>
<td>Vladimir Molkov, Ulster University, UK</td>
<td>28</td>
</tr>
<tr>
<td>Development of the Swedish road tunnel safety concept</td>
<td>Ulf Lundström, Swedish Transport Administration, Sweden</td>
<td>45</td>
</tr>
<tr>
<td>Risk analysis of fire and explosions in road tunnels</td>
<td>Mirjam Nelisse, TNO Netherlands Organisation for Applied Scientific Research, The Netherlands</td>
<td>56</td>
</tr>
<tr>
<td>Human behaviour during fires in tunnels</td>
<td>Gunnar Deinboll Jenssen, SINTEF Community, Norway</td>
<td>63</td>
</tr>
</tbody>
</table>

## Alternative fuel vehicles

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>The use of Natural Gas Vehicles in underground facilities: Application to the Paris-La-Défense underground network</td>
<td>Benjamin Truchot¹, Christophe Willman² &amp; Patrick Personna³</td>
<td>79</td>
</tr>
<tr>
<td>Safe extinguishment of fire exposed compressed natural gas (CNG) and hydrogen (H₂) cylinders</td>
<td>Jonatan Gehandler &amp; Anders Lönnemark, RISE Research Institutes of Sweden, Sweden</td>
<td>89</td>
</tr>
<tr>
<td>Fire safety of parking garages in respect to electric vehicles: the Singelgarage fire and fire suppression</td>
<td>Nils Rosmuller, Tom Hessels, Ricardo Weewer, Johan van der Graaf &amp; Joost Ebus</td>
<td>103</td>
</tr>
<tr>
<td>Experimental study of battery fire in a tunnel: Evolution of flame characteristics and temperature profile under longitudinal ventilation</td>
<td>Nannan Zhu¹, Fei Tang¹, Xiepeng Sun¹, Margaret Mcnamee² &amp; Longhua Hu¹</td>
<td>112</td>
</tr>
</tbody>
</table>

¹ State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, China
² Division of Fire Safety Engineering, Lund University, Lund, Sweden
Risk management & explosion
Hydrogen Tunnel Risk Assessment – numerical study of selected hydrogen incidents and implementation in the Austrian Tunnel Risk Model
Oliver Heger\textsuperscript{1}, Regina Schmidt\textsuperscript{1}, Daniel Fruhwirt\textsuperscript{2} & Martin Aggarwal\textsuperscript{3}
\textsuperscript{1}ILF Consulting Engineers, Graz, Austria
\textsuperscript{2}Graz University of Technology, Graz, Austria
\textsuperscript{3}Hydrogen Centre Austria Ltd., Graz, Austria

Life-safety targets in underground stations
Johan Lundin\textsuperscript{1}, Bo Wahlström\textsuperscript{1}, Erik Hall Midholm\textsuperscript{1} & Oskar Jansson\textsuperscript{2}
\textsuperscript{1}Brandskyddslaget AB
\textsuperscript{2}RiskTec Projektledning AB

Digitalization
RiskTUN: An ICT-based Concept for a Risk-aware Decision Support System for Tunnel Safety
Naeem Khademi\textsuperscript{1}, Henrik Bjelland\textsuperscript{1}, Erik G. Nilsson\textsuperscript{2} & Konstantinos Boletsis\textsuperscript{2}
\textsuperscript{1}University of Stavanger, Stavanger, Norway
\textsuperscript{2}SINTEF Digital, Oslo, Norway

Innovative approach to Improve the Safety of Tunnels and Tunnel Control Centres
Harald Kammerer\textsuperscript{1}, Bernhard Klampfer\textsuperscript{1}, Anne Lehan\textsuperscript{2} & Hendrik Wahl\textsuperscript{2}
\textsuperscript{1}ILF Consulting Engineers, Linz, Austria
\textsuperscript{2}Federal Highway Research Institute, Bergisch Gladbach, Germany

An AIoT-based smart digital twin for real-time tunnel fire safety monitoring
Xiaoning Zhang\textsuperscript{1}, Xiqiang Wu\textsuperscript{2} & Xinyan Huang\textsuperscript{1}
\textsuperscript{1}The Hong Kong Polytechnic University, Hong Kong, China
\textsuperscript{2}Southeast University, Nanjing, China

Locating people in tunnels using Wi-Fi technology
Håkan Frantzich\textsuperscript{1}, Karl Fridolf\textsuperscript{2} Staffan Liljestrand\textsuperscript{3}, Alex Hennigsson\textsuperscript{3} & Johan Lundin\textsuperscript{4}
\textsuperscript{1}Lund University, Lund, Sweden
\textsuperscript{2}The Swedish Transport Administration, Malmö, Sweden
\textsuperscript{3}Bumbee Labs, Stockholm, Sweden
\textsuperscript{4}Brandskyddslaget, Stockholm, Sweden
**Explosion**

Nonlinear analysis of tunnel slab under hydrogen explosion

Wenqian Liu¹, Frank Markert¹, Volodymyr Shentsov² & Luisa Giuliani¹

¹Technical University of Denmark, Lyngby, Denmark
²Ulster University, Newtowabbey, United Kingdom

Explosions in road tunnels Part 3: Target failure probability & design values

Mirjam Nelisse & Ton Vrouwenvelder
TNO Netherlands Organisation for Scientific Research, The Netherlands

**Ventilation 1**

Experimental study of smoke characteristics in double-layer tunnel with multiple point extraction by branch pipe

Zhan Wang¹, Zhi Tang¹, Zheng Fang¹, Zhiming He², Tao Yang³, Ming Zhou², Enshi Wang³, Yinhang Xu⁴, Pei Yu¹ & Qinwen Li¹

¹School of Civil Engineering, Wuhan University, China
²Wuhan Investment Group CO., LTD., China
³Wuhan Zhongjiao Traffic Engineering Co., Ltd., China
⁴Wuhan Municipal Engineering Design & Research Institute Co., Ltd., China
⁵Engineering Research Centre of Urban Disasters Prevention and Fire Rescue Technology of Hubei Province, China

Influence of blockage on smoke control in tunnels

Ying Zhen Li & Haukur Ingason
RISE Research Institutes of Sweden, Sweden

**Fixed fire fighting systems**

Review of Design Fire Heat Release Rate for Tunnels with Fire Suppression Systems

Yunlong Liu, Sean Cassady, Petr Pospisil & Eric Jones
HTNB, USA

CFD modelling of tunnel fires with low-pressure fire suppression systems

Ying Zhen Li¹, Lei Jiang² & Haukur Ingason¹

¹RISE Research Institutes of Sweden, Sweden
²RISE Fire Research AS, Norway

Experimental study of the performance of a water mist system on fires in a full-scale tunnel

Lei Jiang, Robert Harley Mostad, Tian Li & Kemal Sarp Arsava
RISE Fire Research AS, Norway

Design fire heat release rate of flammable liquid fires under water mist suppression in a tunnel

Yunlong Liu, Sean Cassady, Petr Pospisil & Eric Jones
HTNB, USA
Tenability and evacuation

Sprinkler system design using CFD tools for assessing tenability impact and total hydraulic demand
Miguel Ángel Fuentes Llanos, Panos Iliadis & Sohail Alizadeh
Mott MacDonald, United Kingdom

Experimental Report on a System for Maintaining the Evacuation Environment by Early Detection of Tunnel Fire and Control of Longitudinal Wind Speed
Masahiro Yokota, Ken-Ichiro Yamazaki, Taku Nakayama & Takumi Ota
Central Nippon Highway Engineering Tokyo Company, Japan

Progressive Evacuation Approach in a High-Security Hazardous Tunnel
Sandeep Upadhya, Jonathan Tang, Mukesh Tomar, James Fletcher & Rares Zupu
Jacobs, UK

Application and Interpretation of Visibility Through Smoke in Performance-Based Design
Andrew Coles, Mathilde Girault, Peter Senez & Jordan Brown
Senez Consulting Ltd., Canada

Emergency management

Enhancement of the safety management for the three main passenger rail tunnels in Antwerp
Lieven Schoonbaert, Sven Spelmans, Stefaan Vernieuwe, Olivier Bivort & Christof De Backere
Belgian Railway Infrastructure Manager, Belgium

Incident management in long railway tunnels, taking the Koramltunnel as an example
Michael Bacher¹, Helmut Steiner², Daniel Fruhwirt¹ & Peter Sturm¹
¹ Graz University of Technology Austria, 8010 Graz, Austria
² ÖBB Austrian Federal Railways

Evolution of emergency preparedness: A case study of two Norwegian road tunnels
Jeroen Wiebes Kjos¹, Maria-Monika Metallinou¹ & Henrik Bjelland²
¹Western Norway University of Applied Sciences, Norway
²University of Stavanger, Norway

Tunnel fire exercise in the Northern Link
Emil Persson, Björn Hedskog & Bo Wahlström
Brandskyddsleg AB, Sweden

Evacuation

Evacuation shelters in single-tube road tunnels – From a poor reputation to emerging interest
Jeroen Wiebes Kjos¹, Henrik Bjelland², Ove Njå³, & Inger Lise Johansen³ & Sverre Kjetil Rød³
¹Western Norway University of Applied Science, Haugesund, Norway
²University of Stavanger, Stavanger, Norway
³Norwegian Public Roads Administration, Lillehammer, Norway
Analysis of spatial and design factors for users’ acceptance of rescue rooms in road tunnels: An experimental study using Virtual Reality
SINTEF Community, Dept. of Mobility and Economics, Trondheim, Norway

Analysis of visual and acoustic measures for evacuations in road tunnels using virtual reality
Jo Skjermo¹, Claudia Moscoso¹, Daniel Nilsson², Håkan Frantzich³, Åsa S. Hoem¹ Petter Arnesen¹ & Gunnar D. Jenssen¹
¹SINTEF Community, Dept. Mobility and Economics, Trondheim, Norway
²University of Canterbury, Christchurch, New Zealand
³Lund University, Lund, Sweden

Ventilation 2
NFPA 502 Critical Velocity Calculation Methodologies and Dimensionless Fire Heat Release Rate
Yinan Scott Shi¹, Iain Bowman¹, Natasha De Los Rios², Norris Harvey², Kyle Lopez² & Luke Pelessone²
¹Mott MacDonald, Canada
²Mott MacDonald, U.S.A.

Numerical study on the influence of the ventilation strategy on life safety in a metro tunnel
Matteo Pachera, Wouter Van den Berghe, Luc Derie & Johan Dubruel
Sweco, Belgium

Assessment of Jet Fan Installation Efficiency in Shotcrete-Lined Drill & Blast Tunnel
Iain Bowman, David Eckford, Sohail Alizadeh, Jay Ganeshalingam, Tommy Norris & Rebecca Zhao
Mott MacDonald, Canada

Safety management
Medical knowledge as prerequisite for establishing criteria for design, management and emergency preparedness in road traffic tunnels
Geir Sverre Braut¹, Harald Søiland², Haavard Søiland¹ & Ove Njå²
¹Stavanger University Hospital, Stavanger, Norway
²University of Stavanger, Stavanger, Norway

Tunnel safety: how about the safety of maintenance workers in tunnel service corridors?
Nils Rosmuller, Johan van der Graaf & Joost Ebus
NIPV, Netherlands Institute for Public Safety Arnhem, The Netherlands

Fire dynamics and resistance
Study on the maximum temperature rise beneath the ceiling considering the effect of bifurcated plume flow in longitudinally ventilated tunnel fires
Ganyu Wang¹,²,³, Jiangdong Li¹,²,³, Tianhang Zhang¹,⁴, Xiaqi Zhang¹, Jiajun Weng¹, Ke Wu¹,²,³
¹Key Laboratory of Offshore Geotechnics and Material of Zhejiang Province, Zhejiang University, China
²Center of Balance Architecture, Zhejiang University, China
Bonding behaviour of CFRP composite strengthened tunnel structure under fire exposure
Yi Shen1,2, Shi-qi Dou2, Cheng Yang2, Long Zhou2, Hui Wang2, He-hua Zhu1,3 & Zhi-guo Yan1,2
1State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, China
2Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, China
3School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, China

Study on flame behavior of asymmetric double fires with different separation distances in the tunnel
Kun He1, Yongzheng Yao2, Long Shi1, Hui Yang1, Xudong Cheng1
1State Key Laboratory of Fire Science, University of Science and Technology of China, China
2School of Emergency Management and Safety Engineering, China University of Mining and Technology, China

Evolving tunnel research and safety in USA
Gary English, Underground Command and Safety, USA

Posters

A known unknown concerning the road-based transport of dangerous goods
Christian Henrik Alexander Kuran
University of Stavanger, Norway

Case study on the ventilation design of the Kennedy Rail Link
Melchior Schepers1, Wout Verborg1, Xavier Deckers1 & Bart De Pauw2
1Jensen Hughes, 2Tuc Rail, Belgium

Computer aided resilience assessment
Kalliopi Anastassiadou1, Ulrich Bergerhausen1, Franziska Linstrom2, Christoph Zulauf2
1Federal Highway Research Institute (BASt), Germany
2EBP Schweiz AG

Using existing Radar infrastructure for tunnel safety management and emergency response
Sebastian Baucutt & Ozair Baig
Navtech Radar, UK

Computational Assessment of Critical Velocity Criteria in Rail Tunnels
Janaya Walter, Sonia Taylor, Adrian Milford, & Samson Li
Arcadis IBI Group, Vancouver BC, Canada

Smart dynamic exit sign system for tunnel fire evacuation: A lab-scale demonstration
Ho Yin Wong, Xiaoning Zhang, Meng Wang & Xinyan Huang
The Hong Kong Polytechnic University
Initial airflow conditions for fire scenarios based on traffic parameters
Jakub Bielawski¹, Wojciech Węgrzyński¹, Aleksander Król² & Małgorzata Król²
¹Building Research Institute, Poland
²Silesian University of Technology, Poland

A study on the smoke proof test of a positive pressure deployable evacuation passage for subway stairs
Duckhee Lee, Won-Hee Park, Joo-Young Jung & Tae-sun Kwon
Korea Railroad Research Institute

Smoke ventilation tests for multipath subway lines using reduced scale tunnel and station model
Won-Hee Park, Young-min Cho, Su-whan Youn, Tae-sun Kwon & Duckhee Lee
Korea Railroad Research Institute

Generation of carbon monoxide in fires partially suppressed by water sprays
Haydn Lewis¹ & Nils Johansson²
¹Jensen Hughes Pty Limited, Australia
²Division of Fire Safety Engineering, Lund University, Sweden

A numerical investigation on suppressing shielded fires with water mist systems
Azad Hamzehpour, Vittorio Verda & Romano Borchelli
Department of Energy (DENERG), Politecnico di Torino, Italy

The development of an e-learning course designed to strengthen Swedish ambulance commanders decision-making in road tunnel incidents
Johan Hylander¹, Satish Strömberg², Anton Westman¹,³
¹Department of Surgical and Perioperative Sciences, Umeå University, Sweden
²Faculty of Arts, Umeå University, Sweden
³Department of Anaesthesia and Intensive Care Medicine, Karolinska University Hospital, Sweden

The performance of water mist systems on extinguishing shielded fires: An experimental study
Azad Hamzehpour, Vittorio Verda & Romano Borchelli
Department of Energy (DENERG), Politecnico di Torino, Italy

Monitoring of airflow and airborne particles, to provide early warning of irrespirable atmospherics conditions in underground mines
Madeleine Martinsen & Erik Dahlquist
Mälardalens University, Sweden

Extending Cross-Passage Distances
Basar Bulut & Mathias Y.B.Lysholt Hansen
COWI A/S, Denmark

Fire emissions from new and existing materials, an occupational issue now and in the future
Evalyne Arinaitwe, Margaret McNamee & Patrick van Hees
Lund University, Division of Fire Safety Engineering
Why is the Tunnel Fire Safety Competence Situation so Fragmented? The Need for a Tunnel Safety Study Programme

Ove Njå

1University of Stavanger, Ullandhaug, Stavanger, Norway

ABSTRACT

Road and railway tunnels have been erected and put in operation for many decades. Normally the tunnels function well in accordance with their purposes. However, understanding safety levels, safety systems and how safety is maintained is challenging. The tunnelling industry contains large numbers of actors with different roles in the tunnel safety work, many of whom are not aware of each other. We claim the situation as fragmented, which is a hazard to tunnel safety. Fires, accidents and other deviations from normal operation frames the conditions of the safety systems. Other less critical tests are inspections, planned stress tests, exercises and surveillance. Norwegian tunnels are integrated into the owners’ safety management programmes. Still, critical events occur frequently. Some of the events are seen as inevitable, regarded as beyond the tunnel safety systems’ constraints or its design space. This article analyses tunnel safety competence as an important concept of the tunnel safety management system. Competence has not been addressed by regulations and there exists huge uncertainties regarding what is perceived “good” tunnel safety competence. The article uses a combination of learning theory and systems safety theory to obtain a “state of competence tool” that might be adopted by relevant actors. Furthermore, the article provides an assessment of the design and initial piloting of a study programme on tunnel safety, developed by a large number of tunnel owners, operators, emergency services and tunnel-users. The study programme is run by the University of Stavanger and comprises 30 ETSC at bachelor level. So far, the students acknowledge the networking, the interdisciplinary perspectives, group work activities and professional discussions in rather intensive and focused learning activities.

KEYWORD: Tunnel safety, competence, study programme, learning,

BACKGROUND

This article challenges the issue of tunnel safety competence. Tunnel safety could be seen as absence of unwanted events, but the concept contains much more; technological, organisational and operational measures related to design, regulations, operational issues, maintenance etc. These aspects need to be assessed against the involvement of various actors that orchestrates and control tunnel safety. The article draws attention to state-of-the-art knowledge, systems and experiences from tunnel safety management. The primary discussion is associated with road transport tunnels, but viewing tunnel safety competence from the road and rail sectors is necessary and important. The two transport modes frame the presentation of the Tunnel Safety Study (TSS) provided in the second part of this article.

The starting point is however a discussion of where we are today and why the tunnel safety competence is so fragmented, uneven, prejudiced and underestimated. Historical developments both in society and in the transport sectors and industries, have provided the current situation for the prioritisation of tunnel safety. We think that history is important for all countries with its tunnel safety development. In a multinational study with contributors from Sweden, the UK, USA, Australia and
Norway [1], historical developments of tunnel fire safety management is discussed. It is interesting to assess values deemed important in the societies, the structure of the tunnelling industry and contributing professional disciplines. Road tunnels, at least in Norway, have been erected and used for transport purposes in more than 100 years. Tunnels became necessary to enable transport and mobility in western mountainous parts. The first known road tunnel is the Eidfjord tunnel, but tunnels were also erected in the Bratland valley in Rogaland (Kvelvane) and the section from Odda towards Ullensvang (approx. 1880-ies, [2]). Safety in operation phases of the tunnel was never an issue then. It was more dangerous to construct the tunnel than its actual use. This have been an issue in tunnelling work to date. The first railway tunnelling through the Gotthard mountains took 199 lives, and the Gotthard Base Tunnel that opened in 2016 killed 9 workers. However, it is the disastrous fires, such as Mont Blanc, Tauern and St. Gotthard fires (62 fatalities) around the millennium that most people associate with tunnel safety.

A rough estimate is that approximately 50 % of the Norwegian tunnels (approx. 600 of 1200) were opened before 1985. The tunnel safety standard at that time was low, tunnels were erected to sustain traffic flow and mobility in general. However, reporting accidents in tunnels was not an important issue then, even though it was identified 221 accidents with human injury (1970 – 1979, [3]) and 57 accidents with human injury (1980 – 1986, [4] – western Norway). 1975 was the worst year in Norway with respect to all roads traffic accidents (576 killed and more than 4500 seriously injured). By the end of the 1980-ies Norway experienced the Måbø-tunnel accident (a Swedish bus with schoolkids lost its brakes and the driver chose to hit the tunnel wall to reduce speed – 12 children and 4 adults died in 1988), and a half year later 5 adolescents were killed in the Åsane tunnel also hitting the tunnel wall. From 1986 to the millennium a large number of long tunnels (> 4 km) was erected to improve traffic and mobility along the western coast of Norway and across Norway from Bergen to Oslo. The Minister of Transport at that time – Kjell Opseth, a representative from the Western area, was an important proponent of the development of the section, E16, which includes the Lærdal tunnel, the Gudvanga tunnel, the Flenja tunnel [31]. These tunnels have been exposed to major fires since 2010. However, it was the European fires at the millennium, the research efforts subsequent the fires (UPTUN, FIT, SAFE-T, etc), the introduction to the Vision Zero strategy, and the change in regulations that boosted tunnel safety efforts\(^1\) and introduced performance-based requirements in addition to strengthened preaccepted solutions.

In the period 1986-2000, several subsea tunnels were planned and erected. These tunnels are relatively long, they have steep slopes and subjected to pushing limits with regards to length and depth. Those tunnels were minimally equipped with regards to safety systems, because major fires in the tunnels were not considered a viable scenario. The building inspectorates (municipalities) were absent as well as the Directorate of fire and explosion protection. The Directorate for Public Road Administration did not pay particular attention to the safety aspects, since the tunnels did not represent more serious hazards than the roads in the open. Even though road traffic accidents were regarded a major societal problem, traffic safety was not prioritized against the necessity for increased mobility. At the millennium the Vision Zero was politically manifested, tunnels were perceived as hazards with respect to its major accident potential mainly due to fires, and the regulations were revised [6]. Tunnel risk and safety became an issue [7]. Njå and Nilsen developed a draft handbook that provided guidance for the NPRA to integrate tunnel safety issues [8] in all project phases.

Safety thinking from various sectors met; the road safety (data driven – statistics), the building and construction industry (preaccepted solutions – engineering based incremental development) and the oil & gas industry (performance based and goal-oriented engineering). The road transport sector went through major structural changes as well, which gave opportunities to embed new ideas and thinking. However, the major change processes did not affect tunnel safety work particularly, and tunnels were not emphasized in the fire safety thinking until 2013, when the Norwegian Road Authority critically assessed the standards of the tunnel safety against the requirement in the Tunnel Safety Directive [9].

\(^1\) EU Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network
The ongoing tunnel upgrading program shall ensure sufficient standard in accordance with the directive for the TERN-roads and repairing critical deterioration of other tunnels.

In Europe several initiatives were taken that increased competence on tunnel fire safety. Some researchers developed important handbooks [10, 11], and research institutes and international associations (PIARC, CETU, RISE, ITA, IFA to name a few) became active in knowledge dissemination, research and development on tunnel safety. Since Norway is not member of the EU, the effect in Norway was more with an observational status and reflections on how Norway could adapt to regulations and requirements. The Runehamar test tunnel was a bridge between European research institutes and Norwegian efforts (SINTEF and NPRA).

**TUNNELS IN THE STAVANGER AREA – ALSO IMPORTANT FOR THE SAFETY MANAGEMENT DEVELOPMENT**

The Stavanger area was and is a node for the oil & gas industry. In the 1990-ies huge pressures were laid on the geographical area to increase urban and industrial developments and improve the transport mobility along the E39 route. A major part of the value creating industries are located by the E39 section from Trondheim to Kristiansand, in which Stavanger is an important hub for various industries and transport modes (road, rail, sea and air). Ideas to the development of the two longest subsea tunnels in the world were created just before the millennium, and the subsequent planning and construction have been carried out since. These tunnel concepts have gone through a transition during planning, from single tube bi-directional tunnels via tunnels with an escape tube, to fully twin bored uni-directional tunnels. The geometric shapes have changed from steep slopes to slopes less than 5%. Studying those projects provides interesting cases on how the tunnel safety management have developed the last 30 years in Norway. The author became involved in the early phases of the planning of the tunnels. The way safety and risk were discussed raised several issues. The purpose with and use of risk and emergency preparedness assessments seemed to be lacking. The author’s opinion at the time was that use of performance requirements could change the mindset for the industry. A set of performance requirements fit very well with the Vision Zero strategy. However, these requirements were not adopted by the regulator, the NPRA. The risk management approach was immature and one respondent in a study of the Bjørvika development in Oslo (Opera tunnel) ironically referred to how easy it was to influence the risk analysis and its conclusions [12]. My experience from the tunnelling industry since 2000, is that the industry seems to develop in a direction with increased use of performance-based thinking. This development is also acknowledged by Gehandler et al. [13].

**Functional requirements to a safe tunnel system**

The tunnel system’s purpose is always related to its transport production, which is expressed by traffic flow and throughput capacity. However, these operational conditions must be associated with safety. In this subsection a set of functional requirements that will illuminate the breadth and depth of competence needed in tunnel safety management is introduced.

We can think of a superior goal that might be interpreted as a functional requirement for the tunnel system; *The tunnel shall invite to correct/desired speed and it shall be logical end easy to “read” for all road-user categories.* The tunnel design must be adapted to the vehicles that are allowed and the traffic work at the location. Furthermore, the specific functional requirements have been split into *general overall requirements, requirements to normal operation phase and requirements to incident management*.²

²The requirements are developed through discussions with people from the NPRA and course works in Traffic Safety Management (MSc-level and 10 credits), which was developed and first given in 2003. It is important to add that the NPRA never approved a handbook (regulation) on traffic safety management, but a draft handbook was proposed in 2006 [14].
Overall general functional requirements

- **Human abilities and limitations** shall be decisive for the design of tunnels; human coping ability in traffic, human response and strengths in collisions, fires or other incidents, and the human capability to manage deviating situations.
- **The Vision Zero assumes protection against serious consequences from errors.** The tunnel must have protective barriers against serious consequences from driving errors. This must be carefully considered when assessing the tunnel walls.

Functional requirement to normal operation

- The tunnel design shall guide to safe behaviour by being logical and easy to read.
- The tunnel shall invite or guide to correct choice of speed and stimulate awareness.
- In order to be safe for all road user groups, the «weakest» road user groups’ abilities and capabilities shall premise the tunnel system and solutions.
- The design of the tunnel system must enable correct expectations amongst the road users by its geometrical design, marking and signs.
- The tunnel system shall maintain safe traffic management based on predicted distribution of vehicles (heavy/light, variations in speed, navigation characteristics, goods amount and type).
- Traffic management must include special transports through the tunnel.
- The traffic in tunnel must provide surveillance or monitoring devices in normal operations.
- The tunnel must ensure need for planned and non-planned maintenance.
- The tunnel’s safety level and speed limits must be seen in conjunction.
- The entrance and exit zones must maintain the road-users with respect to environment and climate phenomena, light, noise, fear of enclosures, etc.
- Integrate and reflect ordinary road user errors in tunnel safety design, such as slips and lapses, neglecting information, misinterpretation and mistakes, and bad assessments.
- Design with correct “activation level” (low mental workload can imply tiredness, high mental workload can imply “stress” and fatigue):
  - Mental workload influences activation level
  - Optimal performance with an average activation level
  - Too low or high activation level could increase risk of road user errors
  - Too demanding tunnel environment
  - Too monotone tunnel environment

Functional requirements to incident and accident management

The following requirements were developed in accordance with potential demands identified in accident phases:

- **Alerting the surroundings**, for example entering or exiting road users, shall be conducted in a way that humans outside the scene will not be involved in the accident situation.
  - Human ability to self-rescue must be assessed
- **An efficient co-operation** between similar and different enterprises/services responsible for safety and rescue in accident situations is a design principle for the tunnel system design.
- **Alarm** shall be initiated to secure an effective mobilization of all relevant emergency services.
  - The emergency services shall receive rich and real information about the accident situation as early as possible
- **Combat measures** shall be initiated and carried out to prevent a hazardous situation develop into an accident or reduce the consequences of an accident already occurred. The priority is to enable safe and well organised rescue and evacuation, and to the extent possible ensure that other losses are avoided or limited.
  - The tunnel system must be secured for first responders’ activities
  - The tunnel system must be organised for effective incident commanding
- **Rescue measures** shall ensure that missing persons are found and injured persons given necessary first aid and safely evacuated to safe areas where the proper ambulance and health services might be conducted.
- The tunnel length, geometry, and point of attack must be assessed for the optimal performance of rescuing persons.
- Noise and other environmental factors at the scene must be controlled in a way that it does not prevent the emergency services work.
- Long response time for fire and rescue services must not reduce the possibilities for effective rescue and evacuation.

• *Evacuation* from the tunnel shall be performed sufficiently safe and organized so that all persons are brought to safe haven.
• *Normalization* shall ensure that injured people are treated, the environment is recovered to normal conditions and that tunnel damages are repaired.
- The traffic management shall ensure that closed tunnel is remedied with alternative routes for longer periods of time.

The tunnel owner and operator must define and integrate which functional requirements shall base the tunnel design and safety system throughout the planning, construction and operation of the tunnel.

**Summary – the need for a wide spectre of competences**

The historical development encompassing increasing need for tunnels in Norway shows the changes in tunnel safety and security. From being a purely geological and technological working area tunnels are now complex systems integrated in the road and rail infrastructures, the transport - which are one of the vital societal functions. Vital societal function has its own definition and comprehension in the Norwegian societal safety management. The competences needed could be related to interpretations of and responses to the functional requirements. We need engineering competence to design the socio-technological tunnel systems, we need information and communication technology to design the tunnel safety management systems, we need psychology and sociology to understand the communication between the tunnel safety systems and the road users, we need humanities to understand the various ethnicities, languages and learning processes involved in safe driving through tunnels, we need economics, public administration and policy science to understand priorities of safety measures in a socioeconomic political system, and etcetera. The next issue towards tunnel safety competence is to understand how various professionals and competences work together.

**INITIATIVES AND ORGANISING GROUP FOR TUNNEL SAFETY**

As mentioned above the Stavanger region has many tunnels, both older tunnels and tunnels in the planning and construction phases. The universities in the area have approached the tunnel safety issues from different angles; Western Norway University College for Applied Sciences – fire safety, and University of Stavanger – risk management. This has been a topic at the universities for a long time. These academic institutions were also important when the Rogaland County Council made their decision to prioritise tunnel safety in 2012, being the owner of and responsible for the traffic safety of a major part of the public roads (approximately 50%).

Initiatives were taken to finance and organise an industrial innovation cluster (Norwegian Tunnel Safety Cluster - NTSC), a R&D-programme (Capacity Boost Tunnel Safety - KATS), employment of an associate professor at the UiS and establishment of a working group on tunnel safety, to mention some initiatives. A special task force was established to develop an exercise and research facility in conjunction with the rock excavation transport tunnel at Mekjarvik (Randaberg) at the southern entrance of the Rogfast tunnel. The work was presented for the regional head of the NPRA, but was not given sufficient support. This can be changed as Rogfast is now under construction.

Parallel to all activities mentioned above another working group was formed to develop urgent competence increasing activities. Four professionals developed a course, mainly for the fire protection leaders and tunnel safety personnel from the NPRA. The course was piloted and run in Sandnes, Rogaland, at the Societal Safety Centre in Rogaland (SASIRO). At this centre there are outdoor

---

3 Now it is called the Boknafjord tunnel, and it is 26.5 km long, with a roundabout and a detour to the Kvitsøy island.
firefighting training facilities, tunnel fire safety facilities as well as lecture rooms. The area offers possibilities to visit tunnels that might be studied without critical interruption of traffic.

This group developed into a larger working group that developed ideas for a study program at university level, the Tunnel Safety Study - TSS. This was an obvious opportunity since the KATS-project had already identified a similar study program. However, the industry with its small and less robust companies could not afford this education and combined with the COVID-19 situation this was difficult and the study program postponed. During this period the group joined, the railway sector was included and the joint collaboration between the rail sector, the road sector, the emergency service sector and the UiS was created. A separate workshop with the Minister of Transport and Communications, Knut Arild Hareide, was held in 2019, from which he asked the group to provide an application on a National Tunnel Safety Centre, that was intended to be a unit running the study program and become a National competence centre. The working group developed the application with the UiS as the owner, since it is the owner of the Tunnel Safety Study programme. The minister was replaced before the application was administered, but the TSS has been launched and some experiences are presented in the next section.

A separate steering committee for the Tunnel Safety Study has been established. This is a representative group consisting of:

- The County Councils – represented by Rogaland County Council
- The fire and rescue departments – represented by “KS Samfunnsbedriftene” a part of the municipality association.
- The NPRA representing authority and tunnel owner
- The New Roads (Nye Veier)
- The locomotive drivers’ association
- The rail conductors’ association
- The Norwegian truck owners’ association
- The rail infrastructure owner (Bane NOR)
- Counselling Engineering Association – represented by Multiconsult
- Construction industry – represented by Risa
- Coordinator of competence increasing activities in the road and rail sectors – Konnekt

The steering committee represents thus, road and rail users, emergency services, tunnel owners, tunnel operators, authorities, and the engineering and construction businesses. Their roles are extremely important, because they employ the candidates, they know where to look for knowledge gaps, they have concrete experiences, and they embed the study program in the wide tunnelling industry. They will be very important for the assessment, corrections and the further development of the TSS.

THE STUDY PROGRAMME ON TUNNEL SAFETY

The study programme was launched in fall 2022. This was the start of module 1, Societal safety. Prior to this the basic module has been carried out three times. This section provides an overview of the study programme and the experiences so far. The structure of the study programme was developed from a societal perspective on tunnels and transport safety towards the tunnel safety itself and how learning and innovation processes are sustained. 23 students started in 2022 and they have varied backgrounds; tunnel authority, tunnel owner, tunnel administration, emergency services, engineering, HGV transport, train operation and underground excavation. There are four women and the age varies from 27 to 62.

**Good tunnel safety competence**

Let us start with the conceptual issue: *What is “good competence”?* Is it possible to generalise this, at least in the vocational experience-based area?
We can say that competence is about the ability to appropriately approach future and unpredicted situations. Thus, competence is about skills and knowledge, but also about attitudes and values [18]. Knud Illeris [19] looks a bit broader upon the competence definition: *Competence is the ability and preparedness to meet a challenge through action, in which the challenge is unexpected and contextual* (dependent on the situation and surroundings it occurs), *not being routine but new. This means that it is not related to prior developed success criteria, but on the contrary exposed to an infinite number of outcomes* (p 32 – translated from Danish).

Such an issue towards competence might be interpreted as: *Ability to apply the past experiences (theory and practice) in a given situation or context in the present, but also the ability to mentally simulate and imagine, and assess these experiences (theory and practice) in various future situations.* Proactive safety management competence is part of Leveson’s [20] systems thinking.

How do we know that “good competence” is materialised? The tasks are not always observable behaviours and the impacts might be problematic to assess, thus, there might be situations in which we need to develop and apply leading indicators or intermediate factors [21, 22]. We adopted our concept of learning as the; “capability of the new established knowledge to impose changes in structures, processes or results in the relevant settings, [but we] extend the perspective on learning also to cover confirmation of existing knowledge and gaining deeper comprehension of existing practice as legitimate goals for learning” [23].

Bjørnsen [24] defines competence as follows: *Individuals’ ability to deal appropriately with a challenge in a particular context. The challenge is a non-routine task and not reflected in specific success criteria, but rather context-dependent, and reflected as an open result to individuals’ decisions and response actions.* This definition put the candidate in a specific context, that might be the candidates’ vocational setting, related to tunnel safety. For example, a truck driver’s good tunnel competence will in case of a tunnel fire; know the safety systems present, the driver will be able to communicate with the traffic management centre as well as the emergency call centre and the incident commander, the driver will be able to perform fire extinguishing work and the driver will sufficiently know procedures for rescue and evacuation to provide help to other road-users in their self-rescue.

The Norwegian Qualifications Framework [25] define general competence as; *The ability to utilise knowledge and skills in an independent manner in different situations.* This framework is utilized as a premise for the goals identified for the TSS and its subsequent modules. The overall goals for the learning from TSS are split in knowledge, skills and general competence. The program emphasizes the students’ comprehensions of preventive safety management tasks as well as emergency preparedness and contingencies. The tunnels are extremely different and the two transport sectors have different approaches and tools in their tunnel safety management systems, which need to be reflected in the learning processes. The pedagogical solutions are to activate the students from their strong backgrounds and experiences to exploit the possibilities in sharing and solving actual tunnel safety problems. They use information provided during lectures, visits to the system actors and data gathering activities they design themselves. By doing this it is the intention that the student will possess:

<table>
<thead>
<tr>
<th>Knowledge</th>
<th>Skills</th>
<th>General competency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad tunnel safety knowledge in an understanding of the holistic system</td>
<td>Able to assess the safety level of a tunnel by practical review of the tunnel, the equipment and the structure of the safety management system</td>
<td>Contribute to create a culture for learning in the tunnel safety work</td>
</tr>
<tr>
<td>Understand the different roles in tunnel safety work</td>
<td>Able to find, assess and refer to information about tunnel safety that will be relevant to solve challenges</td>
<td>Able to design safety improvements, individually and in cooperation with others</td>
</tr>
</tbody>
</table>

Table 1 Learning goals of the TSS
Knows the status of the R&D-work in tunnel safety

Able to discuss topics related to tunnel safety

Able to perform analyses and assessments of tunnel safety, and reflect upon own performance

Know how to update his/her knowledge with respect to tunnel safety

Know about new ideas and innovation processes with the tunnel safety domain

The TSS structure is shown in figure 1. The 5 ECTS modules (Module 1-5) is gatherings over four days. The project module is flexible and will be adapted the students. They can carry out projects as single students or become a group of maximum three students.

<table>
<thead>
<tr>
<th>Module</th>
<th>Topic</th>
<th>Examination format</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Basic course</td>
<td>—</td>
</tr>
<tr>
<td>1</td>
<td>Societal safety</td>
<td>Oral exam</td>
</tr>
<tr>
<td>2</td>
<td>Road and rail, traffic safety</td>
<td>Written exam</td>
</tr>
<tr>
<td>3</td>
<td>Road and rail, tunnel safety</td>
<td>Practical review of the safety systems in a specific tunnel</td>
</tr>
<tr>
<td>4</td>
<td>Tunnel safety, innovation and the future</td>
<td>Home exam: evaluate an innovation process</td>
</tr>
<tr>
<td>5</td>
<td>Tunnel safety, exercises, experience transfer and learning</td>
<td>Group task: develop/execute a training program</td>
</tr>
<tr>
<td>6</td>
<td>Project; student select relevant topic in tunnel safety</td>
<td>Report and defense</td>
</tr>
</tbody>
</table>

**Figure 1**  The tunnel safety study TSS

Below we present each of the modules.

**Module 0 – basic tunnel safety considerations**

Important topics in the basic module are;

- Tunnel safety seen from the emergency services’ perspectives
- Law on planning and buildings and associated regulations
- Instructions to fire protection leaders in the NPRA – how to realise them in practical work?
- Tunnel safety regulations for the NPRA activities
- Introduction to regulations related to fire prevention, fire dynamics, supervision and practical tunnel safety work
- First aid and response to traffic accidents
- Fires – ignition and development, traffic, car fires including electrical cars
- Planning and execution of various types of emergency training and exercises

The major goal with the course is to provide information and tools directly relevant for the candidates’ working life. The experiences are good, of which the networking and social relations throughout the three days in Rogaland is very important. The participants own experiences are welcomed in discussions, both as part of the lectures but also in groups towards the end of the course. The candidates are involved in practical extinguishing training at the field (SASIRO) and exercise in a tunnel (the Frafjord tunnel).
There have been three courses, once a year with approximately twenty candidates in each course. People from distant regions stay at SASIRO, which make it an overall and intense coursework with the potential for discussing and working on safety issues around the clock.

Module 1 – societal safety and transport as a vital societal function
Societal safety and security contain all activities and arrangements that maintain society’s vital functions to secure the citizens’ lives, health and basic needs. The students were introduced to important concepts in societal safety that included vital societal functions, safety management, risk, performance, vulnerability, resilience, seen in the context of the transport sectors; road and rail. The module started with introducing projects that students would use as discussion throughout the four days at SASIRO. The topics of the projects were:

- **Road transport as vital societal function**
  - Why is the road transport a vital societal function
  - Justify the degree of criticality and discuss the choice
  - How critical is the tunnels as part of the road transport system – discuss vulnerabilities
  - How would you describe dependencies to other societal functions?

- **Rail transport as vital societal function**
  - Why is the rail transport a vital societal function
  - Justify the degree of criticality and discuss the choice
  - How critical is the tunnels as part of the rail transport system – discuss vulnerabilities
  - How would you describe dependencies to other societal functions?

- **Planning societal safety and security of the road and rail transport**
  - What is the influence from National Transport Plan upon tunnel safety actors?
  - How can we use planning in societal safety work – use various perspectives (tunnel owners, tunnel operators, authorities, transport providers, emergency services, local governments, regional governments, engineering, construction)?
  - Emergency preparedness in planning societal safety – pros and cons in planning?

- **Model for safety management – road transport**
  - Use the model depicted in [26] and discuss it in relation to a chosen section that includes tunnels
  - What would you prioritise to develop a good safety management system?
  - New tunnels might contribute to societal safety and security improvements. Identify some examples and how and why this can be obtained.

- **Model for safety management – rail transport**
  - Use the model depicted in [26] and discuss it in relation to a chosen section that includes tunnels
  - What would you prioritise to develop a good safety management system?
  - New tunnels might contribute to societal safety and security improvements. Identify some examples and how and why this can be obtained.

The combination of lectures, visits, group work and social events were highly appreciated. A visit to the joint coordination rescue centre at Sola, the Rogaland county council, and SASIRO tunnel fire rescue facility. The lectures were provided by professionals from various enterprises as well as lecturers representing academia. It provided a mix of safety management theories and how these are transferred into practices in the various enterprises. The oral examination was carried out 6-7 weeks after and comprised the project topics mentioned above and extended with four others:

- **Concepts in societal safety**
- **Various theories in societal safety**
- **Regulation and safety concerns**
- **Roles in societal safety work**

Responses from the oral exams showed an impressive adoption of the perspectives from the course work into the candidates’ own working areas. The grades varied uniformly from A to D.

The students’ evaluation based on oral presentation and a survey was very positive. Group works were appreciated, the venue was perfect. Many students stated that they were not aware of societal safety and that this had put their own work into a much broader context. The intensity of the course work was deemed high, but the time limit (three – four days) is a critical factor for the students. It is difficult for them to extend the time set for each module.
Module 2 – traffic safety an overall issue
Module 2 was carried out in Larvik in the southeast of Norway. The reason for this was that this area contains interesting sections of road and railway, that we would use in the pedagogical outline of the study. Two cases were established:

In figure 2 we depict the same areas of Larvik’s surroundings on maps, in which the left map contains the road section. It is a TERN-road E18 from Lasse’s Kro (well-known place for the NPRA and haulers) before Porsgrunn (industrial hub) further east to Langangen (standard change of road) past Larvik and further on to Torp (close to airport). The section comprises many tunnels and bridges, and the contingency solutions with the down time events are not clear. The right map shows the railway section from Larvik to Porsgrunn, opened in 2018. It consists of seven tunnels of various lengths and the train travels with high speeds – up to 200 km/h through the section. An issue would be to consider the entire section as a tunnel solution.

As with module 1 this module was organised with projects and closely related to risk analysis of the two sections. However, everything was left open and the students were challenged with why we should do a risk assessment of the two sections. How should we define the major issues, and thus, what would be the purposes with the analyses. This was demanding because it put the students in what they perceived as difficult and unclear situations. Most of the students had participated in risk analyses before, but the task was considered difficult and a bit demotivational.

By day two a project description was given and discussed, with the aim of five different groups working on the two cases. From the description the following major issues were developed.

Road:
- Where are the most important accident locations at the section and what makes them accident spots?
- Why will Vision Zero accidents at this road section happen?
- How can we ensure the contingency needs by detour roads that provides sufficient traffic safety?

Rail:
- What events might develop into situations that threatens life and health?
- How can the system deter with time in a way that changes the risk images?
- What is the performance of the emergency response systems that are established in the new railway section?

Table 2 depicts the tasks that each group worked on through the course work. The group activities were organized in between relevant lectures from the rail and road transport industry. Furthermore, presentations from the professional environments working on accident investigations and traffic control were included. A visit to the Road traffic management centre in Porsgrunn was carried out. The group travelled by train the railway section that was part of the case study.
Table 2  
**Case study issues**

<table>
<thead>
<tr>
<th>Data gathering and use of data – road/rail (group 1 and 5)</th>
<th>System description, knowledge and assumptions in analyses (group 2 and 4)</th>
<th>Methodology and analytical approaches (group 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does the major issues influence the choice of data and data gathering?</td>
<td>Characterise and present the system in light of the major issues and show the necessary limitations and assumptions.</td>
<td>Based on the major issues established, what are the methodological challenges?</td>
</tr>
<tr>
<td>How can we assess the relevance of the data?</td>
<td>How would you adapt the system in accordance with the knowledge available and needed?</td>
<td>You are the leaders of the analysis, suggest and justify your analysis designs.</td>
</tr>
<tr>
<td>What are the important uncertainties that must be reflected in the choice of data?</td>
<td>How can we ensure sufficient strength of knowledge related to the systems?</td>
<td>What preparations are necessary in each case?</td>
</tr>
<tr>
<td>Recommend your data gathering approach and reflect upon it.</td>
<td></td>
<td>Discuss pros and cons with your recommended analysis designs.</td>
</tr>
</tbody>
</table>

Problem based educations seems to function very well amongst the experienced candidates. They have access to information and databases, which is not normal for ordinary students. The learning between students and through problems the students solve in the course work is highly valuable. At present the exam is not carried out and thus, we have not had any formal evaluation yet. The students will spend time studying their curriculum and the hope is that the students reflect and make inquiries about the contents of the course work.

**Module 3 – tunnel safety**

This module is currently in the detail planning phase. The course will be carried out at SASIRO, which was the location for the first module. Rogaland is a splendid starting point for lectures, visits and studies of road tunnels, but also the Drangsdal section in this area shows particularly challenges for the railway system and availability of emergency services. There are several competent sources to be involved in the lecturing and course works, such as the Rogaland Fire and Rescue Department (RBR), the Rogfast project (planning and construction phase), tunnels containing critical factors (length, slope, traffic, equipment, etc). Health related issues has been an issue for the Stavanger University Hospital and the engineering and construction industries are well-represented in the region.

This module will be developed to obtain the following learning goals:

- Possess tunnel safety knowledge from the perspective of the emergency services
- Able to understand and use the regulations: the planning and building act, tunnel safety regulations, regulation on fire prevention, regulation for safety management of railway enterprises, TSI-SRT, and relevant guidelines
- Able to adapt “Instructions for fire prevention leaders (NPRA)” into practice
- Possess basic knowledge of fire dynamics that includes initial phases of vehicle fires (railway carriages, HGV, electrical cars) and the tunnel traffic loads
- Know the health related first aid and rescue responses of tunnel accidents
- Able to present and discuss system designs of passive fire protection, active fire protection and other safety and emergency response measures in tunnels
- Able to analyse and discuss safety levels of tunnel systems

Looking at contents and pedagogics, this course will maintain the experiences with problem solving issues. Now we look more into how safety systems communicate and influence the entire tunnel system safety and how safety assessments can be conducted for planned and operated tunnels. The aim is to observe and assess concrete tunnel projects and critically assess the design documentation and analyses. Tunnel fires and how to establish dimensioning scenarios are of particularly interest. The exam will be constructed with a practical review of the safety systems of selected tunnel designs, related to planning documents, design drawings and descriptions etc.

**Module 4 – tunnel safety and innovation**

This module will be planned and executed this fall (2023). The KATS-project is designed to assess, encourage and facilitate innovation processes in tunnel safety work [27, 28]. From the state-of-the-art description outlining the KATS-project tunnel safety improvements must be designed based on road users’ characteristics, needs and mindset. And, for ensuring this situation innovation is needed. What promote and inhibit innovation in systems with strong public performances?
Innovations are unique new ideas that are implemented. The innovation processes are interesting from concept to implementation following a non-linear cycle of divergent and convergent activities that can be repeated in unpredictable ways over time. Findings from Van de Ven’s [29] study (Minnesota Innovation Research Program) suggest that leaders can manage the businesses’ innovation success by developing and practicing learning and management and build relations through the process. Other issues are:

- Open and closed innovation. Increased mobility among experienced and proficient people, increased knowledge, and increased presence of risk-willing investors, as well as quicker marketing of products and services, promote open innovation.
- Active user participations in the process of innovation development. Businesses should self-develop innovation by interacting with the users.

Innovation should not only be considered from the immediate improvements in purpose and services, but should instead be based on assessments of issues related to public values. We will discuss how safety management systems might drive or inhibit innovation. Learning goals in this module:

- Able to introduce innovation as a way of thinking and activity in tunnel safety related work.
- Able to challenge approaches to how innovation could be part of inquiry and tender work related to planning, constructing, maintaining and operating tunnel projects.
- Able to reflect upon actors’ roles and responsibilities regarding innovation in the tunnel safety work.
- Able to assess innovation products and processes.

This course work will invite enterprises working with innovation to give lectures and show their products, which are both regarded as successes and not that successful. There are fresh examples of design solutions that are patented and under piloting. Some challenges the way tunnel safety is regulated while others are less restricted. The students will be encouraged to analyse concrete innovation designs, and this will also be the subject for examinations.

Module 5 – tunnel safety and learning activities
The tunnel safety work and systems are dependent on fire prevention leaders, traffic management operators, fire- and rescue personnel, and management that understand the necessary actions and arrangements that shall prevent development of dangerous situations and reduce consequences of occurred crises. This requires tools for learning emergency preparedness, emergency response and crisis management. The course work utilizes connections between risk analyses, contingency analyses, contingency plans and design premises for safety equipment and systems in tunnels. These are applied in the design of learning activities for various groups with responsibility to ensure tunnel fire safety. Various didactical tools will be introduced, and how and why they promote learning.

Learning theories will be discussed, in which experience based and vocational learning will be emphasized. Based on a specific learning model the candidates will be prepared to plan and develop exercises that might span from tabletop to larger collaboration exercises. To the extent possible these training and exercise activities will be carried out at relevant locations. The learning objectives are:

- Able to analyse and use risk and emergency response analyses and emergency plans for training purposes.
- Able to plan and execute training and exercise activities on critical tunnel events, emphasizing fire events.
- Able to correct or change pedagogical design to adapt the participants’ competencies.
- Understand and discuss learning theories.
- Possess competence in crisis management and comprehend human behaviour in crisis situations.
- Evaluate exercises and training activities with respect to learning effects.
In the KATS-project there are two PhD-dissertations being finalized prior to this module execution. The results and approaches used in the dissertation will be of value for the contents of this module.

**Module 6 – project in tunnel safety**

This module cannot be seen as a sole module, it must be associated with all of the other modules. However, choice of major issue and topics of the study project might involve more information of one of the modules than the others. For example, it would be possible to study learning effects from tabletop exercises. The candidate is responsible for developing a plan for the project work, and it might last for some months and up to two years at the most extreme.

The project might be seen as a learning tool for the student, but also as a concrete challenge to an issue in which the student or his/her enterprise has experienced themselves or what is regarded state of the art problems. The topic must be related to tunnel safety in one way or another, but it might consist of a practical perspective, for example investigate events used to facilitate fire and rescue training. The project must be designed with relevant theories, preferably from the curricula of the other modules, and it must be adapted to a study object. This can be a specific tunnel, it can be an organization or an activity, for example risk management. Learning objectives are:

- Able to develop a relevant major issue in tunnel safety frameworks that might be studied with scientific methods.
- Able to use theories to illuminate the major issue.
- Establish a methodology to answer the major issue.
- Execute the project activities, analyse and discuss data and results.
- Able to discuss results against theories and other studies within tunnel safety domain.
- Able to write report.

The project combines the specific studies from the other modules and provide the candidate with an overall tunnel systems safety thinking. The report will be presented and defended as the final exam in the tunnel safety study.

**DISCUSSION**

The current status for the tunnel safety study is that we have carried out two modules for the pilot group. The willingness to study rather than attend amongst the students has been encouraging. The connection between the working task situations in the tunnelling industry and the contents of the study program is at the core and what we must follow up on a continuous basis. The students bring a wide variety of backgrounds and perspectives on tunnel safety into the study programme. We need to take advantage from these backgrounds and develop new knowledge bases from them, thus it requires that we have an even stronger research based approach to the TSS than we have in normal discipline related study programmes at the UiS. This is also the reason for the justification of a study programme that is framed at an academic level. Very often in fragmented working domains, such as tunnel safety, there exist significant level of intolerance amongst actors. The emergency services might be frustrated with the engineering that have produced complicated communication or evacuation system, in which their performance might be reduced. Transport companies might express frustrations with the huge variety to tunnel safety solutions, which in their opinion neither provide easy operation nor clarification on how to behave in emergencies. These “conflicts” are numerous. The TSS will both be able to identify such conflicts, and it will be an arena to discuss and understand why and how these situations might prevail or change.

At an academic level, the TSS (Tunnel Safety Study) introduces how experiences become theory, and how actors should collect and critically reflect upon data and knowledge. In Norway, there is a huge debate on the “master-sickness”, which is an argument that we are educating professionals beyond the necessary competencies. We think that this discussion is completely wrongly designed. Academically supported education is a way to develop reflexive people being able to think for themselves and
critically approach knowledge; the details are less important. In the digital world, we see developments into restrictive and erroneous world views that must be challenged. Learning to critically assess data sources is thus a vital part of the lifelong learning approach.

Barriers related to people claiming that there exist huge differences between academics and the practical professionals working in the sharp end is also subjected to discussions in the TSS. By organizing projects, the challenges between theory and practice will be scrutinized. Are there huge differences between truck drivers experiencing hazardous situations and risk analysts identifying hazardous situations in tunnels? This kind of knowledge gaps will be interesting to follow up in this study programme, in which we hope to develop an archive that might serve as input for innovation processes. The traffic safety research environment is data driven in which categorizing and counting accidents, deaths and injuries are dominant. These professionals are less interested in physics and how vehicles, infrastructures and road-users interact in the traffic system. For example, the infrastructure and road surfaces in Norway are environmentally conditioned, which imply that the winter tyres are a critical factor. There exists an approval system, but there seems not to be sufficient science-based knowledge on how the various tyres behave in the wide span of weather situations and the various substances added to the road surfaces. These knowledge gaps will be addressed and challenged in the TSS.

Figure 3 shows the core of our learning tool seen across the students and their enterprises as background knowledge. Based on various topics included in the study, for example the risk analysis approach in Module 2, we gathered people with different backgrounds to assess uncertainties included in risk assessments, that were associated with data, analysis assumptions, modelling and future predictions. They investigated inter alia the traffic flow, incident data, road infrastructures, environmental factors to get deeper into the uncertainty assessment. The frameworks are national and international requirements and guidelines that will influence their perspectives. We hope to identify and describe learning by the TSS contributions to changes, confirmation and comprehension within the tunnelling industry. This tool needs to be further developed, but it will be based on Bjørnsen, Braut, and Njå’s model [30].

The tunnelling industry as introduced with the steering committee is of vital importance. The curricula, the lecturing and learning must meet the industry’s needs. Currently the steering committee provides an embedment in the tunnelling industry, but this will not be acknowledged in the long term unless the study demonstrates impacts for the practical tunnel safety work. The symbiotic interplay
between students, the tunnelling industry and TSS is a critical factor for the success. There are several tasks that the TSS has initiated:

- Involvement of organisations in lecturing. We have included lecturers from nine different enterprises in Module 1 and six different enterprises in Module 2. They bring valuable knowledge, but also various perspectives on tunnel safety and security.
- Rail and road transport modes have some similarities, but even more differences in approaches to regulations and tunnel safety work. Bringing these transport modes together in the TSS introduce these differences and it shows what can be transferred and brought into the students’ enterprises practical tunnel safety work.
- The TSS will provide networking mechanisms with arenas for communications. Today the students are enrolled and active at the UiS’ platforms, but there will be developed formal arenas that will be run by the TSS administration. The informal networks develop themselves and is an asset for the TSS. These assets must be communicated to the tunnelling industry.
- To serve the TSS and the knowledge base for the study, a national competence centre on tunnel safety is needed. The TSS can take this role and include the tunnelling industry in this centre. The centre will support the study programme with science-based lecturing, it will provide advice and knowledge for the regulators, provide hearing responses, etc. The TSS already forms into a competence centre, but this needs to be further developed.

Where will the TSS take us? The future is currently in the design phase and open for every input. At present, safety is understood in the perspective of risk management, especially in the design phases of the tunnels. It is mandatory to carry out risk analyses and contingency analyses. The regulations also prescribe solutions, for example ventilation systems, automatic identification devices, emergency stopping bays, extinguishing equipment, emergency call-phones, lighting. However, the tendency is that safety is something that is complied with, the assessments are routine work. The TSS might introduce tunnel safety as a professional discipline working together with other disciplines, such as electrical engineering, ICT, civil engineering etc. in planning, construction, operation and maintenance of tunnels. Such a future would bring discussions about acceptable safety levels, the quality of risk models and how to use and misuse risk assessments, thus, bringing safety as a core value as demanded by the Vision Zero principles. This will provide better knowledge about the potential for major fire events and other incidents that have the potential to kill many road users. The many incidents that have occurred in Norway the last ten years must be seen as indicators that the safety control structure is lacking.

CONCLUSIONS

Why can we say that the tunnel safety competence situation is so fragmented? It is contingent on the tunnel history, where tunnel safety emerged through events. First the events were restricted to car crashes with similar outcomes as the traffic accidents elsewhere. It did not require special efforts, albeit in Norway professionals started to analyse the statistics and found that the entrance areas produced more accidents than other parts of the tunnels. However, the safety information systems did not develop into experience transfer systems across disciplines and sectors. The major road and rail users, such as commercial HGV drivers, bus companies, train operators have their own schools and backgrounds, the engineering professionals have their, the emergency services their and so on. There is no unifying discipline or education that brings them together. We have developed the TSS to meet these challenges. The future will show if the tunnelling industry comprehend this development.

ACKNOWLEDGEMENTS

The Tunnel Safety Study (TSS) programme is a joint collaboration between many enterprises and sectors. The students, the involved enterprises, lecturers and steering committee is highly appreciated for their contributions.
References


Hydrogen vehicles safety in underground traffic infrastructure: overview of HyTunnel-CS findings

Vladimir Molkov
Hydrogen Safety Engineering and Research Centre (HySAFER), Ulster University, Newtownabbey, BT37 0QB, Northern Ireland, UK

ABSTRACT

This keynote presents the overview of the HyTunnel-CS project and some of its main research findings on inherently safer use of hydrogen vehicles in underground traffic infrastructure. The detailed description of all project results can be found in the deliverables at the website www.hytunnel.net and related published journal and conference papers. Here the focus is mostly on a part of HyTunnel-CS research programme related to mitigation and prevention of “new” hazards, i.e. blast wave and fireball following high-pressure hydrogen tank rupture in a fire in confined space. The dynamics of blast wave and fireball development after tank rupture in a tunnel is compared against the case in the open atmosphere. It is demonstrated that hydrogen tank rupture in confined space fire is unacceptable and everything possible must be done to prevent it. Safety concerns about fire test protocol of Global Technical Regulation on Hydrogen and Fuel Cell Vehicles No.13 (GTR#13) are explained. It is concluded that passing the GTR#13 fire test at its lower specific heat release rates compared to possible real fires does not mean the provision of hydrogen storage tank safety in real life conditions. The first ever model for tank-TPRD system design for engulfing fire of arbitrary intensity is presented. The examples of tank-TPRD system design that exclude both a tank rupture in engulfing fire and the pressure peaking phenomenon are given. It is underlined that this safety design will not close the issue of localised fire which must be solved in one or another way, e.g. by using innovative explosion free in a fire self-venting (TPRD-less) tank. The safety strategy for underground parking of hydrogen-powered cars is formulated and results of safety design of TPRD diameter and release direction are demonstrated. This safety strategy can be realised by avoiding flammable layer and high temperature cloud formation under the ceiling of parking. This in turn can be achieved by a proper design of tank-TPRD system for engulfing fires or by the use of self-venting tanks for any kind of fire. Finally, the breakthrough safety technology of explosion free in a fire self-venting (TPRD-less) tank that was nominated for the Best Innovation Award 2021 by Clean Hydrogen Partnership is explained and its experimental validation presented.

KEYWORDS: hydrogen, safety strategies, tunnels, underground parking, tank-TPRD system, tank rupture in a fire, GTR#13 fire test protocol, self-venting TPRD-less tank, HyTunnel-CS project

INTRODUCTION

The title of HyTunnel-CS project is “Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces” following the topic of the call for funding FCH-04-1-2018. The project duration was 3 years and 5 months (01/03/19–31/07/22) with funding of €2.5M assigned to 13 partners from 11 countries. More details could be found at the project website: www.hytunnel.net.

The ambition of HyTunnel-CS is to allow hydrogen-powered vehicles enter underground traffic infrastructure. The specificity of the research approach is in consideration of hydrogen vehicle and underground traffic structure as a single system with the integrated safety approach. The project research is carried out using complementarities and synergies of theoretical, numerical and
experimental studies. The project aim is conducting the pre-normative research (PNR) to close knowledge gaps and technological bottlenecks in the provision of safety in the use of hydrogen-powered vehicles in underground transportation systems.

The main project objectives are:

▪ Generate unique experimental data regarding the interaction of hydrogen with underground infrastructure using the best European hydrogen safety research facilities including real tunnels.
▪ Create deeper knowledge of the relevant physics to underpin advanced hydrogen safety engineering and develop innovative prevention and mitigation strategies.
▪ Develop further existing and new contemporary computational fluid dynamics (CFD) and finite elements models (FEM), engineering correlations, hazard assessment tools validated against unique experimental data, and quantitative risk assessment methodologies for road and rail tunnels as well as underground parking.
▪ Prepare “Harmonised recommendations for intervention strategies and tactics for first responders” (Deliverable D5.4) providing conditions for their life safety and property protection.
▪ Develop “Recommendations for inherently safer use of hydrogen vehicles in underground transportation systems” (Deliverable D6.9).
▪ Produce commonly agreed, scientifically based “Recommendations for the update of relevant RCS” (Deliverable D6.10).

Figure 1 shows the structure of HyTunnel-CS work plan that is composed of seven interrelated work packages.

![Figure 1. Structure of HyTunnel-CS work plan.](image)

The joint research programme is extensive and can be demonstrated through topics of presentations delivered at the HyTunnel-CS dissemination conference on 14-15 July 2022 in Brussels:

▪ Concrete spalling by hydrogen jet fires
▪ Effect of tunnel slope on hydrogen dispersion
▪ Effect of counter- and co-flow on hydrogen jets
▪ Correlation for overpressure during ignited spurious hydrogen release
▪ Dimensionless correlation for blast wave decay in a tunnel
▪ Deflagration of hydrogen releases and in tunnel: large-scale experiments
▪ Scaling experiments at reduced size to real tunnels
▪ Blast wave and fireball after hydrogen tank rupture: real tunnel test and simulations
▪ Drastic difference between fireball dynamics in the open space and in a tunnel
Interaction with water sprays and mist systems with hydrogen fire
- Principles of inherently safer design of hydrogen vehicles for use in confined spaces
- Contribution of hydrogen released through TPRD to heat release rate of a vehicle fire
- Garages and maintenance shops: mitigation of pressure peaking phenomenon
- Underground parking: requirements to TPRD size and release direction
- CFD and FEM study of hydrogen jet fire effect on tunnel structure
- CFD and FEM study of hydrogen tank rupture on tunnel structure
- Erosion of tunnel materials by hydrogen jets
- Correlation for flame acceleration/DDT in non-uniform hydrogen-air mixtures in tunnels
- Deflagration of non-uniform clouds with concentration gradient
- Blast wave attenuation by absorbing materials, water sprays and mist systems
- Deflagration propagation through fire extinguishing foam
- Design of tank-TPRD system to exclude rupture in a fire and the pressure peaking
- Breakthrough safety technology of explosion free in a fire TPRD-less tank
- QRA hydrogen vehicles in confined space: road and rail tunnels, underground parking
- Project findings and their effect on intervention strategies and tactics
- Recommendations for Regulations, Codes and Standards

Research results reported in this paper are limited due to its restricted volume and are focused mainly on mitigation and prevention of “new” hazards, i.e. blast wave and fireball after hydrogen tank rupture in a tunnel fire, etc. The paper includes: results of the study on dynamics of blast waves and fireball after hydrogen tank rupture in a tunnel and its comparison to a similar incident in the open atmosphere; explanation of safety concerns about the fire test protocol of GTR#13; presentation of application of the first ever model for a tank-TPRD system design for engulfing fire of arbitrary intensity which was absent despite the fact that compressed hydrogen storage systems (CHSS) with TPRD are being developed and deployed as parts of various hydrogen systems and infrastructure; examples of application of created and validated models to design tank-TPRD systems that allow avoiding both a tank rupture in engulfing fire and the pressure peaking phenomenon in confined space; introduction of underground parking safety strategy for hydrogen-powered cars based on avoiding of flammable cloud and high temperature products formation under the parking ceiling by a proper tank-TPRD system design or use of self-venting (TPRD-less) tanks; explanation and experimental validation of the breakthrough safety technology of explosion free in a fire self-venting tanks that have a strong potential to solve all safety problems of hydrogen storage systems use in confined spaces.

**BLAST WAVE AND FIREBALL IN TUNNEL COMPARED TO THE OPEN ATMOSPHERE**

The validated CFD model of the blast wave and fireball dynamics after high-pressure hydrogen tank rupture in a fire in the open atmosphere [1] was applied for a series of simulations of different tanks rupture in tunnels of various cross section area and length. Experiments on rupture in a fire of tanks with nominal working pressure NWP=35 MPa and NWP=70 MPa are used to validate the model and get insights into underlying physical phenomena. Parametric studies are performed to understand the effect of different physical sub-models, numerical methods and other model parameters, e.g. instantaneous or inertial tank opening during rupture, on the convergence of simulations and closer reproduction of experiments [1]. The CFD model reproduces experiments well using different turbulence (RNG, Smagorinski-Lilly) and combustion (EDC, FRC) sub-models. It is demonstrated that hydrogen combustion at the contact surface between heated by the starting shock air and the cooled by expansion hydrogen at the initial stage of the process affects the blast wave strength, i.e. the pressure peak of the leading front and the blast wave impulse. These numerical experiments of Ulster University were then used along with methods of similitude analysis to generate the dimensionless correlation for blast wave decay in a tunnel presented later in this section.

The updated recently and validated again CFD model was applied for simulations of incident scenarios when hydrogen storage tank ruptures under a vehicle. The original treatment of turbulence generated by fragments after tank rupture is applied (to be published). The comparison of simulated
blast wave with experimental pressure transients at distance 5 m and 10 m from the tank ruptured in the fire in Japanese test No.2 [1] is shown in Figure 2. In this test tank of volume 36 L at initial pressure 70.69 MPa and initial temperature 282 K was placed in a fire of, unfortunately, unknown specific heat release rate (defines time to rupture, i.e. fire resistance rating), HRR/A, and ruptured after 10 min 54 s when hydrogen pressure increased to 99.47 MPa and temperature to 398 K due to heat transfer from the fire through the tank wall to hydrogen. Measured blast wave peak at distance 5 m was 74.3 kPa and at distance 10 m it decayed to 23.4 kPa. The reported by experimentalists fireball size was about 20 m. The CFD model reproduces well the experimentally measured pressure peaks and impulse. Thus, the model can be used for the numerical experiments to build the dimensionless correlation for blast wave decay in a tunnel.

The phenomenon of temporary fireball “stagnation” in a tunnel was first revealed by numerical simulations at Ulster University. Figure 3 (left) demonstrates that while the blast wave (pressure) propagates out of the tank rupture location, the reaction zone at the contact surface between heated by shock air and cooled due to expansion hydrogen, which can be identified by hydroxyl (OH) and/or high temperature, does not move but rather oscillates at certain position between location of the tank rupture and the tunnel wall. The fireball “stagnation” phenomenon was then confirmed in unique experiments of HyTunnel-CS partner CEA (France) carried out in a real tunnel (Figure 3, right).

There is a drastic difference between behaviour of fireball after tank rupture in atmosphere [2] and in a tunnel. The numerical experiments revealed that while in the quiescent open space fireball raises up, it behaves absolutely different in a tunnel, i.e. it can move with high speed up to 25 m/s along the tunnel behind the blast wave (to be published). If an incident happened close to tunnel entrance, i.e. the most frequent location according to available statistical data for tunnels, then the fireball propagates inside the tunnel following gas flow behind the blast wave with a high velocity. This fast
propagation of fireball along the tunnel for long distance essentially increases hazard distance defined by thermal loads compared to the open atmosphere. This observation underpins the conclusion that a tank rupture in a tunnel must be excluded by all means.

Figure 4 compares 3D blast wave decay in the open atmosphere (diamond symbols in Figure 4) after the largest from studied 171.5 L, NWP=70 MPa (6.96 kg at 288 K) tank ruptured in a fire when pressure increased to 95 MPa and temperature to 390 K against the same and smaller tanks rupture in the single-lane 24.1 m² cross-section area and 200 m length tunnel. Tank rupture location is 50 m from the tunnel portal (only 150 m on one side from the tank rupture location are shown in Figure 4). For rupture of the largest tank in the open atmosphere the blast wave decays to the serious injury overpressure threshold of 16.5 kPa at 18 m, and to the no-harm overpressure threshold of 1.34 kPa at 41 m (two diamond symbols in Figure 4). The situation drastically changes for the same storage tank rupture in a tunnel fire: the fatality threshold of 100 kPa is 35 m away from the tank rupture location and the injury threshold of 16.5 kPa is not reached at all throughout the entire tunnel length making the rest of the tunnel beyond the fatality zone to be the serious injury zone. The situation is similar for smaller tanks with one exception of the lowest volume tank with 0.58 kg when serious injury zone is followed by the slight injury zone at about 100 m (still the no-harm threshold is not reached even for this smallest tank characteristic for motorbikes rather than vehicles).

Figure 4 demonstrates that there is significantly slower decay of the blast wave in a tunnel compared to the open atmosphere. Results of simulations confirm the previous conclusion that tank rupture in a tunnel must be excluded by all means and those means must be available for inherently safer deployment of hydrogen-powered transport in confined traffic structures such as tunnels.

**Dimensionless correlation for blast wave decay in a tunnel**

The validated CFD model is applied to perform numerical experiments and, with the use of methods of similitude analysis, derive the dimensionless correlation for the blast wave decay after rupture of a tank of any volume and pressure in a fire in a tunnel of arbitrary length, cross-section area and aspect ratio. Figure 5 (left) shows the conservative and best fit correlations derived by numerical and theoretical studies at Ulster University. More details on the derivation and use of the correlation can be found in paper [3]. The correlation has then been successfully validated by the unique experiments on the blast wave decay after hydrogen tank rupture in a real tunnel performed by CEA [4] (Figure 5, right). It is recommended after experimental campaign of CEA to use the best fit rather than the conservative form of the theoretically derived correlation.
Figure 5. Dimensionless correlation for blast wave decay after tank rupture in a tunnel developed at Ulster University [3] (left), and its validation by test in the real tunnel performed by CEA [4] (right). The experimentally validated correlation can be used as a contemporary tool for hydrogen safety engineering and quantitative risk assessment of incident scenarios of hydrogen tanks rupture in a tunnel.

SAFETY CONCERNS ABOUT THE FIRE TEST PROTOCOL OF GTR#13

The safety concerns about the fire test protocol of GTR#13 are explained in this section. Gasoline or diesel spill fire is one of typical scenarios for car incidents. The intensity of fire can be characterized by the specific heat release rate, $HRR/A$, which is the ratio of the heat release rate, $HRR$, to the projection area of the fire, $A$. Published during almost half a century (1976-2017) data points out that the real specific heat release rate gasoline/diesel fires is 1-2 MW/m² [5,6,7,8]. Unfortunately, the Proposal for Amendments 1 to Global technical regulation No. 13, Phase 2 [9] requires to perform localised fire at $HRR/A=0.2-0.5$ MW/m² (suggested $HRR/A=0.3$ MW/m²) and increase it during engulfing fire stage to $HRR/A=0.4-1.0$ MW/m² (suggested $HRR/A=0.7$ MW/m²). The introduction of these reduced compared to gasoline/diesel fire $HRR/A$ in GTR#13 could result in hazardous situations when a CHSS that “successfully passed” the regulated fire test will not be able to withstand real fires and rupture with catastrophic consequences.

Figure 6 (left) shows the fire resistance rating ($FRR$) of CHSS, i.e. time to rupture of CHSS in a fire without TPRD (imitating its failure of blockage from fire in incident), as a function of $HRR/A$. The $FRR$ is an important parameter of CHSS requested by firemen and must be reported for each CHSS. Thus, there is a need to amend the GTR#13 fire test to add testing of $FRR$ which is currently not in place that disadvantages responders and threatens their lives. The information on $FRR$ in fires of different intensity, $HRR/A$, is needed to inform firemen intervention strategies and tactics. Both experimental and numerical studies demonstrate the decrease of $FRR$ with the increase of $HRR/A$ and “saturation” of this dependence at about 4-6 min for $HRR/A\geq1$ MW/m² for investigated tanks [10]. The diamond symbol (Figure 6, left) demonstrates the further decrease of $FRR$ to about 2 min for elongated conformable tanks (due to their thinner composite walls caused by reduction of diameter of conformable tanks, e.g. used to optimise the use of space in hydrogen vehicles).
Figure 6. Left - Fire resistance rating of hydrogen storage tanks (FRR) as a function of specific heat release rate, HRR/A. Right - Change of FRR with increase of HRR/A from 0.29 MW/m$^2$ (no rupture) through 0.62 MW/m$^2$ to 1 MW/m$^2$ (rupture for both scenarios) for the same hydrogen storage tank.

Figure 6 (right) demonstrates change of FRR with increase of HRR/A from 0.29 MW/m$^2$ through 0.62 MW/m$^2$ to 1 MW/m$^2$ for the same hydrogen storage tank (volume 36 L, NWP=70 MPa, the ratio of length to diameter L/D=2.8). The descending lines show the progression in time of the resin degradation front through the wall thickness and the ascending lines appear the minimum load-bearing wall thickness that increases with time due to the increase of hydrogen pressure as the result of heat transfer from the fire. The duration of the localised stage of the GTR#13 fire test is 10 min (during this stage TPRD is typically not affected by fire). From three considered here fires of different intensity only the fire with the lowest fire intensity of HRR/A=0.29 MW/m$^2$ allows to withstand the regulated localised fire of 10 min duration without rupture because its rupture would happen after 836 s if there would be no switch from localised to engulfing fire at 10 min (600 s) as required by the GTR#13 fire test protocol. The fire with HRR/A=0.62 MW/m$^2$ results in the tank rupture after 554 s and fire with HRR/A=1 MW/m$^2$ would rupture even in the shorter time of 411 s, i.e. both tanks will rupture before switching from the localised to engulfing fire stage at 600 s when TPRD will be affected by the engulfing fire (please note that the situation is complicated even further by the fact that TPRD response time could be a few minutes).

Figure 7 explains how the suggested lower value of HRR/A for the fire test protocol of GRT#13 (Phase 2) "assists" in the passing of fire test but creates hazards in real fires of higher intensity, e.g. gasoline/diesel spill fires or batteries fires. Indeed, with a fire of low intensity of HRR/A=0.2 MW/m$^2$ the estimated by the graph FRR is about 24 min (Figure 7, left), i.e. much longer than duration of the localised fire stage of 10 min and thus TPRD, if it is initiated (!) by this comparatively low intensity fire, can prevent the tank rupture by releasing hydrogen. However, if localised fire intensity is that characteristic for gasoline/diesel spill fires, i.e. HRR/A=1 MW/m$^2$, the tank will rupture in 5 min (2 min for conformable tank due to a thinner wall) before the TPRD is initiated by the engulfing fire (Figure 7, right).
Thus, to exclude tank rupture during the localised fire stage, the $HRR/A$ “should be reduced” as it is done in the proposed fire test protocol of GTR#13 (Phase 2): it is suggested to use $HRR/A=0.3 \text{ MW/m}^2$ at the localised fire. This means that we could have CHSS that would pass the regulated fire test but could rupture in real fires of higher intensity, e.g. gasoline/diesel and batteries fires, etc. To make the GTR#13 fire test more relevant to real life fire safety, it should be carried out at $HRR/A \geq 1 \text{ MW/m}^2$ for both localised and engulfing fire stages. Yes, this would require development of hydrogen storage tanks with higher fire resistance. The fire test should as well include definition of $FRR$ (time to tank rupture for failed or blocked in incident TPRD) to inform firemen following their requests. The “difficult” question “What should be fire resistance rating of compressed hydrogen storage systems?” has a “simple” from the author’s point of view answer “CHSS must withstand any fire without rupture!”.

**TANK-TPRD SYSTEM DESIGN FOR ENGULFING FIRE OF ARBITRARY INTENSITY**

It is surprising that until 2021, i.e. before the publication of work [10], there were no models that can be used to design tank-TPRD system for safe performance in an engulfing fire that excludes its rupture. It must be underlined that this section considers only engulfing fire because the issue of tank performance in localised fire of real-life intensity cannot be resolved by using TPRD [11].

Figure 8 demonstrates the application of the model [10] for inherently safer design of 244 L NWP=70 MPa tank-TPRD systems against rupture in engulfing fire. This is Type IV tank with high-density polyethylene (HDPE) liner. It is subject to a gasoline fire with $HRR/A=1 \text{ MW/m}^2$. TPRD response time is taken as 3 min.
Figure 8. Performance of 244 L tank with TPRD diameters 0.50, 0.75, 1.00 mm in the engulfing fire with HRR/A=1 MW/m².

Figure 8 shows that for 244 L tank the TPRD diameter to satisfy the above mentioned requirements can be reduced to 0.75 mm. Similar study for 36 L tank demonstrated that the TPRD diameter could be reduced to 0.45 mm. The top descending curve in Figure 8 is the resin degradation front propagating into the composite wall. The three descending curves originating at “TPRD activation” point are the decreasing wall thickness that is sufficient to withstand the decreasing hydrogen pressure in the tank (due to release through the TPRD and later due to additional leak through the wall when liner is melted) for TPRD diameters 0.50, 0.75, 1.00 mm. The 244 L tank starts to leak through the wall after melting of HDPE liner of 3 mm thickness at 1349 s of fire duration in addition to the release through TPRD=0.75 mm (started after 180 s of fire initiation following the assumption on TPRD response time). It should be underlined that the secondary leak takes place for HDPE liner and cannot be realised for polyamide (PA) liner with higher melting temperature. The timing of the secondary leak could be shortened if a thinner liner is used (subject to permeation test approval).

The question to be answered is “What TPRD nozzle diameter will exclude: the tank rupture in engulfing fire, the pressure peaking phenomenon (see relevant section below) in a hydrogen storage room, e.g. onboard of train, or garage, and the formation of flammable cloud (to exclude follow-up destructive deflagration or even detonation) and combustion products layer with T>300°C under an underground parking ceiling”? The HyTunnel-CS study using developed models demonstrated that the sought inherently safer TPRD diameter is 0.45 mm for considered 36 L tank, and 0.75 mm for 244 L tank.

Effect of the state of charge (SoC) on the FRR

Figure 9 presents an example of performance of Type IV tank with HDPE liner of 3 mm thickness and of volume 62.4 L and NWP=70 MPa without TPRD (failed or blocked in incident TPRD) in a fire with HRR/A=1 MW/m² for two incident scenarios [12]. In the first scenario the hydrogen storage tank is at NWP=70 MPa with the state of charge 100%. In the second scenario the pressure of hydrogen in the storage tank is reduced, e.g. as a result of driving, to 30 MPa. In case of traffic incident with hydrogen-powered vehicle with pressure in the tank of 70 MPa, the tank will rupture in the gasoline/diesel spill fire in 446 s if the fire is localised and not affecting TPRD, e.g. when TPRD is blocked by wreckage during collision of cars, or if the TPRD is failed to open by whatever reason, e.g. too small fire intensity in the TPRD location.
The safety performance of the tank in the fire is drastically changes at reduced pressure in the tank. The decrease of tank’s SoC to 51% for this particular tank results in hydrogen leak through the wall after HDPE liner melting after 700 s of fire. This excludes tank rupture as was observed in the FireCOMP project. However, it should be underlined that this performance is characteristic only for HDPE liner of particular and should not be expected for PA liner. In this sense we consider HDPE liner as inherently safer choice for manufacturing and use in CHSS as compared to PA liners.

THE PRESSURE PEAKING PHENOMENON

The pressure peaking phenomenon was discovered at Ulster University in 2010 and investigated in a number of follow-up papers. Its description and relevant references before 2012 can be found in the free download e-book book of the author [13]. In the HyTunnel-CS project, partner USN (Norway) carried out experiments in a typical size commercial container of volume 14.9 m³ (Figure 10, left). Previous validation experiments were performed in HyIndoor project at enclosures of only 1 m³ volume. Figure 10 (right) shows comparison between USN experimental pressure dynamics in test No.18 (mass flow rate of 11.47 g/s) and CFD simulations performed by Ulster University. This CFD model is recommended for the use in hydrogen safety engineering of hydrogen storage rooms, e.g. onboard of trains, ships and planes.

Figure 9. Performance of 62.6 L, NWP=70 tank with 3 mm thick HDPE liner and blocked/failed TPRD in a HRR/A=1 MW/m² fire for two SoC: SoC=100% resulting in rupture, and SoC=51% resulting in hydrogen microleaks through the tank wall after melting the HDPE liner.

Figure 10. Left – photo of 14.9 m³ container. Right – comparison of simulations against experimental pressure dynamics (top), and the mass flow rate profile applied in the experiments.
AVOIDING TANK RUPTURE AND THE PRESSURE PEAKING PHENOMENON

HyTunnel-CS developed a model to design tank-TPRD system to avoid tank rupture in engulfing fire of arbitrary intensity [10]. For tanks or CHSS of comparatively large volume the diameter of TPRD needed to avoid its rupture in a fire could be comparatively large to avoid the pressure peaking phenomenon in garages, maintenance shops, and hydrogen storage rooms with comparatively small vent size. Because a calculated for particular CHSS diameter of TPRD that allows to avoid tank rupture in a fire cannot be reduced below the defined value, the only way to prevent a structure destruction by the pressure peaking phenomenon is to increase the vent area in the enclosure. This can be very challenging especially for hydrogen storage rooms onboard of trains, ships and planes.

Let us consider tanks of two different volumes: 36 L and 62.4 L. To prevent rupture of a tank in a fire, TPRD>0.45 mm is needed for this particular 36 L tank design, and TPRD>0.5 mm for 62.4 L tank. Figure 11 shows that the pressure peaking phenomenon and thus destruction of typical enclosure can be excluded, i.e. overpressure will not exceed typical threshold of 10 kPa to which civil structures could withstand (destruction threshold A), for 36 L tank and TPRD=0.45 mm for the 30 m³ enclosure with vent area of 100x250 (two bricks) mm, and for “inherently safer” in sense of tank rupture prevention TPRD=0.65 mm for the increased vent area of 150x250 mm (three bricks). For 62.4 L tank with TPRD=0.5 mm the vent area should be equal or more than 100x250 mm (two bricks) and for TPRD=0.75 mm 200x250 mm (four bricks).

Figure 11. The pressure peaking phenomenon in typical SAE garage of 30 m³ volume during ignited hydrogen blowdown from 36 L (left) and 62.4 L (right) tanks at NWP=70 MPa for different TPRD diameters and enclosure vent areas.

UNDERGROUND PARKING SAFETY STRATEGY

The safety strategy for underground parking of hydrogen vehicles is very straightforward. The design of vehicle must avoid creation of both: flammable cloud (scenario of unignited release of hydrogen by whatever reason) or high temperature products of hydrogen combustion above 300°C under the parking ceiling that could affect ventilation system (scenario of jet fire from TPRD).

This safety strategy can be realised either through a proper design tank-TPRD system or by the use of breakthrough safety technology of self-venting (TPRD-less) tank described in the next section. For systems with TPRD the reduction of TPRD diameter to avoid flammable cloud and hot products of combustion above 300°C entering ventilation system can be done at the condition that TPRD diameter is not reduced below that necessary to exclude rupture of this tank in a fire.

Reduced models are not capable to assess safety of car parks with multiple ventilation openings and downward releases from TPRD. Results of CFD simulations for underground parking of dimensions 23.5x3x45 m with ceiling height 2.1-3.0 m and air change per hour ACH=0-10 with downwards
release at “optimum” angle $45^\circ$ from TPRD=0.5 mm and TPRD=2.0 mm from a tank (62.4, L NWP=70 MPa), and ACH=0-10 were carried out in HyTunnel-CS.

Figure 12 shows snapshots of largest in time flammable envelope (top) for unignited release and ignited blowdown (bottom, visualisation of temperature above 300°C) from TPRD=0.5 mm in the underground parking. No flammable cloud or hot products with temperature above 300°C are present under the ceiling for TPRD=0.5 mm.

![Figure 12. Release from TPRD=0.5 mm in the underground parking: unignited release (top), and ignited release (bottom).](image)

Figure 13 demonstrates results of unignited (top) and ignited (bottom) releases but increased diameter TPRD=2 mm. It can be seen that flammable cloud can be formed under the ceiling during the unignited release from TPRD=2 mm that can deflagrate/detonate if ignited. Combustion products with temperature in excess of 300°C reaches the underground parking ceiling and could harm the ventilation. Thus, TPRD=2 mm that is currently used by some OEMs should be avoided to exclude these hazards for underground parking.

![Figure 13. Release from TPRD=2 mm in the underground parking: unignited release (top), and ignited release (bottom).](image)

The performed in HyTunnel-CS research demonstrated that TPRD=0.5 mm is acceptable for provision of inherently safer release from TPRD in underground parking (and hence in tunnels which have higher ceiling heights). However, currently used TPRD=2 mm imply obvious safety concerns. It
would be great to proceed with $\text{TPRD} = 0.5 \text{ mm}$ to provide safety of underground parking of hydrogen-fuelled cars underground. However, it is not possible for all CHSS as they could require larger TPRD diameter to exclude rupture in engulfing fire. This makes some scenarios with safety of hydrogen-powered vehicles in underground traffic infrastructure critical. Fortunately, the problem of safe underground parking can be resolved by the use of self-venting TPRD-less tanks described in the next section that are explosion free in any fire and do release of hydrogen through the tank wall in a form of microleaks and/or microflames.

**BREAKTHROUGH SAFETY TECHNOLOGY OF SELF-VENTING (TPRD-LESS) TANK**

The breakthrough safety technology of explosion free in a fire self-venting composite hydrogen storage tank that does not require TPRD is introduced in this section. It exploits the microleak-no-burst ($\mu$LNB) safety technology for reaction of CHSS to a fire developed at Ulster University [14]. This safety technology provides melting of hydrogen-tight liner in the fire before hydrogen-leaky composite wall losses its load-bearing capability. The melting of liner leads to microleaks of hydrogen through the composite wall. Hydrogen microleaks either burn in tiny microflames without or with resin or quickly decays to concentrations below the lower flammability limit (LFL) if the leak flow rate is below the flame quenching limit or above the blow-off limit. The technology implies that when a fire is extinguished the microleaks would not create flammable atmosphere around the tank surface and beyond due to extremely small size and discrete character of microleaks. The $\mu$LNB technology mitigates the pressure peaking phenomenon and excludes accumulation of hydrogen in a storage room or garage at minimum natural ventilation requirements. The key advantage of the technology is that it doesn’t require TPRD, which failure rate in localised fire is high following conclusions of the FireCOMP project, and whose response time to different fires and thus reliability in that fire are not available to stakeholders. By prevention of tank rupture in a fire, the technology eliminates catastrophic consequences of incidents with tank rupture: no devastating blast waves, no fireball and no projectiles, etc. The implementation of the technology by CHSS and vehicle manufacturers would assure the achievement of even lower level of risk in using hydrogen-powered vehicles compared to fossil fuel cars.

Before describing the TPRD-less tank it is worth demonstrating issues with the use of TPRD by examples from real life. Figure 14 shows photos before (smouldering fire stage) and at the moment of explosion of CNG tank on a garbage truck in the USA [15, 16]. The high-pressure storage tanks seem to be equipped by even two TPRD, one on each side of the tank cylinder. Unfortunately, TPRDs were not initiated by what is thought was a smouldering fire inside the garbage truck. However, this small intensity fire yet was able to degrade the tank wall resin and cause its rupture.

![Figure 14. Smouldering fire of garbage truck (left) and explosion of CNG tank (right) [15, 16].](image)

The original tank failure mechanism suggested and verified at Ulster University is explained schematically in Figure 15. The standard tank has a liner, which limits hydrogen permeation to the regulated level, and load-bearing carbon fibre reinforced polymer (CFRP) overwrap. Under thermal load of fire the resin degrades, and fibre plies become loose in places where the resin of composite degraded and thus not any more able to bear the pressure load. The resin degradation front propagates into the wall (red colour area in Figure 15). Pressure inside the tank grows in time due to heat transfer...
from the fire through the wall to hydrogen. This results in the increase of the wall fraction needed to bear the increasing pressure load (minimum regulated safety factor for burst pressure is currently 2.25 of NWP, i.e. only 1/2.25=0.44 fraction of the wall thickness can withstand NWP). The sufficient to bear the pressure load wall thickness fraction is shown in Figure 15 by the black dash line. When the inward propagating resin decomposition meets the outward moving load-bearing wall thickness fraction the tank ruptures (Time 3 in Figure 15).

Figure 15. Explanation of the failure mechanism of a composite tank in a fire.

Figure 16 shows the performance of standard (left) and μLNB (right) tanks in a fire. The difference between μLNB tank design and standard tank design is in the use of two composites instead of one in the wall and the science-informed selection of their thermal and geometrical properties. The external part of the double-composite wall is marked in Figure 16 (right) as thermal protection layer (TPL). It has lower thermal conductivity compared to the internal part of the double-composite wall marked as fibre-reinforced polymer (FRP), and can be load-bearing as well. The thermal parameters of the liner, the TPL and FRP layers and their thicknesses are selected to melt the liner before the resin decomposition front meets the load-bearing fraction of the wall and tank ruptures. Initiated through the composite wall microchannels leaks reduce the hydrogen pressure and to some extent cool down the resin at decomposition front thus delaying the “meeting” of decomposition and load-bearing wall fraction fronts, i.e. preventing the tank rupture.

Figure 16. Explanation of μLNB safety technology for composite Type IV tanks: original tank (left) and μLNB tank (right) performance in a fire with time.

Figure 17 shows snapshots of a validation fire test following the GTR#13 protocol (with typical for realistic gasoline/diesel fire of $HRR/A=1 \text{ MW/m}^2$) for μLNB tank prototype of NWP=70 MPa, 7.5 L. The μLNB tank had practically the same volume, size and weight as the original (standard) tank (outer diameter of liner was 160.96 mm for original tank and 160.70 mm for μLNB tank, outer diameters of the tanks were 186.9 mm and 186.1 mm respectively, i.e. slightly smaller for the μLNB
tank). The original standard tank wall thickness made of one FRP was 13 mm. The LNB tank thickness was even shorter - 12.7 mm (7.2 mm of FTL#1 and 5.5 mm of FRP#2). This and other μLNB tanks prototypes with different fibres and resins have successfully passed the regulated burst test, hydrostatic test and fire test. The μLNB tank not only corresponds to the regulation requirements yet acquired unprecedented new safety performance – elimination of tank rupture in a fire of any intensity and its catastrophic consequences in the form of blast wave, fireball and projectiles.

Figure 17. Snapshots of one of μLNB tank prototypes behaviour in a fire test with HRR/A=1 MW/m².

ACKNOWLEDGEMENTS

The author is grateful to the HySAFER staff and all project partners contributed to the success of pre-normative research project HyTunnel-CS to achieve the presented in this keynote results. This research has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under the European Union’s Horizon 2020 research and innovation programme under grant agreement No.826193 (HyTunnel-CS) and No.875089 (HyResponder). This Joint Undertaking receives support from the European Union’s Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe Research.

CONCLUSIONS

Impact of the pre-normative research project HyTunnel-CS includes but is not limited to the following. Stakeholders, including OEMs, have access to the beyond the-state-of-the-art “Recommendations for inherently safer use of hydrogen vehicles in underground transportation systems”, including new engineering tools for the e-Laboratory of Hydrogen Safety supported currently within HyResponder project (to get free access at the HyResponder project website please visit URL: https://elab.hysafer.ulster.ac.uk/ and use Login: HyResponderTrainer, Pass: safetyfirst).

HyTunnel-CS seriously advanced tackling hazards of hydrogen vehicles protected by TPRD in engulfing fires. Using the project results it is possible now to:

- Design any tank-TPRD system to exclude tank (CHSS) rupture in engulfing fire of any intensity beyond that unreasonably reduced by GTR#13 (Phase 2) localised fire intensity of HRR/A=0.3 MW/m² and for any TPRD response time.
- Define TPRD diameter to exclude the pressure peaking phenomenon in private garages and maintenance shops, in hydrogen storage enclosures onboard of trains, ships, planes, and facilities at hydrogen refuelling stations.
- Design TPRD parameters to exclude formation of flammable cloud and hot products at limited by standards temperature of 300°C under the ceiling to allow inherently safer underground parking of hydrogen-powered vehicles.

HyTunnel-CS has validated further invented at Ulster University the breakthrough safety technology of explosion free in a fire self-venting tank that does not require TPRD. This innovative microleaks-no-burst, μLNB, safety technology allows hydrogen-powered vehicles enter and park in any confined space at risk below current risk for fossil fuel vehicles. It excludes tank rupture at realistic gasoline/diesel spill fires with any specific heat release rate and was tested at HRR/A=1 MW/m², i.e. beyond suggested by GTR#13 (phase 2) HRR/A=0.3 MW/m² for the localised fire stage and 0.7 MW/m² for engulfing fire stage. The technology allows to achieve unprecedented level of safety:
- No blast wave,
- No fireball,
- No projectiles,
- No long flames (microflames could be present instead),
- No formation of flammable hydrogen-air cloud under the ceiling of underground parking,
- No formation of hydrogen combustion products above 300°C under the ceiling of enclosure,
- No the pressure peaking phenomenon in storage enclosures with natural ventilation,
- No life and property loss.

First responders are informed by “Harmonised recommendations for intervention strategies and tactics for first responders” that provides conditions for their life safety and property protection.

Hydrogen and relevant industries are provided by “Recommendations for the update of relevant RCS”, prepared under leadership of HyTunnel-CS partner NEN (Dutch standard development organisation delivering the duties of the secretariate of CEN/CENELEC/JTC6 Hydrogen in Energy Systems).

Researchers, including academia within Hydrogen Europe Research and beyond, benefit by access to new knowledge, closer of numerous knowledge gaps and addressing technological bottlenecks in hydrogen safety provisions, shared beyond the state-of-the-art knowledge in hydrogen safety science and engineering, including for use in training and education of new workforce for emerging hydrogen economy.

REFERENCES

9. Proposal for Amendments 1 to Global technical regulation No. 13, Phase 2 (Hydrogen and fuel
cell vehicles). Submitted by the IWG on hydrogen and fuel cell vehicles, GTR13-Phase 2.
Informal document GRSP-71-09 (71st GRSP, 9-13 May 2022 agenda item 3).
Development of the Swedish road tunnel safety concept

Ulf Lundström
Swedish Transport Administration (Trafikverket), Stockholm, Sweden

ABSTRACT

Since the turn of the millennium there has been a 180-degree turn in the safety concept in Swedish road tunnels. Through a number of large urban road tunnel projects, a simple and robust concept for fixed fire fighting systems has been developed to be able to deal with the challenges of combining dense traffic and longitudinal ventilation. The development has been done in close cooperation with world leading sprinkler expertise and different research institutes, especially RISE in Borås. Experience of eight years of operation has led to growing confidence in the concept, and it is now being retrofitted in some old Swedish tunnels.

KEYWORD: FFFS, Fixed fire fighting system, Urban road tunnels, Northern link, Norra länken, Bypass Stockholm, Förbifart Stockholm, Muskö

THE BEGINNING OF THE PROCESS:
STOCKHOLM IN THE 90`S

Stockholm is a city located on 18 islands. This has for a long time put a strain on the region’s development of communications, including the road network. For a thousand years up to the new millennium the solutions have been to build bridges. In the 1990’s it was decided that any new highway near the city centre should be in road tunnels because of environmental reasons, and to save valuable space in the city. Due to the constrained traffic situation, it was decided that a complete ring road of tunnels around the city centre needed to be built (see the original ring road in Figure 1). To facilitate the need for local transport to different parts of the city centre, the tunnels had quite a lot of entrance and exit ramps. This meant that the tunnels would be quite complex, both in means of construction and traffic situation. The project was delayed and the ambition level lowered due to political disagreements, but in 1998 the construction of the southern part of the ring could be started with the project Southern Link.

SOUHERN LINK

The Southern Link (Södra Länken) is a 3 km long tunnel of urban highway under the southern part of Stockholm city centre. It has two main tunnels with unidirectional traffic in two or three lanes. There are six exits and entrance ramps connecting to the city road network, which means a total of 15 km of tunnel tubes in the system. The design relied heavily on international praxis and recommendations, but tended to end up in the higher end of the safety scale. For example, the dimensioning fire size for the longitudinal ventilation was 100 MW, the escape routes had four doors giving a total of 180 minutes in fire resistance between the main tunnels, and the distance between the adjacent escape routes was only 100 m. The local fire brigade also demanded a FFFS (Fixed Fire Fighting System),
due to the risk of queues and slow traffic in combination with longitudinal ventilation. However, the Swedish Transport Administration (STA) (former Swedish Road Administration) had for a long time (together with most of the international tunnel community) argued against the use of FFFS in road tunnels. It was decided that no FFFS would be installed. Instead, the STA guaranteed that no queues would occur. The author of this paper worked at the fire brigade at that time, and we were astonished by that claim from STA especially as we knew about the chaotic traffic situation in the city at that time. Finally, the absence of FFFS was accepted by the fire brigade on the term that if queues and slow traffic would occur the tunnel entrances would be closed until the traffic jams were dissolved.

PROBLEMS OCCURS

In 2004 the Southern Link was opened for traffic. It was designed for 60 000 vehicles per day, but within weeks the numbers were over 100 000 vehicles per day. This resulted in daily congestions and a tunnel closure in the middle of rush hour. The taxpayers in Stockholm were not impressed, nor was the local politicians who partly financed the tunnels. It should be noted though that the problem was not the tunnel itself, the queues spread from the surface road network and into the tunnels. After about four years of operation, it was obvious that the traffic situation in the Southern Link wasn’t going to improve, nor was the road authority going to find any other solution to the safety issue than closing the tunnel. This made the local leadership of Stockholm City demand that any new tunnels had to have a safety concept that could deal with slow traffic without traffic restrictions.

NORTHERN LINK AND A NEW SAFETY CONCEPT

This demand from the city shook up the project organisation for the Northern link tunnel. The tunnel had been under construction for over a year, and the safety concept was already established as a copy of the one in Southern Link. A task force was put together in the project organisation lead by Mr Arne Brodin at the consultant company SWEPRO (the author of this paper was recruited to this group from the fire brigade in 2008). At first the focus was on a combination of early fire detection and a quick exit for the vehicles downstream from the fire, together with low air speeds to prevent the smoke from catching up with slow traffic. The low air speed, on the other hand, increased the risk of backlayering, and thus there was a risk that the traffic could not exit the tunnel quick enough despite the reduced airspeed. This concept was therefore not regarded as stable enough, and the question of adding FFFS was finally raised in 2009.

This was a huge step for the STA at that time. For decades the organisation had fought against the fire brigades on this matter, and the European consensus was that FFFS was expensive, unnecessary and even dangerous in road tunnels. In the working group of this project, the opinions were divided. Some appreciated the robustness of adding FFFS, while others pointed to the risk of adding another complex system to the equation. The cost efficiency was also debated. One could not motivate the investment cost by the expected number of saved lives (if a saved life was valued at about 3 million Euros), but if one calculated the socioeconomical cost for closing a tunnel destroyed by fire, the investment could easily be motivated.
In these discussions, the arguments against FFFS in form of high investment costs and maintenance were challenged: Could a cheap, simple and low maintenance system solve these problems? Such a system could not be found on the market at the time, but when the working group consisting of STA personnel, fire consultants and manufacturer, looked into it, some members saw a potential of adding a simple system directly to the existing fire hydrants in the Northern link (see Figure 2 and Figure 3). The installation cost was directly dependent on the amount of pipes needed to be installed, and by combining a cost optimised piping layout with long range sprinkler nozzles an acceptable installation cost was within reach (estimated as 0.5 M Euro per km). The system would be of deluge type, which means that a number of open nozzles are activated in zones. The ideal zone would be half way to the next escape route, with meant a zone length of 75 m. This is related to the fact that in the Northern link the distance between the emergency exits was increased to 150 m to reduce costs.

![The FFFS pipes in the Northern link](image)

This idea was met with an outcry from the sprinkler community and tunnel safety consultants. The list of reasons why this was impossible was long, especially when one started to look into sprinkler regulations. But when the working group started to look into the details, those regulations and praxis didn’t really seem to be adequate for FFFS in Swedish road tunnels. Some examples are water supply, water density, obstructions and inspections, which will be discussed respectively as follows.

**Water supply**
The sprinkler regulations demanded that the FFFS had to be fed from a separate pipe from the fire brigades fire hydrants. In a tunnel with 15 km of tunnel tubes this demand is very costly, and the benefit can be challenged when the purpose of the FFFS is to secure the evacuation before the fire brigade has arrived at the scene. The risk of volatile pressure levels in the hydrant when closing the FFFS-section would be counteracted by the fact that the fire brigade would use their own vehicles to provide the right pressure for their hoses and nozzles. As long as the pressure spikes didn’t exceed the limits of the feeding hose or the pump this issue is not a problem. Instead, it makes a lot of sense to use all available water to fight the fire before the arrival of the fire brigade.

![Same water supply for fire hydrant and FFFS](image)
Water density
There were a lot of discussions about the water density. The available water in the Northern Link tunnel was enough for a 75 m long section with a minimum density of 5 mm/min (in reality 5 to 9 mm/min). This was dismissed as far too low, as according to some experts the density should at least be between 10 and 15 mm/min if the tunnel was considered to be equivalent to a high risk storage warehouse in a fire technical sense. The reasoning for this was that if the tunnel space was filled with heavy goods vehicles side by side, loaded with combustible material, one would have a situation where 5 mm/min was not sufficient according to the sprinkler regulations. But the purpose of these regulations is to save the warehouse from being destroyed, while the purpose in the road tunnel is to slow the fire growth so that people could evacuate from the tunnel. Nobody seemed to be able to show that was not possible with 5 mm/min, especially if the FFFS were to be activated in an early stage of the fire. It was obvious that a lot of practical testing was necessary to settle this discussion. Actually, some full scale tests have confirmed that 5 mm/min with large droplets can prevent fire spread between vehicles or parts of a vehicle. It has also been shown that a potential 100 MW shielded fire could be controlled to 30 MW or less [1].

Obstructions
For every sprinkler nozzle there are detailed regulations of how the spray pattern is allowed to be obstructed by installations and furnishings. This is to make sure that the efficiency of the total system is not compromised. Again, the design regulations for protecting high risk warehouses were not fully applicable for a road tunnel. There are installations in the tunnel that can obstruct the water spray: portals, cable trays, light armatures and road signs. In some cases this means that areas of a few square meters have reduced protection, contrary to the sprinkler regulations. But when the longitudinal fire ventilation is started, the turbulence and the drifting spray distributes water all over the activated zone, regardless of the initial obstructions, and this reduces the impact of the obstructions considerably (see Figure 4). Also, in the tunnel the aim was to prevent a large fire, not to extinguish every small one. And a large fire simply doesn’t fit in the small areas with reduced density caused by the obstruction from the tunnel installations.

Figure 4   Example of obstruction with negligible effect on safety. Photo taken in Northern Link with one deluge section of FFFS activated.
Inspections and controls
The Swedish sprinkler regulations specifies that a sprinkler installation must be inspected by a certified sprinkler controller four times a year. This could make sense in a warehouse or an industry facility where intense operations could be in place 24 hours a day, and the risk of damage or interference of the installation is always present. But in the Swedish road tunnel concept all sensitive equipment is placed in the heated and monitored escape routes, where nearly no activities could be in months. This makes the risk of external interference of the equipment minimal, and this means that the need for inspections is less than in other environments such as warehouses. A large tunnel like the Bypass Stockholm has more than 1000 sections, and it would be a monumental task to have them inspected by certified inspectors four times a year. (In the Norther Link the controls are constituted by the tunnel operator to a test run every year with an ocular inspection of the spray pattern. After eight years of operation the fail rate at these tests is small, and it is now discussed to increase the time between the tests to two years.)

DEVELOPMENT OF A NEW FFFS CONCEPT, STARTING IN THE TUNNEL

When these adjustments needed from the present sprinkler regulations were identified, a principal decision was made by the project management that the FFFS in the Northern link would not follow rules and praxis that was not applicable for road tunnels. From a practical point of view, the aim was not a design of a sprinkler installation, and instead it was to facilitate a local delivery of a well designed water sprays in case of fire. This resulted in a possibility to design a system that was optimised for the conditions in the Northern link tunnel. The focus was on optimizing the pipe layout, minimizing the complexity and maximizing robustness and ruggedness. “Simple and stupid” was the motto. The number of moving parts were down to two per 75 m section (membrane valve and solenoid activation valve, and these were in a protected environment in the escape routes). In the traffic tunnel the water was distributed by a pair of sidewall nozzles back to back in the middle of the tunnel ceiling. The spacing between those nozzle pairs was 5 m, giving each deluge section 15 nozzle-pairs. The nozzles chosen for the Northern Link were the Tyco SW24, which could cover 7.5 m sideways, giving the system capacity to cover up to 15 m between the tunnel walls using one pipe positioned in the central line of the ceiling.

The Scandinavian road tunnels are extremely challenging environment for technical installations. The winter conditions mean that there is a large amount of salt, moisture and dust from spike tyres, which makes corrosion an important issue. The corrosion class in the tunnel is C5 Marine, which is the same as for the offshore industry use. To meet this requirement a thermoplastic-coated steel pipe from Alvenius was selected (see Figure 5). One advantage with this system is that its prefabricated parts are mounted together with couplings with just nuts and bolts like a big Meccano (or an IKEA made sprinkler system). This speeds up the installation and also facilitates repairs of damaged sections.

RESEARCH, TESTING AND VERIFICATION

The decision not to fully comply with sprinkler regulations in the road tunnel meant that the project had to evaluate and prove the effectiveness of the system, rather than just relying on the standards. This opened up a need for cooperation with scientists from RISE Research Institutes of Sweden (former SP). The team leading and responsible scientist from RISE was adj. Prof. Haukur Ingason. There were a number of issues that needed to be addressed: The effect of the use of SW-24 nozzles against vehicle fires, the spray pattern over the cross section and road surface, the effect of using the
FFFS with spills of flammable liquids on the road surface (see Figure 6), the Alvenius pipes resistance against fire, the effect of longitudinal ventilation on the water spray and visibility through an activated section. A large number of tests and practically applied research projects were conducted by RISE from 2010 until today. All test results and reports are publicly accessible [1,2,3,4]. The results did convince the STA, the Swedish Transport Agency and the fire brigades of Stockholm and Gothenburg that the new FFFS concept was an efficient measure to increase safety in these complex road tunnels. The research achievements were also noted by EU, i.e., in 2019 RISE was awarded the EARTO prize in the category “Impact delivered” for the research and tests done for FFFS in road tunnels.

AUDIT AND ACCEPTANCE OF THE CONCEPT

Before opening for traffic, the Norther Link project went through a thorough audit from the Swedish Transport Agency, who’s responsible for approving new tunnels according to the EU-directive. The safety concept and the safety documentation were reviewed by a group of international experts that had experience of reviewing projects from the aspect of fire safety and risk analysis. This was the first time the agency formally was faced with the idea that FFFS could protect slow traffic in a longitudinally ventilated tunnel, and there was a reluctance to accept the concept. In addition, some of the international experts also had a disputing approach in their judgements. But after a series of workshops analysing the concepts and scenarios, and with great help from RISE experts to explain the science behind the new FFFS, the approval was finally given. The first part of the Northern link was open for traffic in 2014.

Another authority who supervises fire safety in road tunnels is the fire brigades. Their main role is to oversee the fire safety in construction works and buildings according to the legislation of “protection against accidents”. There was no problem in getting their acceptance for the fire safety concept, despite that there were large deviations from the sprinkler standards. There was an acceptance that the choice was between getting this FFFS or none at all. In general, there was a great satisfaction in the fire brigade that FFFS now finally was being introduced.

THE NEXT TUNNEL PROJECT AND CREATION OF “T-REX”

During one of the tests conducted for the Northern Link tunnel in 2012 in the RISE fire laboratory (former SP laboratory) one of the sprinkler experts, Mr Conny Becker from Brandskyddslaget AB, said he “wanted to test something”. It turned out that he had built an up scaled version of the Tyco SW24 nozzle back home in his garage (see Figure 7), and he wanted to do a water distribution test just out of curiosity. When the nozzle replaced the SW-24 in the test rig the result surprised everyone. A 9 m long spray plume of large cascading water droplets filled the laboratory. It was obvious that the working group had found a candidate for the next large tunnel project, the Bypass Stockholm.
In the hotel bar after the tests there was a discussion of what to call the prototype. T-25 was suggested after *Tunnel nozzle 25* (with was the size). “T-25? No, it’s T-rex, the biggest and baddest of them all”. The name T-rex kind of remained in our thoughts.

The working group reached out to former Tyco (present Johnson Control) to hear if they were interested to develop a product similar to “T-rex”. Mr. Henrik Johansson at Tyco’s European office was very helpful in persuading his American colleagues to develop the new nozzle, named TN-25. It has the same performance as the T-rex, about 10 mm/min over a 9 x 5 m area at 1 bar (see Figure 8). In 2013 there was a handful of TN-25 available for full scale testing in Runahammar (a Norwegian abandoned road tunnel, now used for fire tests). RISE conducted a series of six full scale tests with a shielded fire load at potential 100 MW (420 wooden pallets in the shape of a truck bed) [1]. The results were impressive, the fire was attacked and limited to 10-20 MW in size, and suppression was achieved after about one hour. The original ambition for the Northern Link system was to use the SW24 nozzles to slow the fire growth and reduce the spread into other vehicles. With the TN-25 we now had a concept that could suppress large fires. In 2014 it was decided that the Bypass Stockholm tunnels would be fitted with the TN-25, and that waters supply and drainage systems should be dimensioned for 10 mm/min in two 50 m deluge sections. The detailed designing of the system is in progress as this was written in December 2022. The first part of the Bypass Stockholm is due to be opened for traffic in 2026.

*Figure 8*  Distribution tests of a pair of TN25 nozzles in the RISE fire laboratory in Borås. The mezzanine floor to the left simulates a 4.5 m high HGV [5].
RETROFITTING THE FFFS CONCEPT IN OLD TUNNELS LEADS TO FURTHER DEVELOPMENT

Götatunneln
Once the original resistance against FFFS was gone in the STA, things happened quite fast. In Gothenburg there is a 1.6 km tunnel named Götatunneln, that had a similar traffic problem as the Southern Link, but not yet as bad. In 2015 there were discussions if it was time to do a retrofit of a FFFS, but it was not considered necessary yet. A year later, it was discovered that the construction of a rail tunnel needed to claim each tube of the Götatunneln for six months, thus forcing the tunnel operator to allow bidirectional traffic in another tube. The Tunnel Safety Officer was not impressed, and pointed out that this was not allowed, nor by the EU-directive or Swedish law. It was suggested that one way to achieve an acceptable safety level with bidirectional traffic was to fit the tunnel with FFFS. Now the decision was taken rapidly, since the rail tunnel obviously had a high priority in the transport administration. In 2018 both tunnel tubes had the FFFS in operation. It was a blueprint of the Bypass Stockholm-concept: TN-25 nozzles in 50 m long sections, water density of 10 mm/min. In 2020 and 2021 the tunnel closures with bidirectional traffic in one tube were conducted without any major incidents. See the visibility after FFFS activation in Figure 9.

Tingstadstunneln
Another example of retrofitting FFFS is the refurbishment of the Tingstad tunnel in central Gothenburg. It is a 500 m submerged concrete tunnel under the river Göta älv. It is almost 60 years old, and the fire resistance in the old concrete construction does not meet modern requirements. It was decided that a FFFS should be installed to reduce the risk of severe damages to the tunnel. The problem is that the cross section is very narrow, so there is absolutely no room for installations in the ceiling. Therefore, the pipes and nozzles are installed half way up on the tunnel wall to throw the water spray upwards in arcs into the center of the tunnel cross sections, and into the ceiling (see Figure 10). This is probably also a large deviation from Swedish sprinkler standards, but as explained earlier, STA does not pay too much attention anymore. The FFFS will be fitted with TN17 nozzles, which is a new smaller version of the TN25.

Figure 9 A full scale exercise in Götatunneln in 2019. Note the good visibility, despite 10 mm/min density. This is due to large droplets and low pressure.

Figure 10 The pipe half way up on the wall in the Tingstad tunnel. Foto: Louise Alfvén
**Muskötunneln, automatic sprinklers**

An interesting tunnel that has not yet been fitted with FFFS is the Muskö tunnel in the southern archipelago of Stockholm. This 60 years old, 3 km long bidirectional subsea tunnel has no emergency exits at all. Since it is bidirectional with low traffic numbers, the air velocity is normally less than 1 m/s, and temperatures are above freezing point. This opens up for an application using *automatic* sprinkler heads, which would reduce the investment cost considerably since one pipe in the ceiling serves for both the water supply and the fitting of the nozzles. The science behind this concept have been investigated by RISE, both in scale tests (1:3) [6, 7] and full-scale water spray tests in fire laboratory [5]. See photos from the tests in Figure 11. When the STA decides to refurbish the tunnel, this concept will be taken under serious consideration as a mean to increase the fire safety for road users. Once again the idea is to slow down the fire growth so that motorists can leave the tunnel before critical conditions occur. The reduced damage to the tunnel is also regarded as a large advantage.

**Southern link**

There is now consensus about that it would be very useful to have the Southern Link fitted with a FFFS with the same type of concept as in the Northern link (SW24 nozzles). The problem is that the tunnel is in operation, and the disturbance of the traffic system by such installation work is regarded as unacceptable. Also, the sensitive construction of the ceiling implies that it is forbidden to attach any installations in those surfaces. This means that the concept with a central pipe in the ceiling is out of the question. Therefore, a concept with one pipe on just one wall to cover the complete cross section is being investigated. There have been some promising tests conducted with combinations of modified sprinkler nozzles that could cover a 15 m wide tunnel from just one side (see Figure 12). This could also mean that installation could be done with some traffic retained (one or two lanes). This would massively reduce the socioeconomic effect of the installation, and perhaps this will be the way forward with FFFS in the Southern Link.
LESSONS LEARNED FROM OPERATING THE NORTHERN LINK

The Northern link tunnels opened for traffic in 2014. When this article was written in December 2022 over 200 million vehicles have passed through the tunnel system. There has been roughly one fire incident per year, and so far no heavy goods vehicle has been involved. The fire safety concept has so far proven to be effective, and all motorists have come out of the tunnels unharmed. The largest problem that has been identified is that the motorists do not stop when they arrive at the scene of the fire. Instead they pass by the burning vehicle and drive into the smoke downstream (even when the FFFS is activated and all lanes closed by the MCS-signs). So far everybody has managed to drive all the way through to safe areas, but if there is a heavy goods vehicle on fire this behaviour could be really dangerous. STA is looking at means to prevent this behaviour by improving the messaging by signs and radio broadcasts.

In one fire in 2017 there was a real problem with visibility in the activated FFFS zone. Later it was ascertained that this was partly because of a meteorological phenomenon: The air in and outside the tunnel had very high relative humidity, and a smog was formed by a combination of fog due to the temperature drop by the water spray, smoke, and condensed vapour from the fire. Some evacuees had problem locating the escape routes due to this phenomenon. At the time STA still operated the ventilation at 1.5 m/s when there was a risk of slow traffic downstream, but after this incident it was decided to use the normal 3 m/s at all times. In motivating this it was very helpful to have the data from all the tests RISE had conducted, especially the air speeds’ miniscule effect on the heat release rate in an activated FFFS zone (1.5-3 m/s).

The largest fire we yet have encountered was a campervan fire in spring 2022 (see Figure 14). It has been estimated by adj. Prof. Haukur Ingason at RISE that the fire peaked at around 10 MW, but without the FFFS the fire had a potential to reach an estimated value of 30 MW [8]. The tunnel could be opened after two hours, but if it had been a 30 MW fire the closure probably would have been much longer, and more costly.

CONCLUSIONS

In the author’s opinion, the development of the new tunnel safety concept in Sweden has been a success. The transport administration in Sweden have added valuable robustness to the transport system, and facilitated the possibility of further development of urban road tunnels. By cooperating with world leading scientists and experts we were able to tailor a concept for local Swedish conditions. By formulating precise questions to the science and academic community it was possible
to instantly adopt the results in the tunnel design. This requires short decision paths in the project organisation though. When a question arises in a tunnel project, there should be ways to instantly commission a narrowed and focused research or testing activity to solve the issue. This generates a close dialog between tunnel operators, tunnel designers and the research community, that gives a “critical mass” of knowledge that is necessary for taking the next step forward.

ACKNOWLEDGMENTS

The author would like to acknowledge the colleagues at STA who were involved in the discussions, the involved fire consultants from Brandskyddslaget (BSL) and Swepro, the involved personnel of the manufacturer Johnson Control (former Tyco) and Alvenius AB as well as the scientists and technicians at RISE.

REFERENCES

Risk analysis of fire and explosions in road tunnels

Mirjam Nelisse
TNO Netherlands Organisation for Applied Scientific Research, Delft, The Netherlands

ABSTRACT

As we all know, road tunnels play a critical role in transportation infrastructure, enabling the safe and efficient movement of people and goods. However, they also pose unique challenges in terms of safety, particularly when it comes to the risk of fire and explosion events. In the past 20 years, risk analysis in the area of fire and explosion safety has evolved to a much broader accepted area of expertise. Risk analysis helps to make decisions about life, structural safety and economic optimizations. Methods have developed, data is better accessible, and calculations are faster. However, also the safety in tunnels itself evolves: other fuels, truck platooning and smart mobility are developments that needs to be taken into account in new or updated risk analyses. In this paper a look into the history and the future on risk analysis in fire and explosion risk in road tunnels, is given.

KEYWORD: ISTSS, keynote, risk analysis, reliability, fire, explosion, new fuels, truck platooning, smart mobility, probability, consequences.

INTRODUCTION

As we all know, road tunnels play a critical role in transportation infrastructure, enabling the safe and efficient movement of people and goods. However, they also pose unique challenges in terms of safety, particularly when it comes to the risk of fire and explosion events. Over the past few decades, there have been a number of incidents of fires and explosions in road tunnels, some of which have resulted in significant loss of life and damage. These incidents highlight the importance of effective risk analysis for identifying and mitigating the risks associated with tunnel operations. In this paper, some of the key developments in the field of risk analysis for fire and explosion risk in road tunnels are discussed, as well as some of the challenges that remain.

The idea to use the concepts of probability theory in the field of structural safety is already more than 50 years old [1]. However, in the field of fire and explosion safety in (road) tunnels, risk analyses are relatively new. In the nineties a number of very large tunnel fires occurred in Europe. The fires in amongst others the Tauern tunnel (1999), Mont Blanc tunnel (1999) and Gotthard tunnel (2001) have cost the lives of many people and caused large damage to the structure of the tunnel. Public and political attention asked for an answer to questions about the safety of tunnels. This attention lead to the start of a number of large European research projects, such as UPTUN [2,3], DARTS [4], FIT [5] and L-SURF [6]. The focus of the research in these projects was in particular on the understanding of fire size and fire behaviour, the modelling of fire, measures to reduces the fire such as sprinklers and water mist systems and the resistance of the tunnel. The focus of these research projects was therefore mainly on (limiting) the consequences of an accident and not so much on the probability of an accident occurring. However, to determine the risk, both the probability and the consequences of an accident, fire or explosion needs to be known. This brings us to the question: “how has risk analysis on fire and explosion risk for road tunnels developed in the last 20 years and what is the added value of risk analysis in the design of road tunnels for fire and explosion?”
What is a risk analysis?
In the end, a risk analysis is used as a basis for decision making. Multiple decisions can be based on a risk analysis, such as a decision about the accepted risk for people or a structure, for example to license a permit. Or the decision about which measures need to be taken to lower the risk, in order to achieve an acceptable risk level. Also decisions whether to allow a certain hazard, for example certain hazardous goods, can be based on a risk analysis. A risk analysis is used to identify, structure, analyse and objectify relevant information regarding risks in order to make decisions. This can be a risk analysis regarding life safety, structural safety, external safety and even a combination thereof.

Risk analysis is an important tool for ensuring fire safety in road tunnels. A risk analysis comprises of several steps and typically involves a systematic process of identifying and assessing potential hazards, evaluating the likelihood and potential consequences of those hazards, and developing strategies to mitigate or manage the risks. Figure 1 shows the overview of a risk analysis as presented in [7], which can in general also be used for fire and explosion risk in tunnels. The first step is the definition of the scope and limitations. Then a qualitative analysis is done, basically to identify causes of the undesired event (fire, explosion, etc.) and the consequences thereof. This can be followed by a quantitative analysis, where the probability of an undesired event and the scenarios leading to that undesired event are quantified as well as the consequences of that undesired event. The resulting risk can then be estimated or calculated, and evaluated against a set target risk. If the risk is deemed too high, measures can be taken or the scope and assumptions need to be reconsidered. As a last step the resulting risk needs to be (preferably explicitly) accepted and can be communicated. Since the consequences of fire and explosion in road tunnels may be very large, but the probability of occurrence is usually small, a risk analysis gives insight in the economical evaluation of risk and risk reducing measures.

![Figure 1: Overview of risk analysis [7]](image)
Advantages of a risk analysis

There are several advantages of performing a risk analysis for fire and explosion risk in road tunnels.  
1. Improved safety: Perhaps the most significant advantage of performing a risk analysis is that it can help identify potential hazards and risks in the road tunnel environment, allowing for the development of effective risk mitigation strategies. This can help reduce the risk of fires and explosions, improving the overall safety of the tunnel for motorists and other users.  
2. Cost savings: While implementing risk mitigation strategies may require an initial investment, it can ultimately lead to cost savings over time. For example, implementing fire-resistant materials can help reduce the consequences of fires, which can in turn reduce the need for costly repairs and cleanup in the aftermath of an incident.  
3. Regulatory compliance: Many jurisdictions have regulations and standards in place that require the performance of risk analyses for road tunnels. By performing a risk analysis and implementing appropriate risk mitigation strategies, tunnel operators can ensure compliance with these regulations and standards.  
4. Improved emergency preparedness: By identifying potential hazards and risks, a risk analysis can help develop effective emergency response plans and procedures, allowing for more effective and efficient responses in the event of a fire or explosion.  
5. Public confidence: Finally, performing a risk analysis and implementing effective risk mitigation strategies can help build public confidence in the safety of the road tunnel, which can be an important factor for motorists and other users when making decisions about whether or not to use the tunnel.

Challenges of performing a risk analysis for fire and explosion hazards in a road tunnel

Of course the overview from Figure 1 looks quite simple, but the devil is in the detail! The challenge lays in being complete and correct in determining the scenarios, finding or estimating the relevant probabilities and calculating the size of the consequences. Next to the knowledge on risk analysis, one also needs the knowledge of the tunnel itself, being a system in its environment. Challenges regarding this knowledge may comprise:  
1. Complex and dynamic environment: Road tunnels are complex and dynamic environments, with a variety of factors that can affect the risk of fire and explosion, such as traffic flow, ventilation systems, and the presence of hazardous materials. These factors can be difficult to model and predict accurately the size and impact of fires and explosions, which can make it challenging to perform a comprehensive risk analysis.  
2. Uncertainty in data: In many cases, data on the potential hazards and risks associated with road tunnels may be incomplete, outdated, or unreliable. This can make it difficult to accurately assess the probability and consequences of different hazards and develop effective risk mitigation strategies.  
3. Limited access: Access to road tunnels can be limited due to safety concerns, which can make it difficult to collect data and perform inspections and maintenance. This can make it challenging to identify potential hazards and assess the overall risk profile of the tunnel.  
4. Political and economic considerations: The development and operation of road tunnels can be influenced by political and economic considerations, which may prioritize factors such as cost and convenience over safety. This can make it difficult to implement risk mitigation strategies that may be costly or inconvenient.  
5. Human factors: Finally, human factors such as operator error, fatigue, and communication breakdowns can all contribute to the risk of fire and explosion in road tunnels. These factors can be difficult to model and predict, and may require specialized expertise in areas such as human factors engineering to effectively address.

USE OF RISK ANALYSIS IN ROAD TUNNEL SAFETY

In the beginning…

In the late nineties and early 2000’s, risk analysis in road tunnels was not a general practice. During my Master thesis (1999-2000), tunnel safety was considered as something that could not (easily) be measured and a qualitative approach was used [8]. Shortly after, research work into risk analysis was...
started within EU research projects such as DARTS (Durable And reliable Tunnel Structures) [9,10] but also at de Netherlands Ministry of Transport [11] and the OECD [12].

In those years also a European Directive on road tunnel safety was written and published [13] where risk analysis is presented as a method to demonstrate equivalent or improved safety when alternative measures than the prescribed ones in the Directive are desired or deemed necessary. However, that Directive does not give direction regarding how a risk analysis should be done. Article 13 member 2 states “Member States shall ensure that, at national level, a detailed and well-defined methodology, corresponding to the best available practices, is used and shall inform the Commission of the methodology applied; the Commission shall make this information available in electronic form to other Member States”. Member 3 adds “By […] * the Commission shall publish a report on the practice followed in the Members States. Where necessary, it shall make proposals for the adoption of a common harmonised risk analysis methodology in accordance with the procedure referred to in Article 17(2)”. In the corrected [14] version of 07-08-2009 the date of 30 April 2009 has been added. However, neither the report on the practice nor a proposal for a harmonised risk analysis methodology could be found.

**Developments and applications in tunnels safety**

Over time the risk analysis methods have developed, data has become better available and calculations are less time-consuming than they used to be. In the beginning the risk analyses were applicable on tunnels that were quite standard from the point of geometry, but in the course of years, also risk analyses of tunnels with a more complicated geometry were developed. An example is one of the alternatives for an underground connection underneath the Dutch city of Leiden. The so-called Churchill tunnel [15] was designed with multiple entries and exits along the length of the tunnel, leading to more lane changes and maneuvers than in a regular tunnel, resulting in a higher probability of an accident (collision). The QRA-tunnels model that is used for regular geometries needed to be adapted to also include the additional risk resulting from the entries and exits.

Risk analysis was also used to study the risk of terrorist attacks on vital infrastructure, including tunnels [16]. Since the probability of a terrorist attack on a certain tunnel or underground structure is extremely uncertain, the focus of these studies is mainly on the size of the consequences and the possible measures to limit these consequences. This is also called a “consequence analysis” instead of a risk analysis. The structured analysis however helps in studying the size of the consequences, determining whether they are acceptable or not and to didentify measure to prevent the consequences from happening or limit the size of the consequences.

Also a risk analysis was performed regarding large (>25 MW) fires in Dutch road tunnels [17]. Since only a limited number of large fires in European tunnels have occurred and, at the time of the research, only one large fire in The Netherlands, a Bayesian approach has been used. Shortly after, a second large fire occurred in The Netherlands, in the Heineenood tunnel [19]. This second fire was a reason to update the first Bayesian analysis and see whether the probability of a large fire had significantly changed [18]. The conclusion could be drawn that the second fire did not lead to a significant change. Interestingly to mention is that when a frequentistic approach would have been used, by means of dividing the number of large fires by the vehicle kilometers through tunnels, a doubling of the original probability would have occurred. This shows the importance of the correct methods and data.

Explosions in tunnels posed a comparable challenge for risk analysis: not only has a very limited number of explosions occurred in road tunnels, but also the size of explosions is difficult to measure or calculate. Research has been done into the probability of an explosion of an LPG truck in a road tunnel, the consequences thereof in terms of type of explosions, their probability of occurrence and their size in terms of peak pressure and impulse. A design target reliability and design values for the peak pressure and impulse have been deduced [20,21,22].
Current and future challenges
Due to the energy transition, more and more vehicles will drive on new fuels, such as electricity or hydrogen. The fuel stations for vehicles, ships, etcetera, need to be fueled with these new fuels as well, leading to an increase in trucks carrying these fuels through road tunnels. The probability of an accident might perhaps not change as a result of new fuels, but the scenarios leading to fire or explosion and the probabilities of occurrence may change. Also the consequences, in terms of the size of fire for example, may be different [25]. Will the current safety measures be adequate for events including new fuels as well? We do know that fire in electric vehicles are difficult to extinguish. Most probably additional research, possibly including tests, need to be performed to be able to adjust the risk analyses to the changed traffic composition.

A future challenge may be truck platooning: a form of automated riding. With truck platooning, multiple trucks ride on a short distance after each other, not physically coupled, but electronically. In this way fuel can be saved, and possible the drivers in the second and further trucks can rest, while the driver in the first truck pays attention to the road, but doesn’t necessarily have to do something. There are various scenarios about the speed, the distance between the trucks and the number of trucks in a platoon [23]. The resulting risk of a platoon involved in an accident in a tunnel may be different than the same number of trucks not in a platoon. One may think of the number of trucks that may be involved in a fire, drivers sleeping and having a longer response time, etc. These changed risks need to be taken into account in the risk analysis of new and existing tunnels.

Smart mobility is a concept that includes many changes in the mobility sector in the coming years. From the electric car, to car sharing, to the self driving car. From information, advising and acting. From reactive to proactive, from collective to individual and from mobility to mobility as a service (MAAS). Digital connections between vehicle and roadside equipment can lead to an increase in safety and better, timely and individual information. Smart mobility may also improve more efficient driving: less emissions, better flow and efficient use of the existing road capacity.

However we will be in transition and dealing with mixed traffic of “old” and “new” for quite some time, perhaps a decade or more. The new mobility will be supported by both physical and digital infrastructure. However, one of the challenges is the “replace and renewal” time of the various systems: road side equipment and traffic control centers are renewed every, say, 30 years, while the “time-to-market” of cars is around 10 years and an app on a smart phone takes a couple of hours to be available for consumers. This “transition time” may lead to additional or unforeseen risks that are not yet identified in risk analyses.

Advantages for tunnel safety can be seen when cars are going to perform as sensors. “Car-as-a-sensor” can for example detect temperature raise or smoke, but also knows the exact position of the car. This means that, when a car-as-a-sensor catches fire in a tunnel, the fire as well as the position is detected and can be communicated to both the tunnel operator and the fire brigade. This saves seconds, maybe even minutes, and as we all know, that can make a tremendous difference. Another advantage can be the in-car systems to improve safety, such as “stay-in-lane” systems, collision prevention systems and even height detection onboard trucks. It is likely that these systems limit the probability of accidents and therefore influence the resulting risk in a risk analysis [24].

CONCLUSIONS AND RECOMMENDATIONS
Risk analysis is a powerful tool to use as a basis for decision making, to identify risks, quantify risks and identify safety measures and their influence on the resulting risk. Also an economic analysis can be made to assess whether the risk is acceptable or not and what design values or target reliability values are. In the past 20+ years the methods and tools have developed and the use of risk analysis as part of the design, construction, operation and renovation process has increased and has become broadly accepted. However, the development of risk analysis has not come to a standstill, since also developments with respect to vehicles, safety measures and systems and the tunnel itself are continuing. A look into the future reveals that the use and transport of new fuels, truck platooning and
smart mobility will require new or adjusted risk analyses, and therefore also research and development regarding input. Input such as new risks, eliminated risks, changed probabilities of occurrence, changed size of consequences and new innovations in risk mitigation.

REFERENCES

2. UPTUN, Uptun: cost-effective, sustainable and innovative upgrading methods for fire safety in existing tunnels | UPTUN Project | Fact Sheet | FP5 | CORDIS | European Commission (europa.eu)
3. Nelisse, R.M.L., The First Year’s research results of the european project UPTUN, Proceedings of the International Symposium on Catastrophic Tunnel Fires, 20–21 November 2003 and many more papers in these proceedings
4. DARTS, Durable and reliable tunnel structures | DARTS Project | Fact Sheet | FP5 | CORDIS | European Commission (europa.eu)
11. Rijkswaterstaat Bouwdienst, Steunpunt tunnelveiligheid, Het RWSQRA-model voor weg tunnels, versie 1.1, definitief, 28 april 2006
13. DIRECTIVE 2004/54/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network
quantitative risk analysis, ISTSS, 2020
ABSTRACT

Tunnel fires are a serious safety concern due to their potential for catastrophic consequences, such as loss of life, property damage, and disruption to transportation networks. In recent years, research has given new insights into human behavior in tunnel fires, through in-depth interviews of survivors of real tunnel fires and true to life virtual reality (VR) studies. This paper reviews current research highlighting new findings, validation of existing knowledge and how new technologies may alter risk and human behaviour in road tunnel fire. By learning from real tunnel fires and incorporating these lessons into fire safety protocols, it is possible to minimize the risks associated with tunnel fires and ensure the safety of everyone involved. Overall, our studies show that road users can find evacuation rooms in a smoky tunnel environment, feel safe when staying in such evacuation rooms and accept to stay there in high temperature and humidity provided the right design and equipment. Theories on human behaviour in road tunnel fires are to a large extent verified, except that evidence from real tunnel fires show people are much more altruistic and helpful in tunnel fires than to be expected based on the self-preservation theory. The Virtual Reality simulations have shown that people follow the instructions from the Road Traffic Control Centre (VTS) and find first aid even in poor light. Perceived safety is highest in evacuation room design with good lighting and an illusion of blue sky and extra ceiling height in critical situations. Evacuation rooms are well-known technology used in other high-risk sectors, such as the petrochemical industry and the oil and gas industry, which have accident scenarios at least as serious as tunnels. Based on the studies reported here, we will recommend, including safety criteria, EU (ESA) approval to be able to use evacuation rooms without access to the open air in long low traffic single tube road tunnels for temporary residence as part of assisted rescue.

KEYWORDS: Road tunnels, Human behaviour, Tunnel fire, Virtual Reality, Emergency exit systems, Automation, Evacuation rooms

HUMAN BEHAVIOUR DURING TUNNEL FIRES

Imagine you are driving through a mountainous tunnel, and after some kilometres the tunnel gets pitch dark. You enter a 1000 m section of the tunnel which has been without light for weeks due to an electric fault. As you see a glimpse of tunnel lighting again in the distance traffic is slowing down, until you end up at a standstill behind a polish registered heavy goods vehicle (HGV). Why is it standing still? Is there a queue? Roadworks? This is a single tube tunnel with two-way traffic. It is tricky to turn. It is dark and you can not see far. A car passing by in the opposite direction is blinking with his lights. Why is he doing that? All of a sudden you see a burst of flames and smoke coming out from under the cabin of the HGV. The truck is on fire. What do I do? Stay put? Turn around? No! that is not easy in the narrow tunnel. I decide to overtake the burning HGV. As I pass an even stronger burst of fire and smoke licks my window on the right side. I continue to pass. It gets pitch dark. The tunnel in front is already filled with black smoke.

What would you do in this situation? If you arrive as the first behind the burning truck? What if you are further back in the queue unable to see flames or smoke? If you decide to stay put, what do you do after a while, when you hear crackling noise, car doors banging shut, voices calling out? What if you
are outside the tunnel and see red blinking stoplights at the tunnel entrance? What if smoke is coming out of the tunnel. Do you still enter?

**Gudvanga tunnel fire**

The story above is based on in depth interviews of people trapped in smoke during the Gudvanga tunnel fire in 2013 [1]. Along with a team of SINTEF scientists I entered the tunnel together with expert investigators from the Norwegian National Accident Investigation Board (AIBN). We were there to inspect the incident site and interview key personnel in the local public Roads administration and fire brigade. We wanted to have the facts on the table before we interviewed the 67 survivors who were trapped in the smoke-filled tunnel. We also aimed to interview other rescue services. The doctor arriving from Bergen in a helicopter, the ambulance personnel. The medical staff at the local hospital etc.The Gudvanga tunnel at hand is 11.4 km long single-tube tunnel. Compared to central Europe tunnels it has a low traffic volume (Annual Daily Traffic Volume 2200), but with increasing heavy goods traffic in the last decade. Sixty-seven persons were trapped in the smoke in the tunnel, 28 persons sustained acute smoke injuries and 5 of them would have died without immediate medical treatment and oxygen when they arrived outside the tunnel. Fresh air is not enough according to experts from the Oslo University Hospital. In the AIBN's opinion, there were four major failure points:

1. The tunnel was not equipped with any kind of monitoring or device for counting vehicles that could have provided continuous information about how many vehicles were in the tunnel. The Road Traffic Centre (VTS) and the fire service thereby did not have an overview of how many people were on the side of the fire towards which the smoke was ventilated.
2. No information was given to the road users that immediate evacuation was necessary. Only those in the immediate vicinity of the fire scene or who realized what was happening at an early stage managed to evacuate before the tunnel filled with smoke.
3. As a result of the pre-defined strategy for fire-extinguishing and rescue work that is set out in the emergency response plan for the tunnel, the Road Traffic Centre, immediately after the fire was reported, routinely starting the fire ventilation, so that the smoke from the fire was ventilated 8.5 km in the direction of Gudvangen. The smoke blocked the only possible evacuation route for the road users on the Gudvangen side of the fire.
4. The tunnel design and the tunnel's technical equipment did not adequately facilitate self-rescue.

**Oslofjord tunnel fire**

The Oslofjord tunnel fire (2011) was the first major tunnel fire within three years period and five more were to come in the next six years. I was involved in the post-fire investigation of the first one, the Oslofjord tunnel fire in 2011 on behalf of the National Public Roads administration. [2] An incident later studied in depth by researchers from university of Stavanger, with interviews of survivors [3]. On 23 June 2011, a fire broke out in a Polish heavy goods vehicle in the 7 km long Oslofjord tunnel The heavy goods vehicle was passing through the tunnel from the west side of the fjord (Hurum) towards Drøbak in direction of the Swedish border. Approximately 5.5 km into the tunnel, and approximately 1.8 km before the exit on the Drøbak side, the heavy goods vehicle stopped because a fire had started in the engine. Søndre Follo fire service entered the tunnel from the Drøbak side to put out the fire.

Ventilation may have a significant effect on human behavior in tunnel fires. In order to provide good visibility for the firefighting efforts, the ventilation air was set to flow towards the Hurum side. This caused 5.5 km of the tunnel to fill up with dense, black smoke. Several road users had problems evacuating, and nine persons were trapped in the smoke. It took approximately two hours before they were evacuated by the rescue crews. The fire extinguishing from the Drøbak side functioned in a satisfactory manner and as expected. The rescue effort from the Hurum side encountered major problems due to the smoke development, risk of collisions and the distance to the fire location. Twenty-five of 34 road-users exited the tunnel unaided (self-rescue). Nine road-users were later evacuated from the tunnel by rescue crews. The overview VTS had through CCTV monitoring of the tunnel and direct contact with road users in the SOS phone booths, in addition to the emergency
services’ fire and rescue efforts, saved lives. Several people were found hurdles together in the emergency phone booths. One person was found behind the tunnel lining, behind a geological inspection hatch. No-one was killed in the event, but 34 persons were trapped in the tunnel and some of them seriously injured due to toxic gases.

Post fire interviews gave information about the road-user behaviors, which were characterized by great uncertainty about the situation in the early phase of the incident [3]. For many road users it delayed their decision to escape. Some people (4-5) decided to sit in their vehicles using the recirculated air. Some activated recirculation on purpose, some because the vehicle automatically turns on recirculate when significant pollution is detected. Some drivers tried to turn their vehicles around to drive downstream from the fire to the tunnel's western entrance. Most of them succeeded, but a number of drivers (9-12) did not make it and were forced to find shelter in the tunnel. As mentioned above, they ended up behind hatches leading to the space between the tunnel arch and the mountain profile, or in emergency phone booths as they tried to open any door they found as they stumbled along the tunnel wall. One person walking out was hit by a car trying to drive out through the black smoke. All victims were brought to safety and hospitalized within two hours after the fire broke out.

So why do these accidents happen and why are the conditions for self-rescue so bad. In both cases a HGV catches fire possibly due to technical failure (Gudvanga) or overheating of brakes or motor in a tunnel in a subsea tunnel with a steep gradient above 7% (Oslofjord). Both tunnels are long single tube tunnels with two-way traffic. In the 11.4 km long Gudvanga tunnel there are no emergency exits. In the Oslofjord tunnel, at the time of the fire, it was only one emergency exit. In both tunnels there were no emergency exit signs or systems to help ease and speed up self-rescue. Both tunnels have emergency lighting, but with a spacing of 25-30 m it is impossible to see from one lamp to the other in thick black smoke. Some researchers claim that "systems will tend to migrate towards states of higher risk" [4,5]. They claim that better knowledge of the system is the only possibility to meet this.

The attitude among many who work with tunnels seems to be that we have control over the smoke through the ventilation systems, and that it is therefore not that dangerous. One person even asked if we did not have better things to focus on than the post-fire investigation of the Gudvanga Tunnel fire. Such an attitude is not rooted in knowledge. In both the Oslofjord and the Gudvanga tunnel fire of 2013, fire ventilation was initiated according to the contingency plan, engulfing most road users in black smoke without knowledge of their position or situation in the tunnel.

A THEORETICAL VIEWPOINT

Human behaviour during fires in tunnels can vary depending on a number of factors such as the severity of the fire, the location and layout of the tunnel, the number of people present, and the availability of emergency equipment and guidance. According to the literature regarding fire in buildings, some common behaviours that can occur during fires in tunnels include:

1. Crowding and pushing: People may crowd around exits and push each other in an attempt to escape;
2. Disorientation: Smoke and low visibility conditions can make it difficult for people to navigate and find their way to safety;
3. Fear and panic: The intense heat and flames can create a sense of fear and panic, leading to irrational behaviours and decisions;
4. Delayed action: Some people may delay taking action, either because they do not perceive the threat as serious, or because they are waiting for guidance from others.

The Normative perception (how we think people should behave) is that in general during a fire, people will typically try to evacuate the area as quickly and safely as possible. However, panic can set in and cause people to act irrationally, leading to confusion, congestion and potential accidents. But is this the case in road tunnel fires? The opposite perception would be formative (how people actually
behave) and adapt design and egress systems accordingly. The layout of the tunnel can also play a role in human behaviour during fires. For instance, in long and narrow tunnels, people may have limited space to turn and drive out. Limited visibility, makes it difficult to navigate and locate exits. In addition, tunnels that have only one entrance and exit can create a bottleneck effect, causing congestion and making it more difficult for people to escape and emergency response teams to assist.

There are several acknowledged theories about human behaviour in tunnel fires:

1. **The social identity theory**: This theory suggests that people's behaviour in a tunnel fire may be influenced by their social identity, which is the part of their self-concept that is derived from group membership. People may be more likely to follow the behaviour of others in their group, even if it is not safe to do so. This is also related to the phenomena that people may follow persons they perceive have authority, whether it is correct or not [6]. This may be a policeman, fireman or a person with a yellow vest.

2. **The self-preservation theory**: This theory suggests that people's behaviour in a tunnel fire is primarily motivated by a desire to protect themselves and their loved ones. People may take risks to help others, but their primary focus is on getting themselves to safety. The concept of panic is part of this theory. The common notion of panic is a person who tries to run away from immediate danger. This hurried response implies some element of intensity in response to a hazard. Panic is a response to considerable stress and fear caused by an external threat that could harm or kill you. This response impairs the quality of people’s decisions, and in some cases renders them completely unable to act. The latter is related to the Freeze response. We know from the animal world, that for example the grouse lies still and lowers its heart rate when confronted with a threat. People may react differently. Some are action-oriented, seeking a way out and take active action. Others get a freeze response and become passive. In terms of evolution, it may make sense for the survival of the species that a proportion reacts differently. The freeze response can make people choose to stay in the car. That does not mean they are not afraid. Nevertheless, they remain in the car, some tearfully saying goodbye to their next of kin.

3. **The fear control theory**: This theory suggests that people's behaviour in a tunnel fire may be influenced by their level of fear and anxiety. People who are highly fearful may be more likely to panic and behave irrationally, while those who are less fearful may be more likely to follow evacuation procedures [7]. The common notion of panic is a person who tries to run away from immediate danger. This hurried response implies some element of intensity in response to a hazard. This emotion has been defined as an extreme response to stress that prepares your body to fight or to flee. It also limits intellectual capabilities to increase the chances of survival. This is why in many cases it is virtually impossible to communicate with people who are in a state of panic. Panic is a response to considerable stress and fear caused by an external threat that could harm or kill you. This response impairs the quality of people’s decisions, and in some cases renders them completely unable to act. The latter phenomena often referred to as a freeze response. The freeze phenomenon raises the question of whether training and information can provide greater security and more rational behavior desired because the tunnel safety campaign or training has provided recognizable scripts for self-rescue behavior. We have indication that it may be effective from some real tunnel fires.

4. **The cue-utilization theory**: This theory suggests that people's behaviour in a tunnel fire may be influenced by the cues and information available to them. If people have clear and accurate information about the location of exits and the safest evacuation routes, they are more likely to follow them. The theory of affordances coined by James J. Gibson, the founder of ecological psychology, has been influenced by the cue-utilization theory. Gibson introduced a radical empiricist approach to perception and action centered on direct perception in naturalistic environments that was counter to popular representational views of his time [8,9]. This direct perception approach and the associated introduction of the affordance concept have been extremely influential in several fields of study [10]. According to the theory of affordances the quality or property of an object defines its use or makes clear how it can or should be used. We sit or stand on a chair because those affordances are fairly
obvious. Research has been aimed at understanding how visual perception is linked to action. In the years after Gibson introduced the theory of affordances there is widespread evidence that perception and action are linked with one another which may open for behavioral change. In an emergency exit situation, affordances to comfort and reassure users that they are safe or going in the right direction becomes important. Affordances that reduce the number of action choices are equally important.

Emotional affordances represent a recently introduced concept which model all the mechanisms used to collect/transmit emotional meaning in the context of human interaction with technology. Emotional affordances may play a part in our tendency to follow others, especially those who belong to our own group or express some authority. This implies that affordances of fear and trust may play an important role in decisions to act. The theory has been used to design tunnel emergency exit systems [11,12]. According to the cue utilization theory tunnel design and technology can support correct behaviour in tunnel fires (see Figure 1). Warning signs, signals and in-vehicle information can make road users understand the nature of the hazard and make the right actions. For example act as decisions support to stop outside a tunnel with red blinking stoplights or decisions to leave your vehicle and search for an emergency exit or evacuation room. Technology and emergency exit signs and systems inside the tunnel can support and speed up correct wayfinding. Without any technology or tunnel design support the lack of cues (affordances) to support behaviour, may lead people to walk in the wrong direction (towards the fire). Typically people who leave their car follow the center line markings until invisible in the black smoke, then they find a wall and follow this searching for a way out. Emergency signs and systems support human decision making in subtle and overt ways. In thick smoke, sensory redundancy is necessary through visual, acoustic and/or tactile emergency exit support systems. For example by in-vehicle information, continuous emergency lighting, loudspeakers above emergency exits and evacuation rooms, language neutral and psychoactive acoustic wayfinding systems with directional sound. Tactile input can be used on handrails making it smooth when you slide your hand along in one direction and rough/uncomfortable if you use it in the wrong direction.

5. The cognitive-affective theory: This theory suggests that people's behaviour in a tunnel fire may be influenced by both cognitive (thinking) and affective (emotional) factors. For instance, people may be influenced by their previous experiences, their beliefs about the likelihood and severity of the fire, and their emotional reactions to the situation. This theory is closely linked to the theory of naturalistic decision making (NDM) [13]. There are two main elements that characterize NDM, situational assessment and mental simulation, both of which are given by the context (surroundings) and linked to the person's experiences and competence. A main model within NDM is the so-called recognition model, Recognition-Primed Decision (RPD) [14]. The model has been developed from several different crisis situations such as forest fires, fires in buildings, military operations, critical health assessments [14].

6. Neuroscience: Recent development within neuroscience shows the amygdala is a key brain structure involved in awareness and alertness. Several studies have examined the role of the amygdala in detecting smoke and fire. For example, a study using functional MRI (fMRI) show that the amygdala is activated when individuals are exposed to smoke and other aversive stimuli. Another study found that individuals with damage to the amygdala were less sensitive to the emotional impact of a simulated fire alarm. [15,16,17]. The amygdala is very sensitive to smell and can thus be characterised as the human equivalent to the smoke alarm we use in buildings. It is part of the neurological system for action control, alerting, alarming survival and coping. The system is linked to release of the neurotransmitters Adrenaline, Noradrenaline and Dopamine, which gives quick release of energy one needs in an emergency situation. Too much activation on the other hand activates the release of the neurotransmitter Cortisol a well-known stress marker in humans. Overactivation and stress can manifest in uneasiness, worry, uncertainty, discomfort and in more severe cases in fear, anger, aggression, and anxiety. Stress also causes our navigation grid cells to shut down and the cognitive map of the surroundings (e.g. tunnel) is strongly impaired. The consequential disorientation and prediction errors may lead people to walk toward the fire instead of away as intended, or unable to sense if they are walking up hill or down. Work on the human navigation system was awarded with the Nobel prize in psychology and medicine [18,19].
These theories can provide a framework for understanding human behaviour in tunnel fires and developing effective fire safety measures. By considering the social, psychological, and environmental factors that influence human behaviour, it is possible to develop strategies to improve evacuation procedures, communication systems, and other fire safety measures. Table 1 shows a list of theories and related evidence of human behaviour in the recent tunnel fires in the Oslofjord and the Gudvanga tunnels.

Table 1  Theories of human behaviour in tunnel fires related to support of predicted behaviour in real tunnel fires.

<table>
<thead>
<tr>
<th>Theories</th>
<th>Evidence from human behaviour in the Gudvanga fire</th>
<th>Evidence from human behaviour in the Oslofjord fire</th>
<th>Support of the theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The social identity theory</td>
<td>People acted as others in their group (family, co-travellers)</td>
<td>People from different groups sought shelter in phone booths</td>
<td>Yes</td>
</tr>
<tr>
<td>2. The self-preservation theory</td>
<td>People helped each other across nationality end group. The only person who managed to drive out after they were trapped in smoke, picked up two groups of evacuees</td>
<td>Some people entered were invited in other vehicles occupied by strangers to them. One car who managed to turn around and drive out in the smoke, picked up 5 evacuees on the way out</td>
<td>No</td>
</tr>
<tr>
<td>3. The fear control theory</td>
<td>Episodes of irrational behaviour and panic documented. Those who stayed in their car or bus (freeze response) feared for their life. Some even lost control of their bodily functions (bladder control)</td>
<td>Some stayed in their car until rescued by the fire brigade. This may have been due to panic related freeze response</td>
<td>Yes</td>
</tr>
<tr>
<td>4. The cue-utilization theory</td>
<td>Documented people search for cues in an early phase. Some visual cues and acoustic cues (shouting, crackling) were used; others were not e.g., cars blinking their lights, because they did not understand the significance. The emergency lighting fixtures with 25-30 m spacing had no wayfinding effect in zero visibility</td>
<td>Documented people looked for any possible shelter. Door handles was one such tangible cue. Acoustic cues to the nature and severity of the situation were given in the form of Information to road-users (radio information). The emergency lighting fixtures with 25-30 m spacing had no wayfinding effect as visibility was close to zero</td>
<td>Yes</td>
</tr>
</tbody>
</table>
5. The cognitive-affective theory and the theory of naturalistic decision making

<table>
<thead>
<tr>
<th>The road-users had very little knowledge about tunnel fires and how to react in the situation. Their situation awareness was only aided by cues / information over their in-car radio and cues from fellow road-users at the site. Their behaviour was socially conditioned, and they became focused on fleeing from the fire with the goal to search for tenable spots. A critical decisions that contributed to the positive outcome (no fatalities).</th>
</tr>
</thead>
</table>

6. Neuroscience

<table>
<thead>
<tr>
<th>Smell could have alarmed people, but the natural ventilation drove the smoke away from people in the first phase of the fire. Evidence to a shutdown of the human navigation grid present. Several road users had a clear plan to walk away from the fire, but as they left their car and walked around it they lost sense of direction and walked towards the fire, only to turn when met by increasing heat.</th>
</tr>
</thead>
</table>

RESPECT FOR TUNNEL CLOSURE

Avoiding secondary accidents in tunnel fires pose a specific challenge. The number of injuries may escalate if drivers continue to enter a tunnel fire past red blinking stoplight. It is a phenomenon not restricted to road tunnels. A recent analysis of media coverage and scientific literature on driving against a red blinking stoplight [20], related to road tunnels, bridges, railway crossings and closed roads due to avalanches, rock or mudslides, - indicates several plausible causes of this type of infringement. Among other, that failure to stop for red blinking stoplights are due to:

1. Lack of respect (deliberate transgression);
2. Lack of knowledge and misunderstandings. Does not know the meaning of the signal nor the risk of violation. Can be attributed to a lack of information about the reason for closure (fire, accident, etc.);
3. Lack of respect for closure (wolf-wolf type);
4. Long waiting time (length and frequency of closure);
5. Rushing, speeding;
6. Technical error, (rail crossing);
7. Faulty Road design (no speed reduction by design, visibility of closure or signal);
8. Low detection risk (absence of speed cameras, video surveillance and visible police);
9. Lack of advance notice and repetition of notice, and;
10. Ordinary traffic lights (headlights -1080) are easier to understand and obey.

The study concludes that driving against red stop blinking stoplights occurs frequently. The search in the media yielded 30 hits in the period 2011-2021, with most articles from the last three years. This may be related to the media's routines for archiving and how long cases are available for online search. There are also requirements for news value and a relatively high threshold for mentioning such cases. There is probably a significant under-reporting of driving against a red stop light based on coverage in the media alone. Traffic control center (VTS) operators in Norway estimate that 20% of road users drive against a red blinking stop light. However, VTS currently does not keep a systematic log of such incident. The Norwegian police (Kripos) register for 2020, shows that 700 fines were issued under code 02A Driving in violation of fixed/flashing red light signal [20]. We must assume the number of violations is even larger since a number of road users drive against a red blinking stop
light without being detected and prosecuted by the police. This means that the scope of such infringements are, in reality, far more extensive than around 700 cases a year in Norway.

**SELF-RESCUE**

The self-rescue principle is the basic principle for evacuating road tunnels in the event of a fire. The Tunnel Safety Regulations stipulate that escape routes and emergency exits must be adapted to road users both on foot and with their own vehicle [21]. However, the fire service is expected to respond when it is professionally acceptable based on a safety considerations and on the basis of agreed emergency preparedness arrangements adapted to the individual tunnel. The self-rescue principle is not specific to road tunnels, and it generally applies in connection with evacuation from objects (buildings etc.) in fire. The 2020 edition of the Norwegian Public Roads Administration's N500 road standard describes that evacuation of tunnels is carried out according to the self-rescue principle.

**Evacuation rooms as part of assisted rescue in road tunnels**

In the wake of the 7 serious tunnel Norwegian tunnel fires, the AIBN, the Road Safety Authority and the Office of the Auditor General have all pointed out that the self-rescue principle that governs rescue efforts in the event of a fire or other serious incident in road tunnels does not work fully in practice.[19].In principle, this challenge can be mitigated in three different ways:

1. By creating better conditions for road users to be able to get out on their own, either by driving out or by going out;
2. That the emergency services assist road users through rescue to get out when the road users themselves cannot escape;
3. That in the tunnel there is a possibility of rescue through cross-connection to the opposite tunnel where this is relevant or by offering rooms for temporary stay (evacuation rooms).

Point 1 applies generally in all tunnels regardless of whether points 2 and 3 apply or not. In any case, it is important that road user find the fastest way out of the tunnel, possibly to the escape door/evacuation room. Access to evacuation rooms in long and/or steep one-lane tunnels in the event of a serious incident can be crucial as a temporary rescue stay before being rescued by the emergency services or that the individual is able to go out himself. This may also be the case in tunnels where there may be queues of vehicles so that self-rescue when driving out with your own vehicle is not applicable.

SINTEF on behalf of the NPRA has conducted a series of research projects on self-rescue:

1. A literature survey on self-rescue
2. A study of wayfinding to rescue rooms
3. A study user acceptance and behaviour in evacuation rooms
4. A study of an acoustic language neutral psychoactive emergency exit system.

Studies 2 and 3 are presented at this ISTSS conference this year and will only be summarized briefly here. Study 4 is published in the journal Fire Safety [22].

**LITERATURE SURVEY ON SELF-RESCUE**

Recent literature reviews show that the main problem people experience with staying in rooms below ground level is a sense of danger and of being trapped. With long stays underground, problems are experienced in relation to isolation and monotony. There are studies whose duration can be several months, and they are therefore not representative of shorter stays (i.e. up to 3-4 hours). Knowledge of what creates unwanted feelings may nevertheless be important. The design aspect that people mention can give indication of what may play a role also for shorter stays. Feelings of isolation and monotony are linked to a lack of window, obvious way out, limited visibility and visibility to the outside world. Concern about fire and water leaking in or that the cavern will collapse is also frequently mentioned as a concern [23]. Rooms below ground level are also more easily perceived as cramped and
Oppressive, even during shorter stays of time. Visible pipes and the smell of mould and dust can contribute greatly to a negative basement feeling [23].

Simulator studies of rock cavern extensions in tunnels show that they provide a positive experience for all road users and not least those with fear/anxiety about tunnels. Such extensions reduce monotony, create identity, and at the same time increase security. Not only real extensions, but lighting (e.g. blue light window in ceiling - view out to sky in the open) can contribute to the illusion of increased sense of space far beyond the real expansion in width and height [24,25,26]. There are examples of the successful use of illusions from underground military facilities where curtains in front of a window frame are enough to create peace of mind by the illusion that there is a window behind and a way out, even if it is 40 m underground and only rock wall or concrete behind the curtain. A bright room creates the illusion of a tunnel opening/outdoor experience. In addition, feelings of monotony are associated with a lack of visual variation and being able to see green plants and trees. Problems with staying in rooms below ground level can, in the worst case, lead to anxiety, stress, fatigue, poor judgment or aggression.

How people react to stays in underground rooms is both individual and influenced by socio-psychological conditions. An emergency where people who do not know each other are crowded together and have to share a limited area can be very challenging: It can be people of different age groups, genders and nationalities. Some may have burns, shortness of breath or have physical injuries of another nature. Measures that can counteract unfortunate aspects of such stays in underground rooms will then be even more important. Important design aspects that through research have been shown to affect safety and perceived comfort when staying in underground spaces are the design of: a) Entry zone, b) perceived ceiling height, c) lighting, d) air flow and e) thermal comfort f) perceived threat g) perceived control and g) Communication with the outside world [27,28,29].

![Figure 2. Key factors in design of underground spaces. Adapted from [28,29].](image-url)
In a controlled full-scale Virtual Reality (VR) study, it is possible to study the effect of such design parameters. It is known that evacuation rooms have been used to compensate for escape routes to the open air. In one case with major consequences when the room was not designed to withstand great heat. This was demonstrated in connection with the fire in Mt Blanc in 1999, where two people died in the rescue chamber. This indicates that strict requirements should be set for both the physical and cognitive and emotional environment in the evacuation room if it is to be used successfully. There is research that shows the advantages of evacuation rooms in other contexts, for example in connection with the construction of tunnels, rescue containers that are mobile [30]. The perceived environment of people in tunnels has only been investigated to a limited extent. One such study [31] shows that lighting and colouring are important. This study was also carried out with VR as an experimental methodology, but in an older technique called "CAVE" and not with a head-mounted display (HDM) that provides a significantly improved sense of presence in the situation. Results from experiments with VR technology are therefore consistent with previously referenced experiments, which reinforces the validity of results performed with VR.

The literature review includes experiences with the use of evacuation rooms in road tunnels, railways, metro, the construction phase of tunnels and underground facilities, the mining industry, and comparable businesses where the road out or to safe area is long, such as in offshore oil installations and tall buildings. Experience and knowledge are mainly based on knowledge from actual events, full-scale experiments or simulations. In the wake of several major fires in Norwegian long and subsea single tube tunnels, the AIBN, the Road Safety Authority and the Office of the Auditor General have called for measures that can increase safety and facilitate effective self-rescue to a safe place. Safe areas are rescue options that allow evacuees to find protection until an emergency is over or rescue services can evacuate them. This type of safe area is mainly used in mines and on underground construction sites, in the construction phase of tunnels, and in finished underground facilities as a supplement to self-rescue. Strategies on the use of safe areas in tall buildings, and in the form of rescue capsules offshore, have gradually also gained a good foothold.

Requirements and guidelines may vary from country to country and evacuation rooms can either have fixed locations or be a mobile evacuation room. As mentioned, evacuation rooms are not permitted in Norwegian road tunnels in accordance with the Tunnel Safety Regulations. This is in line with EU guidelines for safety in tunnels, which also do not allow the use of evacuation rooms. There are primarily two reasons why evacuation rooms are not allowed in the EU and in the Norwegian regulations and these are based on the evaluation of the Mont Blanc fire: 1) Road users cannot find evacuation rooms on their own, 2) Unsafely designed evacuation rooms.

Two road users died in an evacuation room during the 1999 Mont Blanc tunnel fire and according to the report of follow-up investigations, road users will not seek emergency exits or evacuation rooms unless accompanied by personnel. The reason why two road users died was that the evacuation rooms were not dimensioned for the real fire load they were exposed to, but a much smaller fire with a duration of 2 h and temperatures only up to 800 °C. Instead of adjusting the requirements for evacuation rooms, a ban on their use was introduced. However, the literature search for the present report shows that many people saved their lives in the Mont Blanc tunnel using evacuation rooms further away from the fire. All of them, including the two who perished, found evacuation rooms. Norwegian tunnel fires show that road users escaping on foot grope their way along the tunnel wall and search into rooms they find. Two people probably found and saved their lives using evacuation rooms in the event of a fire in the Oslofjord tunnel in May 2017. One of the two had walked 87 m when he found the room and told in post fire interviews that out of exhaustion, he could not have gone any further. Neither in the Mont Blanc tunnel nor in the Oslofjord tunnel were people accompanied to evacuation rooms by personnel, which contradicts the conclusions drawn in the aftermath of the Mont Blanc tunnel fire. The challenge seems greater in getting people to understand the seriousness and leave the car than in searching for a safe place once they are out of the car. In 2019, the Norwegian Public Roads Administration conducted a study on "safe behaviour in the event of incidents in road tunnels". This study became the basis for an information campaign on social media in the autumn of 2019.
In the Oslofjord tunnel, 26 evacuation rooms were furnished as a temporary arrangement after the fire in 2011. The exemption from the regulations applies until a new tunnel has been built and accepted by the EU. However, providing support for the design of good guidance systems that also work in dense smoke is important so that people reach a safe place as quickly as possible, without necessarily finding their way all the way out. Both professional firefighters and ordinary road users easily lose their sense of direction and sense of whether they go up or down in a stressful situation, as documented through interviews with road users and rescue crews who were caught in the smoke during a fire in both the Oslofjord tunnel 2011 and Gudvanga tunnel 2013. The literature indicates that messages via various information channels, radio, mobile phone, signs, dynamic guiding lights, well-marked doors can be a good support for self-rescue. Nevertheless, it may not be sufficient in dense smoke. When visual evidence is difficult to find in the smoke, audible messages in the car, tunnel room, and acoustic call signs that direct road users to emergency exits and evacuation rooms can be a good supplement.

Road users in the Gudvanga Tunnel stumbled and groped their way through a gravelly ditch against the tunnel wall and could barely see a length of hand in front of them. In such a situation, it is important that the tunnel floor is level and easy to walk on, that there are no signs and other installations at head height that they can injure themselves on and a handrail that they can rely on, a tactile guideline towards a safe place. Such combinations of measures that take into account that we can orient ourselves with the help of multiple senses have not yet been fully tested for use in exposed Norwegian one-lane road tunnels, in support of self-rescue. It provides the basis for the design of more optimal guide system and entrance doors and evacuation rooms. The important role evacuation rooms can play in self-rescue in emergency situations has been documented in the mining industry and in the construction phase of tunnels where 22 people around the world have saved their lives in the period 2007-2017 using evacuation rooms. [32,33] The location of evacuation rooms, number and capacity must be dimensioned for the individual tunnel based on identified risk scenarios and traffic. Using existing models for evacuation can be highly misleading. According to experts, they are out of date and not suitable for use in exposed Norwegian one-bore tunnels. Among other things, they do not take into account the walking speed in smoke, the degree of elevation or the possible toxicity of the smoke. How toxic the smoke is can affect when incapacitation occurs. Experience from the fire in the Oslofjord tunnel, May 2017, shows that evacuation rooms can also have an important function for the firefighters’ efforts. Both for communication in a noise-free environment providing emergency network coverage, and gain new strength and with opportunities to refill your own oxygen cylinders without venturing out of the tunnel completely.

STUDY OF WAYFINDING TO RESCUE ROOMS

Tunnel emergencies due to collisions, fires, hazardous liquids, volatile gases, or terrorist activities can be particularly challenging when they occur in long and/or underwater tunnels. The closed environment in the tunnel can concentrate heat, smoke or other toxic gases as a result of events. In narrow single tube tunnels a partially blocked lane or fire can trap vehicles and prevent access for rescuers. Response time for rescue services in Norway may be quite long (30 min) in rural areas due to distance an part time work status of fire fighters. In dense smoke, it is difficult to turn in a tunnel. Vehicles collide with the tunnel wall, with each other or other objects. As a result, evacuation on foot towards exits, emergency exits, evacuation rooms or other safe areas is often the only option. If self-rescue is to work and road users have a real chance of carrying out evacuations in smoky environments on their own, the tunnel must be designed and equipped with technical installations that will aid and support to road users in an emergency. Examples of measures that will strengthen the ability to self-rescue are the use of automatic detection of incidents to ensure the detection of fire early in the course and the use of continous escape lights along the tunnel wall. Use of voice messages in-vehicle over the radio channels combined with loudspeakers in the tunnel can ensure that road users receive early warning of incidents and dangers, as well as start evacuation.

Serious incidents that challenge the self-rescue principle are primarily incidents with a high fire heat release rate and strong smoke development. In tunnels, the smoke will eventually cover the entire
tunnel section and move gradually in the direction of migration. Most Norwegian tunnels have natural draft or longitudinal ventilation. This means that the smoke remains in the tunnel or gradually pulls towards a portal in line with the speed of ventilation implemented. If the fire ventilation is set to 3 m/s, road users downstream of the fire will quickly be overtaken by the smoke front. Incidents that mainly involve heavier vehicles in long tunnels are most demanding. Fires in passenger cars or in shorter road tunnels challenge the principle to a lesser extent than fires in heavier vehicles in road tunnels with a longer distance for evacuation. A sharp rise can complicate evacuation and therefore affects the possibility of self-rescue. It is important to consider experiences from real events. Safety work has historically placed more emphasis on how road users should behave (normatively) than how road users actually behave in the event of incidents in tunnels. Emphasis on what road users actually consider doing and actual behaviour in the event of incidents can reveal the design prerequisites for the location, and warning of road users, whether it is driving out or finding their way to the nearest emergency exit, evacuation room or portal.

The regulations relating to minimum safety requirements for certain road tunnels (Tunnel Safety Regulations 2007) Annex I, 1.1.1., states that: "Safety measures to be implemented in a tunnel shall be based on a systematic assessment of all aspects of the system constituted by infrastructure, use, road users and vehicles". This means that measures must be assessed based on what road users actually assess and do in different phases of an incident and not just what they should do. Safety equipment should make it easier to evacuate in a smoky tunnel and lead road users to the desired behaviour. How the tunnel is designed and equipped can affect the real possibility of self-rescue. Orientation on distances, ventilation, signage and various guidance systems can be crucial, whether it is driving out, evacuating on foot, or finding your way to the nearest emergency exit, evacuation room or portal.

Simulation in VR to find door to evacuation room

The project, which was carried out by SINTEF Mobility in Trondheim in collaboration with the University of Lund, Sweden, involves a simulation of evacuation in a road tunnel and the main purpose of the simulation was to document that safety in the tunnel is ensured by road users finding evacuation rooms without access to the open air. A full-scale laboratory simulation has been carried out with walking platforms in combination with Virtual Reality (VR) and 3D modelling of the reality of an evacuation situation in a long and steep underwater smoke-filled road tunnel, in this case the Oslofjord tunnel. Six different scenarios were tested where lighting and acoustics measures varied, and two scenarios had evacuation rooms on both sides of the tunnel.

There is quite a lot of research on human movement and walking speed at events, but this research is not specifically aimed at tunnels. Important aspects in this case are, the distance to the evacuation room from a given place in the tunnel, for example, whether the doorway to the evacuation room is wide enough and without stairs and thresholds that can prevent users of wheelchairs. Wheelchair users may have difficulty moving through the doorway if the surface is not perfectly even. There are not only thresholds that can prevent people with disabilities, but also climbing conditions in the tunnel and between the tunnel and escape routes. Such aspects of accessibility are essential for safe self-rescue for everyone, but sometimes they are forgotten. To avoid unnecessary obstruction, doors should be easy to open and the opening mechanism should be easy to understand. Even in this case, the design should be based on what is normal in other contexts, i.e. a common normal door pressure and door handle are preferred over more sophisticated solutions. The door handle or door opener mechanism itself should be designed in a material that does not heat up by fire. During a fire in the Oslofjord tunnel (May 2017), where two truck drivers used an evacuation room, the one who opened the door suffered significant burns to his hands. They probably would not have survived without the use of evacuation rooms. With a walking speed of 1.2 m/s (current guidelines) and 100 MW of fire, a road user walks 15–60 m before incapacitation (occurs after 1–5 minutes). How toxic the smoke is may also affect when incapacity occurs. In reality, road users grope their way along the tunnel wall at a speed as low as 0.2 m/s as documented for those who walked in the smoke plug during the fire in the Gudvanga tunnel 2013. If the average walking speed is increased to 1.4 m/s, an increased proportion of road users will be able to reach evacuation rooms before incapacitated. The Oslofjord
tunnel also has a longer stretch with a 7% incline, which can make escape challenging. On this basis, the establishment of evacuation rooms every 250 m is to be regarded as a natural starting point.

**STUDY OF USER ACCEPTANCE AND BEHAVIOUR IN EVACUATION ROOMS**

Simulation in VR of design criteria for the design and furnishing of an evacuation room is needed for obtaining the clearest possible documentation of a sense of security associated with staying in such evacuation rooms. The following requirement specifications were entered for the content of the simulation: 1) Explore the extent to which people staying in evacuation rooms feel safe, and whether they feel that their safety is adequately safeguarded based on the design and furnishings of the room; 2) Which parts of the décor/equipment in the room affect the feeling of security the most/least? 3) How do they relate to other road users who are injured/need care and safety?

The design should consider physical, functional, and psychological conditions that can be linked to perceived safety and security in the room. Which parts of the furnishings/equipment affect the feeling of security the most/least were mapped. Behaviour and social psychological conditions related to how they relate to other road users in the room who are injured/need care and safety were recorded and documented. The extent to which safety and security when using evacuation rooms without access to the open in tunnels is satisfactory with the given design criteria was studied through the use of full-scale laboratory simulation with walking platform in combination with virtual reality (VR) and a 3D model of a Norwegian road tunnel, in this case the Oslofjord tunnel. Emphasis was placed on realistic rendering of the surroundings, correct depth perception, realistic walking speed, as well as great flexibility in the basic 3D model for use in VR with regard to the design of scenarios and experimental parameters. Head Mounted Display (HMD) with built-in eye-tracker was used to document what people focused on for how long and how often.

Two types of evacuation rooms (caverns and containers) and five different variants of these were tested. All the simulated evacuation rooms were designed for 50 people, had a lock with a door to the room and a door back to the tunnel. The report from the simulation is based on a full-scale Virtual Reality (VR) study in an ISO certified climate laboratory at SINTEF Health Research (Work Physiology Laboratory). This is a laboratory where it is possible to have full control over humidity and temperature. The study was conducted in the climate laboratory based on the calculation of temperature and humidity before 50 people enter (18 °C), ventilation (capacity - amount, replacement), material and type of insulation in the walls and clothing. Each road user will produce 75 W and the temperature will after an hour pass 32 °C and the humidity will rise to 70% in an evacuation room with minimal ventilation. If people had been replaced with a heater of 3750 W, the temperature would quickly exceed 50 °C. In addition, the climate laboratory has natural fan noise of 90 dB. This makes longer stays uncomfortable even in terms of noise. In this sense, perceived safety in evacuation rooms has been tested under the worst possible conditions.

The purpose of this VR study was to obtain reliable research-based knowledge about behaviour and perceived safety during stays in evacuation rooms as a function of design criteria. The design criteria are the result of a literature review conducted by SINTEF, the result of a feasibility study (focus group) and input and discussions with an expert group from the project owner, the Norwegian Public Roads Administration.

**CONCLUSION AND RECOMMENDATIONS**

Learning from real tunnel fires can provide valuable insights into how humans behave during such emergencies and help to improve fire safety measures in the future. Some examples of lessons learned from real tunnel fires include:

1. Rapid detection of fire: Early detection of fires and a quick response from emergency services can make a significant difference in the outcome of a tunnel fire. Effective detection and response systems, including automatic fire alarms and sprinkler systems, can help to minimize damage and reduce the risk of injury or death.
2. Precise information about fire object: if possible (type of cargo, position)
3. Position and number of vehicles and people in tunnel: Smoke and toxic gases can quickly build up in tunnels during a fire, which can hinder evacuation efforts and make it difficult for emergency responders to access the site. Proper ventilation systems can help to remove smoke and fumes from the tunnel, improving visibility and air quality.
4. Clear and precise information to road users: a) what is happening, b) what should you do.
   This applies to emergency tunnel fire situations, before entering (closed tunnel, in queue (no visual contact with fire), or on foot searching for a way out.

The above mentioned information, items 2 and 3, are needed to avoid fire ventilation trapping the majority of road users in thick black smoke. Tunnel fire safety information campaigns, training and drills can help to ensure that everyone knows what to do in the event of a fire, reducing panic and confusion. This can help to improve response times and increase the chances of a successful evacuation.

By learning from real tunnel fires and incorporating these lessons into fire safety protocols, it is possible to minimise the risks associated with tunnel fires and ensure the safety of everyone involved. Overall, our studies show that road users are able to find evacuation rooms in a smoky tunnel environment, feel safe when staying in such evacuation rooms and accept to stay there in high temperature and humidity provided the right design and equipment. Theories on human behaviour in road tunnel fires are to a large extent verified, except that evidence from real tunnel fires show people are much more altruistic and helpful than to be expected based on the self-preservation theory.

The VR simulations have also shown that people follow the instructions from the Road Traffic Control Centre (VTS) and find first aid even in poor light. Perceived safety is highest in evacuation room design with good lighting and an illusion of blue sky and extra ceiling height in critical situations.

Evacuation rooms are well-known technology used in other high-risk sectors, such as the petrochemical industry and the oil and gas industry, which have accident scenarios at least as serious as tunnels. On the basis of the studies reported here, we will recommend, based on tunnel and safety criteria, the EU (ESA) approval to be able to use evacuation rooms without access to the open air in long low traffic single tube road tunnels in Norway for temporary residence as part of assisted rescue. This should include requirements for the design of evacuation rooms, e.g. on what they should endure and for how long time, wayfinding systems to rooms, spacing between rooms, capacity of rooms, communication systems, first aid available etc.

REFERENCES

1. AIBN-Accident Investigation Board Norway (2015) Report on fire in a heavy goods vehicle in the gudvanga tunnel on the e16 road in aurland on 5 august 2013. accident investigation board norway (aibn), road 2015/02


21. Samferdselsdepartementet - Forskrift om minimum sikkerhetskrav til visse vegg tunneler (tunnelsikkerhetsforskriften), 2007-05-15


32. Corbee J. (2016) A study of underground rescue chambers as alternative to several egress paths. Report 5512, Brandteknik Lund University, Sweden

The use of Natural Gas Vehicles in underground facilities: Application to the PARIS-LA-DÉFENSE underground network

Benjamin Truchot¹, Christophe Willman² & Patrick Personna³
¹Ineris, Verneuil en Halatte, France
²CETU, Bron, France
³PARIS LA DEFENSE, Paris La Défense, France

ABSTRACT

Considering the current strong development of natural gas vehicles and their use in many underground infrastructures, this paper focuses on the corresponding risk induced in such situations. It consists in applying the analysis of the consequences of the huge and complex underground network of the La Défense business center, in the suburbs of Paris. The different types of natural gas vehicles were considered, compressed natural gas (CNG) and liquefied natural gas vehicles (LNG). Based on existing knowledge in risk analysis, the main dangerous phenomena that can occur for those vehicles, jet fire, vapor cloud explosion, and tank burst, were all considered and modeled for each technology. To evaluate the release source term, the very beginning for both jet fire and flammable cloud characterization, the classic gas release model was used while considering the pressure decrease in the tank to get the mass release time variation. This was mainly interested in estimating the resulting jet fire heat release rate and duration and the corresponding impact on the global heat release curve. As far as vapor cloud explosion (VCE) is concerned, the worst-case situation, more precisely the largest flammable mass is obtained in the first seconds following the release beginning. The specificity for VCE represents the tunnel confinement’s influence on the pressure wave propagation. In such an environment, the commonly used multi-energy approach, based on semi-spherical wave propagation is inappropriate, reflexion phenomena should be introduced to provide a better prediction. The consequence modeling shows that, for both technologies, the worst dangerous phenomena remain the tank burst, especially for LNG where the lethal effect may affect most of the people present in the tunnel, for CNG lethal effect should reach 30 m and more for the same tank burst scenario. This huge consequence highlights the importance of preventing its occurrence through the efficiency of dedicated safety measures but also fire prevention since such a tank burst is induced by a fire in the surrounding of the tank. For the jet fire case, the consequences are a global vehicle heat release rate increase, during the gas release, while this could influence the efficiency of the tunnel ventilation, this does not significantly modify the thermal consequences for people. Regarding the vapor cloud explosion, lethal overpressure would affect passengers of the few closest vehicles for LNG and users in an area of 4 to 20 m centered on the vehicle for CNG.

KEYWORD: natural gas for vehicle, jet fire, vapor cloud explosion, tank burst

INTRODUCTION

According to the current global warming, new energy carrier vehicles are currently under strong development. While electric vehicles represent a large proportion of clean vehicles, natural gas vehicles present some advantages since they could provide a larger range and faster charging. They are consequently used to improve public transport solutions in many cities worldwide. In the specific case of Paris, natural gas vehicles represent a significant proportion of clean vehicles to be used in the coming years. Consequently, the safety aspect due to those vehicles should be addressed and,
considering underground facilities could increase the consequences of each accidental situation, those facilities represent a key issue for that new energy carrier development. One of the most complex underground networks near Paris is the La Defense business center, evaluating the influence of using such natural gas vehicles in such an environment is then a challenge. The present paper summarises the evaluation that was achieved. While the key issue concerns bus circulation, the different types of vehicles were considered, by the specific characteristics of all tunnels.

After presenting the natural gas vehicle characteristics, in terms of gas quantity, safety system, and proportion on the road, and the main characteristics of the tunnels in the La Defense center, this paper focuses on risk evaluation. Regarding this evaluation, for each technology, compressed natural gas, and liquified natural gas, the release mass flow rate computation is first detailed since its importance for jet fire and vapor cloud explosion. Those two last phenomena are then characterized using an algebraic approach, integral model, and specific tools, mainly for wave propagation since free field wave propagation correlation cannot be used in such a confined environment. The tank burst consequences are then evaluated, taking into account, once more, the influence of confinement on those consequences.

VEHICLES AND INFRASTRUCTURES CHARACTERISTICS

Natural gas vehicles

Natural gas as an energy carrier for vehicles evolve quickly, then the first step to evaluate potential accident consists in identifying and determining key characteristics of natural gas vehicles. First, the two fuel storage possible conditions should be distinguished, the most commonly used solution nowadays remains compressed natural gas (CNG) but liquified natural gas (LNG) is under development for long-distance applications, typically for trucks or buses. In CNG vehicles, natural gas is stored in gaseous form compressed to 200 bar while LNG vehicles use cryogenic tanks where the gas is cooled to -162°C at (or near) ambient pressure. According to the current market, CNG is considered for all types of vehicles, i.e., cars, trucks, and buses, while LNG is considered only for trucks and long distances buses.

The gas quantity in CNG vehicles is an important parameter that strongly varies. For cars, the gas quantity typically varies by a factor larger than two, between 8 kg in a Dacia Duster GNV to 19 kg in an Audi A4 G-Tron. When including light commercial vehicles, less than 3.5 t in this list, the mass of gas could reach 70 kg with the Piaggio NP6. For trucks and buses, the gas quantity is larger again, reaching up to 250 kg. Using LNG leads to doubling the natural gas mass in the tanks.

To provide first information about the probability of an accident involving natural gas vehicles, their proportion on the traffic should be considered. An analysis achieved in France [1] mentions that 27,000 natural gas vehicles were used in France in 2021 August the first, for a total number of vehicles of around 45 million, this means that natural gas vehicles, mainly CNG currently represent about 0.05%. The expected number of natural gas vehicles is 54,000 in 2028. This average proportion should however be used carefully since CNG is more used for infrequent vehicles, Figure 1, having in mind that cars represent 70% of the used vehicles. The proportion of natural gas light commercial vehicles is typically bout 0.15%, representing three times the average value. Furthermore, due to the clean public transport policy, natural gas buses are more and more used and may represent a significant proportion of buses in the coming years.
The La Défense underground network

The public institution "PARIS LA DEFENSE" manages the whole development of the business district of La Défense near Paris. Due to its design inherited from the 60s with a pedestrian slab, the district includes numerous underground infrastructures from quite classic tunnels to multipurpose underground structures. A map of the La Defense center is reproduced in Figure 2.

The tunnel characteristics vary between each in terms of dimensions, length varies typically for about 100 m to 800 m, in terms of traffic, between around 150 veh/j to more than 20 000 veh/j but also in terms of proportion of each type of vehicle with some tunnels dedicated to buses, some with numerous delivery zones, i.e., a large proportion of light commercial vehicle and trucks with few cars and some with a large majority of cars. Furthermore, the potential number of people that could be inside the tunnel in case of an accident having in mind that bus stops are in some tunnels.

**RISK ANALYSIS FOR CNG AND LNG VEHICLES**

Before going any further in risk evaluation, identifying dangerous phenomena for each natural gas technology is mandatory. This paragraph describes the identified phenomena for both CNG and LNG.
CNG vehicles
As mentioned earlier, CNG consists in using natural gas stored in a pressurized manner, around 200 bars. The main safety measure for this type of storage is a TPRD (Thermally Pressure Release Device) that consists of a venting line automatically opened, after a certain delay, when the surrounding temperature reaches 120°C. using, commonly, a eutectic metal. Specific risk analysis was proposed in the literature and shows that new dangerous phenomena should be considered when such vehicles are present [2][3].

The first event that should then be considered is a leak on the gas line that could be induced by either a breach on this line or an undesired opening of the venting line. Such an event would induce a pressurized gas release with either a jet fire, in case of immediate ignition or a vapor cloud explosion (VCE) in case of delayed ignition. In this second case, VCE, a jet fire can be formed after the explosion, but the associated flow rate will be reduced since a significant proportion of the gas would be involved in the explosion.

Another phenomenon to be considered is the tank burst that could result in a choc that reduces its mechanical resistance of it, or a surrounding temperature rise, i.e., a pressure rise in the tank, together with the venting line opening system failure.

LNG vehicles
The number of risk analysis studies is less numerous in the literature while previously mentioned papers provide some valuable information.

It should be first reminded that the safety system to prevent pressure rise in the tank differs from the CNG one, pressure valve is used for the LNG tank, which means that the physical quantity that triggers the safety system differs between the two systems. However, potential additional dangerous phenomena are quite similar. The first event to be considered is consequently an unexpected opening of the safety line that implies LNG release. Such a release may then imply a jet fire or a VCE depending on the ignition sequence. A burst of the tank remains also possible in case of tank heat exposure and safety valve(s) non-opening.

CONSEQUENCES MODELING FOR CNG VEHICLES

Evaluation of the mass flow rate
As discussed in the previous paragraph, for both CNG and LNG vehicles, jet fire, vapor cloud explosion, and tank burst were considered and modeled. For both jet fire and vapor cloud dispersion and explosion, the first step consists in determining the mass flow rate evolution and leak duration considering the evolution of the physical conditions in the tank. Then, based on this mass flow rate, jet fire consequences and explosive mass can be estimated.

The mass flow rate is estimated based on the tank pressure, the estimated release diameter, 2 or 4 mm, based on the Birch model [4]. To use such a model, it should be first evaluated whether the flow is choked or not:

\[
\frac{P_{\text{res}}}{P_{\text{amb}}} \geq \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma}{\gamma - 1}}
\]

Then the mass flow rate through the opening is computed:

\[
q_g = C_d \times A_b \times \psi \times \sqrt{\frac{P_g \times P_{\text{res}} \times \gamma}{\frac{2}{\gamma + 1}}}
\]

Where \(\psi\) is 1 is the flow is choked and, if the flow is not choked, is:

\[
\psi = \sqrt{\frac{2}{\gamma - 1} \times \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma}{\gamma - 1}} \times \left(\frac{P_g}{P_{\text{res}}}\right)^{\frac{1}{\gamma}} \times \left(1 - \frac{P_g}{P_{\text{res}}}\right)^{\frac{1}{\gamma}}}
\]

At each time step, the released mass is removed from the tank and the new resulting pressure inside the tank is estimated to get the mass flow rate evolution over time. An example of such mass flow rate evolution is reproduced hereafter in Figure 3.
Figure 3: Example of mass flow rate evolution, case of a 245 kg tank, release through a 4 mm diameter.

In this approach, the tank cooling effect that results from the leak is neglected, leading to a slightly overestimated flow rate after a certain amount of time. The source term for explosive cloud formation and jet fire is known.

Jet fire modeling
Jet fires should be considered in two aspects: the consequences of the jet fire itself and its influence on the global heat release rate (HRR), which could, for underground infrastructure, modify the ventilation design.

For cars and vehicles with downward-directed openings, regarding the consequences of the jet fire itself, an integral approach was developed. This approach is based on a representation of the jet fire by two horizontal flames assuming that the flow deviates when impinging the ground. Figure 3. The flame length is estimated by assuming that the mass flow rate is divided into two flames.

Figure 4: Schematic view of the jet fire simplified model.

Two configurations were modeled, with the same 200 bar pressure inside the tank, but two different diameters, 2 and 4 mm. Those two cases lead respectively to 116 and 465 g/s flow rate and flame length of 3.4 and 6.2 m. The associated flame length for such a case would be respectively 3.4 and 6.2 m, those values correspond to the safety distance.

On top of the jet fire itself, the influence of the gas release on the global vehicle fire should be considered. An example of such a modified curve is plotted hereafter in Figure 4.
While the evaluation of the impact of the jet fire on the HRR for ventilation design purposes is just a conversion of the mass flow rate in terms of HRR based on the heat of combustion, the specific consequences of the jet fire itself should be specifically addressed. This was done using both an adapted integral approach and a computational fluid dynamics model to consider the specific characteristics of the underground facilities, mainly the geometry.

**Vapor cloud explosion**

Considering the vapor cloud explosion, a dispersion model, coupled with experimental data, enables determining the flammable mass. Then, the multi-energy method [5] is used to determine the initial explosion pressure. Having in mind that the multi-energy curve corresponds to hemispheric wave propagation in an open environment, a semi-empirical wave propagation code was used to predict the overpressure distribution in the infrastructure.

To evaluate the flammable mass, the integral tool Phast [6] was used. The code enables computing the gas dispersion in a given airflow. The velocity profile was set to flat with a constant value along the tunnel height for this specific application. The source term in the code is represented by the tank itself, at a given pressure with a leak diameter, it includes a mass flow rate module that enables computing the leak characteristics based on the initial tank conditions that lead to the worst situation. This first step provides the flammable cloud characteristics including the gas concentration, Figure 5, and the flammable mass. The computed flammable mass for this 4 mm in-diameter case is about 20 g.

*Figure 5: Example of modified HRR curve for a light commercial vehicle with 70 kg of gas.*
This approach is then simplified and does not consider the possible jet impingement on the tunnel walls or ceiling. The resulting flammable mass would be strongly modified in such a case. Experimental data indicate that the multiplication factor between a free jet and impinging one would be between 2 and 10 [7]. Therefore, to take into account the possible jet impingement in this risk evaluation, 10 was chosen as the multiplication factor to cover all the situations including the worst one. The flammable mass for impinging the jet was then fixed to 10 times the free jet one, which means 200 g.

One of the key issues of the multi-energy model consists in determining the explosion level that gives the initial overpressure. To ensure representation of the worst possible situation, level 6 was considered for the multi-energy simulation, such a level implies an initial maximal overpressure of 500 mbar. Reminding that the multi-energy method is based on hemispheric flame propagation, a specific model, DIFREX, that includes wave reflection on structures was used. This model is based on the same propagation correlations but with considering reflection phenomena. An example of overpressure resulting from such a VCE is plotted in Figure 6.

Figure 6: Example of gas concentration in case of TPRD opening, flow velocity 1 m/s, 4 mm in-diameter, pressure 200 bar.

Figure 7: Overpressure in the tunnel, top view, for a 200 g of flammable mass explosion.
This modeling enables one to conclude that the significant lethal effects (200 mbar according to the French regulation), remain in the close vicinity of the vehicle, typically 4 m for the impinging situation. These distances are similar for all types of vehicles since the flammable mass is governed by the release diameter and the tank pressure which do not differ from one type of vehicle to another.

It should be noted that, given the unavoidable uncertainties of the modeling, the value evaluated in the CETU/INERIS study in the general case [3] is considered a high estimate (20 m). The tunnel length considered for significant lethal effects is therefore 4 to 20 m.

**Tank burst**

A similar approach is used to model the consequences of tank bursts. The initial pressure is given by the tank characteristics and the semi-empirical code enables evaluating the overpressure distribution in the tunnel. Given the potentially severe consequences of such an event, the delay before the tank burst is also estimated for a range of situations, based on available experimental data, and using thermodynamic analysis.

These simulations should be translated in terms of risk, considering the presence of people in each infrastructure. Then, an occurrence probability should be estimated considering the probability of the initial event, for example, the sudden opening of a thermally activated pressure release device, with or without ignition, and the estimated traffic data for natural gas vehicles.

A similar approach has been conducted for indirect risk, evaluating the potential consequence of a distant fire, modeled thanks to a classical CFD approach, on a natural gas vehicle. Then, when required, the specific consequences induced by the natural gas vehicle, such as a tank burst typically, were estimated with the same approach as for the direct risk.

**CONSEQUENCES MODELING FOR LNG VEHICLES**

**Jet fire**

For the LNG case, the main important data is that the pressure inside the tank is close to the atmospheric one, the product is maintained in the liquid phase thanks to the cooling, and the temperature is about -160°C. When considering a 4 mm in-diameter hole, the opening section of the pressure valve, and assuming a full liquid flow through this valve, the mass flow rate would be about 21 g/s, leading to a 1 MW fire. For a cryo-compressed tank, with a product stored at 10 bars and -120°C, the mass flow rate would increase to 33 g/s, which means a 1.5 MW jet fire. The jet fire itself does not have any specific consequences that differ from the vehicle fire.

The main difference with CNG which lead to quick emptying is the LNG tank emptying would take about 1 hour, meaning that the global heat release rate for the vehicle fire would be 1 to 1.5 MW increased during the whole fire duration.

**Vapour Cloud Explosion**

Based on the same mass flow rate, 21 g/s, the flammable mass was estimated to be 45 g thanks to the Phast tool. Considering the multiplication factor for impinging jet, the flammable mass would reach 450 g. Based on the same approach as for CNG, i.e., coupling the multi-energy method to determine the initial overpressure and the wave propagation code DIFREX, the overpressure evolution in the tunnel can be computed, and distances are quite similar to those estimated for CNG.

**Tank burst**

This situation corresponds to a failure of the pressure valve to prevent the tank burst in case of fire in the surrounding. In such a case, the product inside the tank will be heated and, consequently, the pressure inside the tank will rise, following the vapor pressure curve. For cryogenic storage, the tank sizing leads commonly to a 16 bar pressure resistance. Reaching 16 bar inside the tank implies the product reaches -113°C in terms of temperature, which means about 50°C heating. When the tank resistance is no more able to resist the internal pressure, the tank will open, releasing the whole product mass into the ambient, having in mind that, in ambient conditions, the product would be gaseous and not liquid, it will consequently vaporize immediately and form a fireball, this is typically a BLEVE phenomenon.
When such an event occurs, it induced two different types of consequences, overpressure and thermal. The overpressure consequences can be estimated in that case using a classic tank burst approach based on the Brode Energy \(E_{\text{Brode}}\) expressed by:

\[E_{\text{Brode}} = \frac{(P_{\text{rupt}} - P_0) \cdot V}{\gamma - 1}\]

In this equation, \(P_1\) is the tank burst pressure, \(P_0\) is the ambient one, and \(V\) is the tank volume and \(\gamma\) the heat capacities ratio of the pressurized gas. According to the tank volume and pressure, the resulting Brode energy remains small enough to have neglectable pressure consequences for this phenomenon, except in the close vicinity of the vehicle.

The second type of consequence, the thermal effect, is more difficult to estimate. Some BLEVE models are available [5] but consider that the fireball is developing in a free environment. Such an approach might be adapted for tunnel application considering that the volume of the fireball will be maintained in the tunnel, but the shape will change. It is important to note here that this approach may overestimate the fire volume since the air entrainment will differ in the tunnel situation, this is not included in the model. This however enables getting some order of magnitude of the potential consequences through the tunnel length potentially affected by the flame. It depends on the tunnel section; some examples of results are provided hereafter in Table 1.

<table>
<thead>
<tr>
<th>Tank volume [m³]</th>
<th>Fireball computed volume [m³]</th>
<th>Tunnel section [m²]</th>
<th>Tunnel length potentially affected by the flame [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>69 500</td>
<td>50</td>
<td>1 390</td>
</tr>
<tr>
<td>0.9</td>
<td>69 500</td>
<td>120</td>
<td>580</td>
</tr>
<tr>
<td>0.7</td>
<td>54 000</td>
<td>50</td>
<td>1 080</td>
</tr>
<tr>
<td>0.7</td>
<td>54 000</td>
<td>120</td>
<td>450</td>
</tr>
</tbody>
</table>

*Table 1*: Example of tunnel length potentially affected by the fireball in case of LNG tank BLEVE.

While some uncertainties remain according to the precise characteristics of the events, these results show that such a tank burst in a tunnel would have dramatic consequences, most of the people located in the tunnel when it occurs would be exposed to lethal effects.

Hopefully, BLEVE is not an instantaneous phenomenon and, depending on the surrounding fire intensity, it would occur after several minutes.

**CONCLUSIONS**

This paper addresses the risks induced by introducing natural gas vehicles in tunnels, using the various characteristics of the La Defense underground network. Based on the modeling of the three main dangerous phenomena, jet fire, vapor cloud explosion, and tank burst, it shows that:

- for CNG and LNG vehicles, the jet fire’s significant lethal effects remain in the vicinity of the natural gas vehicle itself, whatever the vehicle is, which may be an issue for non-empty buses.
- for CNG, the significant lethal effects area of a vapor cloud explosion would have a size of 4 to 20 meters centered on the natural gas vehicle and would affect passengers of the few closest vehicles.
- for LNG, the vapor cloud explosion’s lethal consequences remain limited without consequences on other vehicles.
- for CNG, the significant lethal effects area of a tank burst would have a size between 4 and 20 meters centered on the natural gas vehicle and more than 30 meters for certain vehicles that have a bigger tank (250 l instead of 50 l). This phenomenon should occur 8 min or later after fire ignition. So, it’s likely that users would have self-evacuated and rescue services would mainly be at risk.
- for LNG, the significant lethal effects area of a tank burst would be several hundreds of meters long, due to thermal effects (fireball) rather than overpressure. Depending on the tank insulation and the number of valves (one or two), the time between the fire’s start and the phenomenon’s
occurrence will be the same as for CNG or occur more rapidly. Further research is needed to clarify this point.

- in the specific context of La Défense configuration, the indirect risk does not strongly modify conclusions reached for direct risk.

There are two main conclusions. Firstly a tank burst could have huge consequences: significant lethal effect area between 4 and 30 m for CNG vehicles and hundreds of meters for LNG. Secondly, the significant lethal effect area of a CNG VCE is between 4 and 20 meters. Considering that a tank burst results in a fire in the tank surrounding and having in mind that the tank burst delay will depend on the thermal flux received by the tank, all measures used to prevent fire in the tunnel are one more type of critical issue.

REFERENCES

1. AFGNV – Association française du gaz naturel véhicules – www.afgnv.org
3. C. Willmann, B. Truchot, New energy carriers and additional risks for user’s safety in tunnels, Ninth International Symposium on Tunnel Safety and Security, Munich, Germany, March 11-13, 2020
8. BRODE, 1959, Blast wave from a spherical charge, The physics of fluid, volume 2
Safe extinguishment of fire exposed compressed natural gas (CNG) and hydrogen (H₂) cylinders

Jonatan Gehandler & Anders Lönnemark
RISE Research Institutes of Sweden, Borås, Sweden

ABSTRACT

Vehicles that are powered by gaseous fuel, e.g., compressed natural gas (CNG) or hydrogen (H₂), may, in the event of fire, result in a jet flame from a thermally activated Pressure Relief Device (TPRD), or a pressure vessel explosion in case the cylinder rupture before the TPRD activates. There have been a few incidents where the TPRD was unsuccessful to prevent a pressure vessel explosion in the event of fire, both nationally in Sweden and internationally. Possible reasons are damaged cylinders, that the TPRD was cooled by the rescue service or a local fire exposure far away from the TPRD. If the pressure vessel explosion would occur inside a road tunnel, the resulting consequences are even more problematic. In 2019 RISE investigated the fire safety of CNG cylinders exposed to local fires. The results from that test series raised the question about what the differences would be in the case of water application. Therefore, one purpose of the new fire test series conducted during 2021 was to investigate whether extinguishment with water may compromise the safety of vehicle gas cylinders in the event of fire. Extinguishments comprise the situation that may occur when deluge systems are activated in ro-ro cargo space or in tunnels, or in the case of manual extinguishment. In total seven fire tests were carried out. The fire tests show that the TPRD indeed can be cooled with water, e.g., from a deluge system, and thus preventing it from activation. Despite, this did not compromise safety as the water also cooled the cylinder, and the three types of cylinders that were tested were robust enough to handle the situation; either the gas slowly leaked through the fire-damaged composite material, the TPRD activated, or the cylinder maintained the gas and its strength throughout the test.

KEYWORD: Fire test, vehicle fire safety, CNG, hydrogen, compressed gas, cylinder, rescue service intervention.

INTRODUCTION

Imagine that you are an incident commander and that you respond to a gas-powered vehicle on fire inside a road tunnel. What are the risks? How likely is it that the cylinder rupture in a powerful pressure vessel explosion? How do the fire situation and the response affect the risks? RISE have in a series of fire tests investigated this situation.

Vehicles that are powered by gaseous fuel, e.g., compressed natural gas (CNG) or hydrogen (H₂) may, in the event of fire, result in a jet flame from a thermally activated pressure relief device (TPRD) or a pressure vessel explosion in case the cylinder rupture before the TPRD activates. A pressure vessel explosion is a mechanical, rather than chemical, explosion when the gas stored at high pressures (20 – 70 MPa) suddenly is released into ambient pressure conditions when the pressure vessel ruptures. There have been a few incidents where the TPRD was unsuccessful to prevent a pressure vessel explosion in the event of fire both nationally in Sweden [1, 2] and internationally [3, 4]. Mentioned reasons are damaged cylinders, that the TPRD was cooled by the rescue service or local fire exposures far away from the TPRD.
The fire safety of CNG cylinders exposed to local fires were evaluated in a previous project and report [5]. Eight fire tests were performed on stand-alone CNG (compressed natural gas, methane) cylinders, see Figure 1 below. CNG vehicles are designed according to safety standards of UNECE Regulation 110. To reduce the risk of explosion, CNG cylinders should at least be equipped with a TPRD that should activate at 110 °C ± 10 °C. CNG tanks are tested against a 1.65 m long fire source. The purpose of the tests in 2019 were to evaluate whether a local fire (0.3 m by 0.3 m) could result in a pressure vessel explosion. The four tests with steel cylinders resulted in a jet flame in accordance with the prescribed outcome in the UNECE regulation (see Figure 2 as an example), despite that the regulation does not include a local fire exposure. The tests on the composite cylinders (190 l, Type 4), however, resulted in a pressure vessel explosion in one (a local fire, not prescribed in the UNECE regulation) out of four tests, see Figure 3. The pressure wave was measured with pressure probes at 5 m and 10 m respectively. It would be fatal within 5 m (> 100 kPa) and result in serious injury within 10 m (> 20 kPa), or more from splinters. If this explosion (a CNG bus) would occur inside a road tunnel, simulations show that serious injury could occur within 300 m on the upstream and downstream side from the explosion [6, 7].

![Figure 1](image1.png)  
**Figure 1**  Test set-up in the 2019 test series. The gas cylinder is placed above a pan filled with fuel.  
*Left: a small fire pan. Right: long fire pan in accordance with UNECE bonfire test.*

![Figure 2](image2.png)  
**Figure 2**  A 10 m long CNG jet flame during the 2019 test series.
In the report Gehandler and Lönnermark [5] argued that the cylinder failed because composite does not conduct heat very well, which means that it takes long time for the TPRD to activate, and because the composite material is degraded by the fire. The results from that test series raised the question about what the differences would be in the case of water application. It is currently uncertain whether extinguishing media may prevent the TPRD from releasing and thus cause a pressure vessel explosion. For example,

- An MSB rescue service response report [8] says that cooling of gas cylinders should be performed using water.
- In 2016 a CNG pressure vessel explosion occurred. The investigation argues that the probable reasons why one of the bus’s gas tanks exploded during the operation were the following [9]:
  - Through selected extinguishing methods, the gas melt fuses have been cooled with foam and thus never reached the activation temperature of 110 °C.
  - The gas tanks were affected by the fire, which has led to weakening in the tank’s composite material.
  - An ongoing fire that continuously weakens the jacket of the gas tank. This fire probably consists of burning gas leaking through the composite jacket.
  - The combination of cooling the fuses, weakening the gas tank material due to an ongoing fire and the high pressure in the gas tank led to a pressure vessel explosion.
- Hermansson [10] argues in a bachelor thesis that water should not be directed towards gas cylinders as that may significantly increase the risk that TPRDs are cooled, which hence would increase the risk of explosion. He further argues that cooling of the TPRD most likely caused the pressure vessel explosion in the bus fire incident mentioned above.
- In a recent international review report of rescue service intervention in the event of gas vehicle incidents, Stenius, Nordström, et. al [4] argue that there is no agreement in the guidelines examined whether or not vehicle gas cylinders should be cooled in the event of a fire. Both risk analysis and input evaluations have shown that cooling can lead to an explosion of the gas tanks. Such an explosion can occur if the cooling of the tanks is insufficient to prevent dangerous heating of the tanks at the same time as the cooling leads to the TPRD being cooled and put out of action.

The purpose of the fire test series reported in this paper is to investigate whether extinguishment with water may compromise the safety of gas cylinders in the event of fire. In addition, the tests aim to characterize TPRD jet flames in terms of length and thermal incident heat flux.

Extinguishment comprises the situation that may occur when deluge systems are activated in ro-ro cargo space or in tunnels, as well as manual extinguishment with traditional water hose by the rescue team onboard ro-ro ships or the rescue service in tunnels. However, in order to create a repeatable test set-up, a fixed water discharge was created (approximately 10 - 15 mm/min design target for the water discharge test set-up representative for water mist systems in tunnels or deluge system in ro-ro spaces).
METHOD

Test set-up
Three different designs of compressed gas cylinders for passenger car usage were used in the fire tests. Two CNG steel tanks (Type 1) at 48 l, three CNG composite tanks (Type 4) at around 50 l, and two H$_2$ composite tanks (Type 4) at 52 l. The composite tank constitutes of a plastic cylinder that is wrapped in carbon fibre reinforced polymer composite material. The CNG tanks had an outer diameter of 0.3 m and a length of 0.77 m (0.85 m with the valve). The H$_2$ tanks had an outer diameter of 0.37 m and a length of 0.87 m (0.93 m with the valve). All gas tanks were fitted with valves and a TPRD at one end.

The fire tests were conducted at Remmene shooting field in Sweden, 31st of August and 1st of September 2021. The gas cylinders were fixed approximately 0.7 m above ground level on metal bars. A pan with a rim height 0.24 m was placed below the cylinder. The pan was filled with water and heptane such that the distance between the fuel surface and the cylinder became 0.1 m. The amount of fuel was calibrated to yield approximately a 30 min fire duration. The size of the pan was either 0.3 m by 0.3 m or 0.36 m by 1.2 m. Note that the small pan was placed in the most challenging position for the TPRD, i.e., at the opposite end from the TPRD, with the outer edge of the pan in line with the end of the tank.

Water was applied onto the tanks with a flow rate at 5 l/min via a metal pipe seen in Figure 4 below. In the pipe, eight 3 mm holes were drilled with 0.1 m distance to discharge the water evenly along the cylinder surface. The rod was placed such that the TPRD was wetted. In some tests a hood was placed to cover half of the tank as in Figure 4 (right). The water was turned on after the pan was ignited and turned off after approximately 20 min.

![Figure 4](image1.png) Water application without (left), and with hood (right). The water set-up was adjusted so that the valve and the TPRD was hit by water droplets.

Field measurements
Thermocouples (TC) of type K (Chromel-Alumel) with diameter 0.5 mm were used to measure the TPRD temperature and gas temperature inside the flame, i.e., the flame temperature, see Figure 5. The flame temperature was measured between the tank and the fuel surface in the centre. TPRD temperatures were measured with thermocouples welded onto the valve. The pressure inside the gas cylinder was also measured.
Figure 5  Gas cylinder and fire pan set-up with temperature and pressure measurements on or near the gas cylinder.

The length and width of the jet flame was characterized with space markings and two video recordings, see Figure 6. The incident heat flux from the jet flame was measured with three plate thermometers (PT), see Figure 6. The plate thermometers were placed at a height of about 1 m above the ground. The art of measuring incident heat flux with PT was developed in ref [11]. Incident heat flux towards the plates were calculated with equation (5) in ref [12] and fast PTs with \( K=4 \) W/m\(^2\)/K and \( C=1800 \) J/m\(^2\)/K were used.

Figure 6  Field measurement set-up.

The measurement uncertainty is reported in Table 1. The uncertainty is most significant for jet flame length and incident heat flux measurements.
**Table 1** Measurement uncertainty.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Uncertainty</th>
<th>Comment/reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC surface temperature</td>
<td>± 3 °C</td>
<td>RISE Fire Research Special Conditions</td>
</tr>
<tr>
<td>TC gas temperature</td>
<td>± 2 °C</td>
<td>RISE Fire Research Special Conditions</td>
</tr>
<tr>
<td>PT incident heat flux</td>
<td>± 5 %</td>
<td>[12]</td>
</tr>
<tr>
<td>Cylinder gas pressure</td>
<td>± 1 Pa</td>
<td>RISE Fire Research Special Conditions</td>
</tr>
<tr>
<td>Jet flame length</td>
<td>± 10 %</td>
<td>Estimate based on error from visual interpretation on video recordings and space markings every 2 m.</td>
</tr>
<tr>
<td>Manual timing</td>
<td>± 2 s</td>
<td>RISE Fire Research Special Conditions</td>
</tr>
</tbody>
</table>

**Test procedure and test configuration**

The tests were carried out according to the following procedure:
- Gas cylinder was placed above the pan (fire source).
- The required amount of heptane and water is filled into the pan such that the fuel surface is 0.1 m below the cylinder.
- Video recorders were started.
- Start of timer and temperature measurement, i.e., time 00:00 (min:s).
- The fuel was ignited (see below for exact timing for each test).
- The water was applied onto the tank for approximately 20 min.
- The test runs until the cylinder was empty, either by release of TPRD or leakage through the fire-damaged composite material or by rifle shooting.

The configuration of each test can be seen in Table 2. Test variables varied were:
- The type of tank design: CNG composite/ CNG steel / H₂ composite
- Pan fire size: Long (i.e., widespread fire exposure) / Small (i.e., local fire exposure)
- Water discharge: Yes / Yes with hood / No

**Table 2** Test configuration of the seven gas tank fire tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Tank design</th>
<th>Pan size</th>
<th>Water discharge</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CNG composite</td>
<td>Long</td>
<td>Yes</td>
<td>Water was on throughout the test</td>
</tr>
<tr>
<td>2</td>
<td>CNG steel</td>
<td>Long</td>
<td>Yes, with hood</td>
<td>The pan was not horizontal. Some fuel was leaking.</td>
</tr>
<tr>
<td>3</td>
<td>CNG steel</td>
<td>Small</td>
<td>Yes, with hood</td>
<td>Water is applied during 20 min.</td>
</tr>
<tr>
<td>4</td>
<td>CNG composite</td>
<td>Long</td>
<td>Yes, with hood</td>
<td>Water is applied during 20 min.</td>
</tr>
<tr>
<td>5</td>
<td>CNG composite</td>
<td>Small</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>H₂ composite</td>
<td>Long</td>
<td>Yes</td>
<td>Water is applied during 20 min.</td>
</tr>
<tr>
<td>7</td>
<td>H₂ composite</td>
<td>Long</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

**RESULTS**

**Fire tests with CNG composite cylinders**

In test 1 and 4, the applied water efficiently cooled the TPRD so that it was not released despite being engulfed by flames. Test 5 was a replica of test 8 performed in 2019 where the local fire resulted in a pressure vessel explosion. However, despite that the TPRD did not release in any of these tests, the fire exposure resulted in a safe failure of the cylinder such that the gas slowly was released through
the damaged material, i.e., a leak-before-break tank design. The observations from tests 1, 4 and 5 are summarized in Table 3, Table 4, and Table 5, respectively.

**Table 3**  Observations made during test 1 (CNG composite cylinder).

<table>
<thead>
<tr>
<th>min:s</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>Start of timer and measurements. Tank pressure: 15.6 MPa</td>
</tr>
<tr>
<td>03:50</td>
<td>Heptane pool is ignited. Start of fire test.</td>
</tr>
<tr>
<td>12:12</td>
<td>Maximum pressure 20.3 MPa is measured. Gas starts to leak through the composite material.</td>
</tr>
<tr>
<td>26:00</td>
<td>Pressure is 2.4 MPa. The pan fire runs out of fuel.</td>
</tr>
<tr>
<td>31:00</td>
<td>Pressure is 0.7 MPa. The cylinder is punctured with rifle shooting.</td>
</tr>
</tbody>
</table>

**Table 4**  Observations made during test 4 (CNG composite cylinder).

<table>
<thead>
<tr>
<th>min:s</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>Start of timer and measurements. Tank pressure: 17.0 MPa</td>
</tr>
<tr>
<td>04:26</td>
<td>Heptane pool is ignited. Start of fire test.</td>
</tr>
<tr>
<td>11:52</td>
<td>Maximum pressure 22.4 MPa is measured. Likely gas starts to leak through the damaged composite material.</td>
</tr>
<tr>
<td>12:30</td>
<td>Videorecording reveal that gas is leaking through the composite material. The cylinder pressure is 21.9 MPa.</td>
</tr>
<tr>
<td>25:00</td>
<td>The pan fire runs out of fuel. Pressure is now 1.8 MPa.</td>
</tr>
<tr>
<td>25:30</td>
<td>Cylinder is punctured with rifle shooting.</td>
</tr>
</tbody>
</table>

**Table 5**  Observations made during Test 5 (CNG composite cylinder).

<table>
<thead>
<tr>
<th>min:s</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>Start of timer and measurements. Tank pressure: 15.4 MPa</td>
</tr>
<tr>
<td>04:24</td>
<td>Heptane pool is ignited. Start of fire test.</td>
</tr>
<tr>
<td>09:30</td>
<td>Video recording reveal that gas starts to leak through the composite material. Cylinder pressure is 17.8 MPa.</td>
</tr>
<tr>
<td>11:00</td>
<td>Maximum pressure 19.0 MPa is measured.</td>
</tr>
<tr>
<td>29:30</td>
<td>Cylinder is empty. Completion of test.</td>
</tr>
</tbody>
</table>

**Fire tests with CNG steel cylinders**

In test 2 and 3, the applied water managed to cool the TPRD, resulting in a much-delayed TPRD activation. In test 2, after 11 min widespread fire exposure occurs (can be compared with 1 min in the 2019 test without water), and in test 3 TPRD surprisingly released after two shots had been fired against the tank without any penetration, 25 min after ignition of the small pan, see summarized observations in Table 6 and Table 7. In test 2, 40.3 MPa were recorded when the TPRD released. This shows that the application of water on half of the tank had a minor cooling impact relative to the widespread fire source.

**Table 6**  Observations made during test 2 (CNG steel cylinder).

<table>
<thead>
<tr>
<th>min:s</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>Start of timer and measurements. Tank pressure: 17.5 MPa</td>
</tr>
<tr>
<td>02:40</td>
<td>Heptane pool is ignited. Start of fire test.</td>
</tr>
<tr>
<td>13:03</td>
<td>Maximum pressure at 40.3 MPa. Jet flame from TPRD when 162 °C was measured on the valve. TPRD release in four directions, 2-3 m long jet flame from each.</td>
</tr>
<tr>
<td>14:07</td>
<td>Cylinder is empty. Completion of test.</td>
</tr>
</tbody>
</table>
Table 7  Observations made during test 3 (CNG steel cylinder).

<table>
<thead>
<tr>
<th>min:s</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>Start of timer and measurements. Tank pressure: 17.9 MPa</td>
</tr>
<tr>
<td>06:26</td>
<td>Heptane pool is ignited. Start of fire test.</td>
</tr>
<tr>
<td>25:00</td>
<td>Water is turned off. Water discharge slowly fade.</td>
</tr>
<tr>
<td>32:18</td>
<td>Pan fire runs out of fuel. Maximum pressure recorded at 36.5 MPa.</td>
</tr>
<tr>
<td>33:00</td>
<td>Cylinder is punctured with rifle shooting, which activated the TPRD (maximum temperature recorded on the valve only 56 °C) to release in four directions, approximately 2 m long jet flame in each direction.</td>
</tr>
<tr>
<td>35:00</td>
<td>Cylinder is empty. Completion of test.</td>
</tr>
</tbody>
</table>

The jet flame was released in four directions from the TPRD and measured 2-3 m each. In test 3 the Jet flame occurred after the fire was extinguished which means that the heptane fuel was not contributing to the fire intensity, see Figure 7.

![Image](image1.png)

*Figure 7  CNG jet flame in test 3 (pan fire was extinguished, all flames are from the jet flame).*

These jet flames resulted in low incident heat flux at a distance from the tank, see Figure 8 and Figure 9.

![Image](image2.png)

*Figure 8  Measured plate thermometer temperature (left) and calculated incident heat flux (right) from the CNG jet flame in test 2.*
Steel cylinder post-fire strength

One of the steel tanks was pressurized with water until burst pressure before the fire tests. Its burst pressure was then 50 MPa. Another of the same type of steel tank was exposed to the fire of test 2 and then pressurised with water until it burst after it had cooled down. The burst pressure was then 52.5 MPa, see Figure 10 below.

Fire tests with and without water application on hydrogen cylinders

The difference between applying water onto the widespread fire exposed tank (test 6) and not applying any water (test 7) shows how the TPRD in test 6 was cooled and did not activate until the water was turned off, while, if there would be no water applied onto the tank at all, it would activate within 3 min only, see Table 8 and Table 9.

Table 8 Observations made during test 6 (H\textsubscript{2} composite cylinder).

<table>
<thead>
<tr>
<th>mins</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>Start of timer and measurements. Tank pressure: 40.0 MPa</td>
</tr>
<tr>
<td>03:05</td>
<td>Heptane pool is ignited. Start of fire test.</td>
</tr>
<tr>
<td>21:00</td>
<td>Water is turned off. Water discharge slowly fade.</td>
</tr>
<tr>
<td>25:17</td>
<td>Maximum pressure 49.2 MPa is recorded when the TPRD release in one direction. 8 m long jet flame at activation.</td>
</tr>
<tr>
<td>26:30</td>
<td>Cylinder is empty. Completion of test.</td>
</tr>
</tbody>
</table>
Table 9  Observations made during test 7 (H\textsubscript{2} composite cylinder).

<table>
<thead>
<tr>
<th>min:s</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>Start of timer and measurements. Tank pressure: 41.0 MPa</td>
</tr>
<tr>
<td>04:08</td>
<td>Heptane pool is ignited. Start of fire test.</td>
</tr>
<tr>
<td>07:22</td>
<td>Maximum pressure at 41.1 MPa is recorded when the TPRD release (297 °C is measured on the valve). 6 m long jet flame at activation.</td>
</tr>
<tr>
<td>08:30</td>
<td>Cylinder is empty. Completion of test.</td>
</tr>
</tbody>
</table>

In both tests, the same pan fire was used. The length of the jet flame was about 8 m in test 6 and 6 m in test 7, the difference most likely caused by the higher pressure in test 6 from the longer fire exposure, see Figure 11.

Figure 11  Hydrogen jet flame in test 6 (left) released 5 min after the water discharge was turned off (after in total 22 min fire). In test 7 (right) it released after 3 min fire when no water was applied onto the tank.

Plate thermometer 4 (PT4) was hit by the jet flame in test 7 but all other plate thermometers were not hit by any flame and thus measured the incoming heat flux, see Figure 12 and Figure 13.

Figure 12  Measured plate thermometer temperature (left) and calculated incident heat flux (right) from the hydrogen jet flame in test 6 (Note that the timeline is truncated from 20 min to highlight the peaks of the jet flame.).
In Figure 14 the hydrogen jet flame from test 7 is captured with an IR-camera. The jet itself is rather cold; burning flames in the outer part are warmer. The picture supports that, even though hydrogen have a very high upper flame limit, a fat gas mixture is still achieved in the center of the jet, which is normal for most gas jets which are not pre-mixed with oxygen. The outflowing gas is cold due to pressure losses.

**DISCUSSION**

**Application of water and the risk of pressure vessel explosion**

The water set-up assimilates tunnel FFFS that applies roughly 10-15 mm/min water onto the tank and the TPRD. This was enough to cool the TPRD and thus prevent it from activating for at least 20 min for the composite tanks and steel tanks exposed to smaller fires, and 13 min for a steel tank exposed to a widespread fire. At the same time, the cooling from the applied water protected the tank from rupture and delayed the impact from the pan fire. For instance, CNG started to leak through the composite material after about 8 min with water and 5 min when no water was applied. For a manual fire extinguishment, a larger water flow rate is used that will result in a more significant cooling effect and increased protection of the gas cylinder. At the same time, real sprinkler or manual extinguishment cases might not always hit the TPRD directly which will reduce the TPRD cooling significantly. Nevertheless, for the three different gas cylinders used in these 7 fire tests, none resulted in the most dangerous failure mode: pressure vessel explosion. Thus, it can be concluded that a fast intervention can be the safest option when the risk of life or fire spreading is significant. Note that
water should not be sprayed onto cryogenic PRDs (used for cooled-condensed gas) since they can become clogged with ice which could lead to a cylinder rupture.

Jet flame
Although different plate thermometers were used, a comparison can be made with the 10 m long CNG jet flame in the 2019 test series (see Figure 2) and the 8 m and -6 m long hydrogen jet flames in test 6 and 7, respectively. At the position X=5 m, Y=5 m from the TPRD at origin (X=0 m, Y=0 m), around 5 kW/m² was measured in these three tests. Considering the short duration of long jet flames, this poses a small threat to fire fighters. As can be seen on the measured plate thermometer temperatures, an increase to 60-70 °C would result in a smaller temperature increase of fabric or bare skin, which is tolerable for short periods of time. The highest incident heat flux, 12 kW/m², was measured at position X=0 m, Y=5 m below the 8 m hydrogen jet in test 6, corresponding to 100 °C plate thermometer temperature which is more problematic, but is tolerable for fire-fighters wearing protective clothing, considering the short time duration. In fact, there is one reported incident in Sweden were a firefighter was hit by the jet flame, but without any resulting injuries [7]. Other burnable materials being hit by the flame may ignite, and as has been shown by experiments by Tamura et al. [13], hydrogen jet flames can cause the release of TPRDs on hydrogen vehicles parked next to each other in a risky domino effect. However, the impact on solid structures such as concrete will be minor due to the short duration. Burning jet flames should not be extinguished, although the risk of a vapor cloud explosion from a vehicle TPRD release in a ventilated tunnel is minor [14]. A vapor cloud explosion resulting in dangerous pressure amplitudes inside a typical road tunnel requires larger gas amounts (e.g. > 40 kg) [e.g., 15] than what is stored in CNG or hydrogen tanks used for propulsion.

Firefighting tactics
CTIF is a global firefighting organisation. They published an operational handbook for fire services in 2015 with recommendations on how to handle fires in alternative fuel vehicles. Based on the initial risk assessment, different approaches to the fire may be used. If the vehicle fire does not threaten any lives and there is no risk of fire spread to other objects, then a defensive attack can be preferable to avoid exposure to the hazards of a vehicle fire. A defensive attack means to evacuate the area at risk and if possible, let the vehicle burn out. It can also call for suppressing, cooling, or extinguishing the fire from a safe distance (outside what is called the hot zone >50 m from the vehicle). If there, on the other hand, is a need for rescue or to protect the surroundings, fire extinguishing through an offensive tactic can be preferable. For fire extinguishing using an offensive approach, CTIF advocates a strategy with at least four (five including a team leader) fully equipped firefighters divided into two teams using one hose in each team with a water supply of at least 250 l/min. One team cools the energy storage, and one team extinguishes the vehicle fire. The results from the performed fire tests support this offensive approach since cooling of the gas tanks and extinguishing the fire will safeguard against a pressure vessel explosion. The tests also support to activate fixed firefighting systems, whenever available.

Post extinguishment
In the fire tests carried out above, gas often starts to leak through the composite cylinder after some fire exposure. This has not resulted in hazardous situations but has resulted in a slow and controlled fire. This also means that fire exposed composite cylinders where the TPRD has not activated may be leaking after the fire is extinguished. Since methane and hydrogen are light gases and smaller leakages in tunnels quickly is dispersed below ignition levels, this will most likely not result in any hazardous situations. Tamura [16] has shown that composite cylinders regain its strength when they are cooled, e.g. 30 min after the fire has been extinguished. The tank may, however, as mentioned above be leaking through the cylinder material. In the tests performed in 2019 [5] and 2021, steel cylinders were pressure tested with water before and after fire exposure. The three steel tanks that were pressurized after fire exposure had regained its strength afterwards and even handled a higher

---

1 https://ctif.org/
pressure than when the same type of tank was pressurized without any fire exposure. According to Tamura [16] a double margin of safety is achieved from that:

1. the pressure in the tank increases during fire but is reduced again when the tank has cooled down, which lowers the stress on the cylinder, and
2. the material regains its strength when it is cooled down.

CONCLUSIONS

In the introduction, this paper urged the reader to imagine that he/she was an incident commander responding to a gas-powered vehicle fire inside a road tunnel. For CNG and hydrogen vehicles, one key risk to consider is then a pressure vessel explosion.

How likely is it that the cylinder rupture in a powerful pressure vessel explosion?
Pressure vessel explosions for CNG or hydrogen vehicles have occurred both internationally and in Sweden (at least 3 known cases). They have been attributed to either local fire exposure far away from the TPRD or that the TPRD was cooled with extinguishing media. In 2019, eight tests were designed to investigate local fire exposure. In this paper, seven additional tests designed to investigate the cooling effect from water application are reported. These fire tests show that a local fire exposure can result in a pressure vessel explosion. This occurred once, after 20 min local fire exposure onto a CNG composite tank. The tests also showed that this is a fairly unlikely event since in most tests, the cylinders handled the fire safely despite a challenging test set-up. It should also be mentioned that safer, leak-before-burst, composite cylinders exist on the market that start to leak instead, even in the challenging case of a local fire and/or water cooling. In addition, this event has an even lower likelihood occurring inside a road tunnel.

How do the fire situation and the response affect the risks?
A local fire can, for some types of composite cylinders, lead to a pressure vessel explosion. This occurred in one fire test after about 20 min local fire exposure on a nearly full CNG tank. However, most fires, and most vehicle designs will lead to a more engulfing fire exposure within 10 min; then a jet flame will result from the TPRD. Poor design, e.g., gas tanks above the sunroof on buses, can lead to a prolonged local fire exposure.

The tests with water application show that it is easy to cool the TPRD and thus put it out of operation. However, the cooling will also, to some degree, protect the cylinder material and cool the gas, i.e., lower the pressure inside the cylinder. Therefore, it is highly unlikely that an extinguishing attempt will cause a pressure vessel explosion. In contrary, extinguishing the fire and cooling the energy storage, e.g., with sprinkler system or manual firefighting, is the recommended strategy in an offensive tactic. In order to fully protect gas cylinders exposed to fire, larger amounts of water than what FFFS typically offer is required.

ACKNOWLEDGEMENTS

Anders Jönsson & Per Gullander from Södra Älvsborgs Fire and Rescue Services (SÄRF) are acknowledged for the safety management during the fire tests and for rifle shooting.

Anders Toresson with staff at Torsbo Handels (www.torsbohandels.com) are acknowledged for their assistance with rifles and ammunition.

Trafikverket (The Swedish Transport Administration) are acknowledged for funding of the BREND 2.0 project. The fire tests presented in this paper have also been sponsored by TUSC Tunnel Underground Safety Center. The financiers of TUSC are the Swedish Transport Administration, the Swedish Fortifications Agency, GRAMKO Mining Industry Association, and RISE Research Institutes of Sweden.
REFERENCES

Fire safety of underground parking garages in relation to electric vehicles: the Singelgarage fire and fire suppression

Nils Rosmuller, Tom Hessels, Ricardo Weewer, Johan van der Graaf, and Joost Ebus
NIPV, Netherlands Institute for Public Safety

ABSTRACT

In The Netherlands and other parts of Europe, more and more cars are zero emission. This mainly concerns battery electric vehicles (BEV), and for a much smaller part fuel cell electric vehicles (FCEV). Electric cars use battery packs with lithium ion battery cells for energy storage. Such cars are charged in public and private garages and at charging points in the streets. There have been several BEV-fires, some while the vehicle was charging, and some while it was parked or when it was driven. In 2020, while we were writing a literature review that dealt with the fire safety issues of BEV’s in parking garages [1], an electric car fire (arson) broke out in the public Singelgarage in the city of Alkmaar (the Netherlands), on the second floor underground (early morning 06:21, July 1st, 2020). We studied this BEV-fire and the response by the fire service of Alkmaar and fire services from neighbouring towns and the police [2].

In this paper we discuss the results of this literature review in which we studied scientific papers and databases looking for fire safety characteristics. We have also conducted a desktop study to gain a better understanding of the safety risks of electric vehicles and the charging process. The knowledge thus gained was translated into practical measures and advice in a few sessions with specialists in fire prevention and repression from the Netherlands Fire Service. Cooling battery cells is complex in itself, but cooling is even more complex in parking garages, as the example of the incident response to the BEV-fire in the Singelgarage shows. We studied this fire and the incident response to learn more about the development of the fire and about the response from the fire service and their partners.

From both the literature study and the case-study we concluded that the safety risks of electric vehicles are different from those of conventional vehicles using fossil fuels (ICE’s). The development of a fire in an electric car is generally slower, but the fire lasts longer. A thermal runaway is the cause of a long-lasting self-ignition process and the necessarily prolonged fire abatement activities [3]. Intense and long-lasting cooling of the battery pack is, up to know, the only effective way to suppress a BEV-battery-fire. However, this is difficult and even more difficult in a parking garage as we learned from the fire in the Singelgarage where the battery pack of the BEV reignited several times.

We recommend taking into account the specific issues regarding battery pack related fires when designing parking garages. Firstly, in the construction, for example by adding extra protection to the building structure near parking spaces with chargers. To reduce the probability of fire, charging stations could be fitted with collision protection, or situated at locations where collisions are highly unlikely to occur. Secondly, in the installations, for example by adding a facility that enables the fire service or those present to stop the current to all chargers with a simple action. Furthermore, the use of displacement ventilation/smoke and heat removal can help to increase the probability of a successful offensive interior attack. Thirdly, organisational measures will contribute to fire safety, such as instructions for the use of the indoor car park and its charging facilities (including maintenance) and informing drivers what to do in the event of a fire and how to deal with error messages from the battery management system (BMS) of their car.

KEYWORD: electric vehicle, fire safety, (underground) parking garage, fire service
INTRODUCTION

Many countries (196) signed the 2015 Paris climate agreement [4] in which they promised to take measures to slow down climate change (adoption of the 2015 intentions in 2021). Various of these measures intend to decrease, or even better: to prevent, the emission of carbon dioxide, which results from the use of fossil fuels. In Western countries such as The Netherlands, United States, Germany and Norway, transport activities use to a large extent fossil fuels [5]. Hence, it comes as no surprise that in these countries the traditional fossil fuelled cars (internal combustion cars (ICE)) are being replaced by electric cars (battery electric vehicles (BEV)) in an increasing speed. The Netherlands for example, announced various directives aiming at outsourcing fossil fuelled cars and trucks. To support this transition from fossil fuels to battery electricity, additional regulations are introduced, such as the obligation to have a minimum of one charging point and BEV-parking place per 10 parking places in 2025 in office buildings [6].

Based upon these developments and knowing that fire suppression in parking garages is a hell of a job for fire fighters, we aim to get a better understanding of the dangers of electric cars in parking garages. Understanding the dangers, we will be able to take preventive measures, as well as develop better strategies for the fire service.

In this paper, we show the growing number of electric cars in The Netherlands (section 2) and the complexity of fire safety of parking garages (section 3). We will use the Dutch state of the art car park building regulations as an example to clarify this complexity. In section 4, we will elaborate on the research methodology that we applied to gain insight into the specific safety risks of electric cars in parking garages. We will clarify the specific fire risks of electric cars compared to the internal combustion engine (ICE) of ‘fossil’ cars (emitting carbon dioxide), (section 5). In section 6 we present an electric car parking fire and the lessons learned from the fire rescue services. By combining the specific fire safety risks of electric cars and the lessons learned from suppressing (electric) car fires, we present the Dutch way of suppressing electric car fires in underground parking garages (section 7). We will finish this paper with the conclusions (section 8) and recommendations (section 9).

ELECTRIC CAR NUMBERS

In The Netherlands, 79.6% of cars use petrol (1/1/2022), and 11% use diesel. However, the number of hybrid and full electric cars is increasing. At the beginning of 2022, 725 thousand cars used a battery for propulsion, which is an increase of 37.8% compared to 2021. This means that 1 out of 12 cars in The Netherlands is an electric or hybrid car. On the first of January 2021, 3.1% of the cars in The Netherlands were electric (full or hybrid).

Figure 1 below shows the number of electric cars over the years, subdivided in hybrid and full electric cars. Proceeding from 2015 onwards, we see a continuous increase in the number of electric cars. However, the number of hybrid cars stabilizes from the year 2017 onwards (about 100,000 cars), whereas the number of full electric cars grows exponentially. For this paper, the difference between the two types of electric cars is relevant. Firstly, because the battery capacity of a full electric car (50kWh and more) is much bigger than that of a hybrid car (10kWh). A larger capacity, ceteris paribus, causes a longer lasting fire, and more issues for the fire service. Secondly, the chemistry of both car types can be different. Full electric cars have a lithium-ion battery pack, whereas hybrids may also use nickel metal hydride battery packs. Lithium causes longer lasting fires because of the possibility of a thermal run away.
Figure 1 Electric car development (full electric and hybrid) in The Netherlands

Figure 2 below shows the change (2022 versus 2021) in vehicles in The Netherlands. The upper blue bar indicates the 37.85% increase of electric cars. The share of fossil fuelled cars (LPG, CNG and diesel) in the Dutch vehicle fleet is clearly decreasing [5].

Figure 2 Increase/decrease 2021-2022 in car percentage per fuel type in The Netherlands

FIRE SAFETY OF PARKING GARAGES

When there are no victims in the car, ‘fossil’ car fires in the ‘open’ are relatively straightforward to extinguish. Fire fighters use a hose line to extinguish the car fire, and if necessary another hose to protect assets in the environment from catching fire. It takes them about 10-15 minutes to extinguish the car fire. Such car fires are relatively easy to suppress because the car is clearly visible and can...
Usually be approached without difficulties. Toxic fumes and heat ascend and rarify in the air. Personal protective equipment facilitates an offensive attack [7], although exploding tanks (petroleum, LPG) remain a safety risk for the fire fighters.

However, when the same car is burning in a parking garage, the fire suppression activities become more difficult. A parking garage is a construction in which multiple cars can be parked. They may have several floors and be above and/or below ground level. Some parking garages have many openings to the outside, while some are nearly fully closed. Over the last years, (semi) automatic parking garages have been built; in these garages, a machine parks the cars, often very close next to and above each other. In general, parking garages have to comply with building regulations. Those building regulations specify for example the fire resistance of the construction, the maximum surface, the number of cars allowed, emergency exits, length of egress routes, ventilation and fires suppression systems, smoke and fire detection and in some cases the emergency organisation.

The above mentioned positive circumstances of a car burning ’in the open’ are mostly absent in parking garages. Firstly, it is difficult to pinpoint the position of the burning car. On which level is it parked? And where exactly on that particular level? Secondly, what type of car and what parts of the car are burning, and for how long has it been burning? All these questions are hard to answer because the view on the burning car is hampered by the (toxic) smoke. Thirdly, adjacent cars may obstruct the sight as well as interfere with the approachability of the car. In addition, car parks have low ceilings and are rapidly filled with smoke. Logistics are difficult, such as walking long distances with fire equipment (multiple floors, long routes and stairs). Fourthly, creating situational awareness is extremely difficult for reasons of unfamiliarity with the garage and the abundance of smoke. Finally, if the parking garage is situated below ground level, the above-mentioned difficulties become even more problematic. A more general complicating aspect, at least in The Netherlands, is that building regulations have not evolved with the developments in car design: cars have become bigger and contain more plastic and rubbers, causing larger heat release rates and more smoke. New concepts such as (semi) automatic car parking have neither been included in the building regulations [1].

With electric cars and charging points in garages we face another new development. Charging is an activity in garages for which they have not been designed. There are no rules that allow or prohibit charging cars in a garage. The question is what particular fire risks result from parking and charging electric cars in garages. Based on real electric cars fires, knowing some fire characteristics of electric cars, and realizing that regulations concerning charging activities and the building of parking garages are not in line with fleet developments, we worry about the fire safety of parking garages, in particular with regard to fire development and fire suppression. Below, we will outline the research method of our project which aims to understand and improve the fire safety of parking garages in relation to car electrification and zero emission cars.

**RESEARCH METHOD**

The increasing number of electric cars and the difficulties of fire fighting in parking garages made us think of, and worry about, electric car fires in (underground) parking garages. We first needed to understand the typical safety risks of electric cars and compare these to the safety risks of ICE’s. To understand the safety risks, we searched for international scientific, peer reviewed articles. This literature study resulted in a comprehensive report [1]. In this paper we will summarize the key differences between BEV and ICE vehicles. While exploring the literature, an actual electric car fire in an underground parking garage broke out, enabling us to study the suppression activities of the fire service. To this end, we interviewed several fire officers and read the internal reports. We also wrote a report in which we documented the main lessons concerning fire suppression we had gained.

Knowing the fire safety theory of electric cars and fire suppression in underground parking garages, we applied the basic Dutch fire service principles to pre-specified typical fires. This provided us with a modus operandi for dealing with electric car fires in underground parking garages.
CHARACTERISTICS OF BEV AND ICE CAR FIRES

In general, BEV cars use lithium-ion battery cells for energy storage. Due to various causes (thermal, chemical and electrical abuse) a thermal runaway can start in the battery pack, which consists of separate battery modules. These modules contain the lithium ion battery cells that store the energy. A thermal runaway is the electric-chemical mechanism that leads to the self-heating of a battery cell and may result in a fire (Colella et al., 2016). A consequence of a thermal run away is that an electric car fire, ceteris paribus, lasts (much) longer than a fossil car fire. Parking and charging electric cars in parking garages lead to various other fire causes [8]. Examples of these are damaged cables, cars colliding with the charging point, or battery packs exposed to heat caused by external sources such as nearby cars.

Hundreds of fire test have been executed to clarify the differences between BEV and ICE vehicle fires (see also [8] for an overview). However, the test results need to be interpreted with some caution. To be able to compare these results, it is essential for the starting points of the tests to be identical. For example, it makes a big difference whether or not the fuel tank is filled. And regarding BEV-tests, it is important to use battery packs that are charged to the same level and to know the state of the charge, so as to have the same amount of energy stored. After all, the more energy is stored (a higher state of charge), the longer a fire will last.

Based on literature, we were able to pinpoint relevant fire safety items of BEV and ICE vehicles. The heat or temperature of a burning BEV is comparable to that of an ICE: about 800 +/- 100 degrees Celsius [9]. The combustion products are also similar, although a burning BEV produces 1.8 times more hydrogen fluoride than an ICE [10]. The PHRR (Peak heat release rate) for both the BEV and ICE is about 8 MW [8, 11]. Jet flames and parts of battery packs and cells that are hurled away are also relevant hazards for fire fighters.

Burning BEV cars in which the battery is part of the fire are difficult to extinguish, because of the tightly closed cabinet of the battery pack and the thermal runaway within the cabinet. The cabinet prevents water to reach the battery cells, hence preventing the cells from being cooled. Accordingly, the battery cells reach a state of thermal runaway.

As will be clear, a BEV fire in a parking garage, is very difficult to extinguish. In the next section, we will discuss the fire suppression lessons that we learned from a real-life BEV fire (2020) in an underground parking garage in the Netherlands.

CASE STUDY: SUPPRESSING THE ELECTRIC CAR FIRE IN THE UNDERGROUND ‘SINGELGARAGE’

On the 1st of July 2020, a fire broke out (arson) in an underground parking structure called the Singelgarage in Alkmaar, The Netherlands. This parking structure, which was built in 1998, consists of two subsurface floors (parking levels) below a canal. Two cars were involved in the fire: a fully electric Hyundai Ioniq and a Citroen C3. Both vehicles were parked at level -2 and were standing about 50 meters apart. The fire caused a large incident response from five different fire districts. Two robots from the fire brigade and one from the police were used during this incident.

As it was the first fire of a battery electric vehicle (BEV) in an underground parking structure in The Netherlands, we studied this incident to learn about the development of the fire and the response of the fire service and their partners [1]. In this section, the most essential information is presented: the development of the fire, the incident response, the use of robots and the role of the BEV in the fire.

Fire development

The exact development of the fire is unknown; there was no camera footage available. At 06:22, the fire detection system detected the first CO (Carbon monoxide). At the same time, a 112-call reported a fire in the Singelgarage to the fire brigade. On 09:31, three hours after the fire had started, the two
vehicles were located, and the fire had been nearly extinguished. At this moment, only a few small flames were still visible near the battery pack of the BEV. However, an increased temperature of the battery pack was reported, indicating the instability of the battery pack.

None of the two burning cars caused the fire to spread to other vehicles. The concrete garage construction, together with empty parking spaces next to both burning vehicles, prevented the fire from spreading. The temperature of the smoke layer was not high enough to set fire to other vehicles parked further away from the two burning cars.

**Incident response**

The fire brigade executed an offensive attack in the Singelgarage. During the course of the incident, multiple attempts were made to localize the fire. However, due to the thick smoke, visibility was almost none. No heat was felt by fire fighters or seen on a thermal imaging camera. As sounds of possible explosions were heard, the initial attempts to localize the fire were aborted.

After the initial attempt was aborted, camera footage of the start of the fire became available, indicating the possible location of the burning vehicles. The incident commanders decided to start a final search in order to localize the burning vehicles, in which they succeeded. Both vehicles were burnt out and only the battery pack of the BEV was still producing some flames. After the vehicles had been localized, fire fighters started to ventilate the parking structure and found no other vehicles that were involved in the fire.

**Robots**

In this incident, two firefighting robots were called to the scene. When both arrived, the two burning BEV-vehicles had already been located. Therefore, the robots only were used 1) to ventilate the parking structure and 2) as stand by during the recovery of the BEV.

A police robot was used to remove the BEV from the Singelgarage and transport it to a container for submerging the vehicle.

**Battery electric vehicle**

As mentioned above, it was an electric Hyundai Ioniq that was involved in the fire. The battery pack of the vehicle, which fully burned out, became involved when other parts of the vehicle had caught fire. The ceiling above the electric vehicle suffered more structural damage than the ceiling above the Citroen C3, a fossil fuel car. Due to the involvement of a BEV, a police robot had to be called to the scene to remove the vehicle out of the Singelgarage and transport it to the container used to cool the battery pack of the BEV.

From this case study, we learn that suppressing car parking fires is difficult, and becomes even more difficult when BEV is involved in the fire. A BEV fire lasts longer and requires specific equipment to handle, including a towing robot and a container to cool the battery pack.

**DUTCH FIREFIGHTING IN UNDERGROUND PARKING GARAGES**

The Netherlands Fire and Rescue services (FRS) approach fires based on a set of so-called ‘basic principles of firefighting’, part of their ‘firefighting doctrine’ [12]. According to these principles, a fire is basically approached from outside, following a 360-degree reconnaissance. The fire can only successfully be attacked if:

a) the location of the fire is known, and  
b) the fire can be reached (from outside) and  
c) the available flow rate is sufficient.

Only when strict criteria are met, an interior offensive attack will be carried out: fire fighters enter the building (interior) and try to attack the seat of the fire (offensive). For an offensive interior attack,
a) the building or room has to be small,
b) the location of the fire known and
c) not be too far from the entrance;
d) door control should be possible and
e) there should be enough cooling capacity (flow rate) available.

An underground parking garage, at least in Netherlands, usually does not meet these criteria. A car fire generally has a Heat Release Rate (HRR) between 4 and 10 MW, requiring at least one hose line for one car. When electrical (or fuel cell vehicles) are involved, dangerous fire phenomena like explosions and jet fires should be anticipated. Therefore, an interior attack is only possible if the fire can be seen, is close to the entrance and if only one car is involved. If the fire is bigger or cannot be approached, the only option according to the basic principles of firefighting is the “burn out scenario”: wait until all the available fuel, in this case electricity, has burnt out.

The FRS in The Netherlands have developed a procedure which is currently tested [13]. This procedure, based on the basic principles, involves three scenarios:

1) one car is on fire and approachable, or
2) one to three cars are involved, and ultimately
3) more than three cars are involved.

In the first scenario the fire is dealt with according to the basic principles. The ultimate scenario (number 3) is the burn out scenario: the fire cannot be extinguished. In the second scenario, it is not helpful to mobilize more units and fire fighters with the same equipment; an innovative approach is necessary. This approach consists of putting out the fire using cold cutting extinguishers from outside, or using unmanned vehicles from the inside. This procedure provides fire fighters with guidelines and indicators which they can use to determine what is necessary. Case studies of real parking garage fires could prove whether these guidelines work in practice. However, one thing is certain: if this procedure does not work, parking garage fires are doomed to follow the burn out scenario, despite the FRS doing their best.

CONCLUSIONS

Battery electric cars take up an increasing share of the fleet and can therefore frequently be found in parking garages and on charging points. They bring with them specific safety risks, which implies that they have to be handled differently by fire fighters. In particular, the possible thermal runaway leads to complex situations for fire suppression, with longer lasting fires, hydrogen fluoride gasses, battery parts that are hurled away, and the need for special attention to cooling the battery cells.

Regarding the latter, we assessed 10 fire tactics to suppress BEV fires [16]. Containers used for submerging are effective and relatively save to operate. They are managed by towing companies. Particularly in open fields, these containers are effective in The Netherlands, which is a densely populated country that requires fire suppression activities that reduce long lasting effects such as evacuating areas. Letting BEV-cars burn out is often impossible because of the great number of people and buildings nearby, and the well-used road network would become a grid lock. However, letting the car burn out may prevent contaminating water, although it will cause toxic plumes.

Other fire tactics such as fire blankets and penetrating the battery pack cause safety issues for the fire fighters. Fire blankets do not cool the battery cells. Although they prevent the fire from spreading, they lead to risks for the fire fighters pulling the blanket over the car. In addition, the blankets may accumulate flammable and toxic gasses. When opening the blanket, this may result in flames and an explosion. A water curtain seems to be questionable regarding its effectiveness as it does not cool the battery cells properly.

In parking garages, the fire suppression becomes even more complex due to the fact that a clear view on the car is hardly possible, to difficult fire suppression logistics and to the fire hazards for the fire fighters (high temperature, toxic fumes, explosion risks and disorientation). A container used for
submerging cannot be operated in the garage. Hence, a more defensive fire tactic is advisable, meaning that fire fighters do not enter the garage to extinguish the fire.

Otherwise, one has to wait until all fuel, the electricity, has burnt, and there is no energy left in the battery. This may, however, have serious consequences such as instability of the garage and evacuation of the surrounding area, which is not easy in a densely populated country such as The Netherlands. This implies that in the future the construction of parking garages should be designed and constructed with the discussed car fire developments in mind. However, it would be even better if car manufacturers improve battery integrity and early warning systems for battery deviations beyond the design specifications.

RECOMMENDATIONS

The recommendations are addressed to the stakeholders who, in our view, are responsible for implementing them.

Car manufacturers
We need more information regarding the ageing of lithium battery cells and their integrity. Hence, we recommend car manufacturers to gather those data and make them available to the public.
We also recommend to car manufacturers to improve the integrity of lithium-ion battery cells or develop safer battery technology. Finally, car manufactures are advised to design their battery packs in such a way that fire fighters are better facilitated in suppressing a fire.

Authorities
We recommend the authorities to update their building regulations, taking fleet management development into account in their safety requirements.

Fire and rescue services
Apply the procedures as specified above and administrate the lessons learned. In this way fire fighters learn about the practical implications of the theoretical concepts.

Research community
One of the difficulties in our research was the lack of empirical data: real life (underground) parking garage fires. Such data could be useful for both understanding fire dynamics and fire tactics. The Singelgarage fire is a good example, but we need more to be able to learn generally applicable lessons from such fires. Hence, we have developed a database for registering characteristics of incidents that involved alternative fuelled vehicles (fires, rescues and collisions). The database is used for our annual report [14] and is for a substantial part near to real time online available [15]. This database is not limited to incidents with electric vehicles, but also records incidents which involved hydrogen, LNG, CNG etcetera, both in structures like garages and outside. We would recommend other research communities to also develop such databases. As lithium-ion batteries cause the specific fire safety issues in battery electric cars, we recommend research laboratories to further examine the failure mechanisms of the battery cells, so as to be able to take adequate measures and prevent the cells from getting into a thermal runaway.

REFERENCES

Experimental study of battery fires in a tunnel: Evolution of flame characteristics and temperature profile under longitudinal ventilation

Nannan Zhu¹, Fei Tang¹, Xiepeng Sun¹, Margaret Mcnamee², Longhua Hu¹
¹ State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, China
² Division of Fire Safety Engineering, Lund University, P.O.Box 118, Lund, Sweden

ABSTRACT

Recently, the development of electric vehicles (EVs) with lithium-ion batteries (LIBs) as new energy power systems has been rapid. The fire safety code of EVs in tunnels, representative of long and narrow confined spaces, hence, urgently needs to be improved. In this work, several LIB thermal abuse experiments were conducted at six longitudinal ventilation speeds in a reduced tunnel, including lithium iron phosphate (LFP) and ternary (NCM) cells. The flame morphology and ceiling temperature distribution of new energy battery fires were recorded and analyzed. The results show that the safety venting and uncontrolled thermal runaway (TR) phases are the two critical states determining the flame characteristics. A physical model of LFP and NCM cell fires in a longitudinal ventilation tunnel is developed to describe the flame characteristic differences. In contrast with NCM batteries, the LFP battery fires are more easily affected by wind speed. For the ceiling temperature distribution of LFP batteries, three temperature wave peaks transform into two, one, and almost disappear with increasing wind speeds. Furthermore, the maximum ceiling temperature shows a negative correlation relationship with increasing wind speed for LFP cells. Compared to LFP cells, the maximum ceiling temperature of NCM batteries at wind speeds below 2.0 m/s is essentially > 127°C, which is higher than the maximum temperature of LFP batteries in the absence of wind. Concerning LFP and NCM batteries, the maximum ceiling temperature differences caused by the 2.5 m/s and 0 m/s wind speeds were all 90°C. A new dimensionless parameter is defined to describe the competing effects of the heat release rate of LIB fires and the longitudinal wind in tunnels. In experiments for LFP cell fires, the relationship between the dimensionless maximum ceiling temperature rise and the longitudinal wind can be expressed as a power function. In the future, further experiments are necessary on different charge states of larger battery packs.

KEYWORD: tunnel fire, new energy fire, cross wind, flame characteristics, ceiling temperature distribution

INTRODUCTION

During the recent decade, electric vehicles (EVs) have significantly transformed the global automotive industry, driven by the rapid development of lithium-ion battery (LIB) technology [1]. Furthermore, with the rapid development of cities, the demand for underground space utilization has reached an unprecedented level [2]. Hence, the safety of underground transportation and facilities is becoming increasingly important [3]. Nevertheless, in electric vehicle fires, the fire behavior is very specific owing to the tendency of thermal runaway (TR) of power batteries [4]. Compared with traditional fuel vehicles (gasoline, diesel cars, etc.), the main difference of electric vehicles is the power system, i.e. the LIB pack. Consequently, the electric vehicles are significantly different from traditional fuel vehicles in terms of fire mechanism, fire size, and smoke characteristics [5]. In addition, if EVs catch fire in a confined space, such as tunnel, the applicability of existing fire code is uncertain and should be subject to further study.
In the past, the combustion behaviors and flame characteristics of traditional fire sources in the tunnel, e.g. solid fires such as cables [6, 7], liquid fires such as n-Heptane [8, 9], and gas fires such as propane [10-12], have been extensively studied. Moreover, the flame morphology evolution regarding the TR of LIBs mainly focuses on windless scenarios [13-17]. For example, Kong et al. [18] found that increasing the state of charge (SOC) will raise the peak heat release rate (PHRR) and flame height of jet flame for ternary LIBs, which has been verified by simulation. Zhai et al. [19] investigated the effect of a tilted ceiling on the TR and flame heat transfer behavior of large LIB modules. The results showed that raising the ceiling angle will greatly attenuate the heat transfer behavior of the cell jet flame to other batteries, and thus effectively prevent the TR behavior. Zhang et al. [20] studied the flame extension length on ceiling jet in the context of battery module design. Results verified that the flame extension length of LIBs is suitable for You and Faeth models [21]. Several series of experiments on the thermal abuse of LIBs were carried out in open and confined space by Liu et al. [22]. The findings indicated that after the safe ventilation of LIBs in the confined cabinet, only a brief combustion process occurred and no jet fire broke out. In summary, research on flame characteristics of LIBs have primarily concentrated on cells themselves. Nevertheless, the flame pattern evolution of cell fires under the action of ambient wind requires further exploration.

To date, with respect to temperature distribution under tunnel ceiling, the previous studies have mainly addressed some problems about the traditional fire source [23-27]. Xie et al. [28] compared the temperature characteristics of hydrogen-fueled and conventional fossil-fueled vehicles under longitudinal ventilation conditions in tunnels by simulation. Studies have shown that hydrogen jet fires with strong initial momentum will push hot flue gases back to the ground and cause higher ceiling temperature distribution in contrast to oil pool fire. Tang et al. [29] experimentally studied the lateral ceiling temperature distribution of wall-attached fire with different burner aspect ratios in a 1:8 model tunnel. A lateral temperature rise prediction model considering burner aspect ratios and HRR was developed. The maximum temperature rise in a tunnel with longitudinal ventilation was studied using a propane burner (variables include HRRs and wind speeds) by Yao et al. [30]. The results show that the longitudinal ventilation has a significant effect on the maximum ceiling temperature rise. According to Li et al., a piecewise model for predicting the maximum gas temperature rise was improved and the comparison with experimental results reflected a better consistency. However, there is still a lack of information on ceiling temperature distribution patterns for LIB fires in longitudinal ventilation tunnels.

Tunnels, as representatives of long and narrow confined spaces, will influence the course of battery fires. Firstly, in contrast to an open space battery fire, the confined space of the tunnel will affect the air entrainment of battery fires. Furthermore, another typical feature of tunnels, the longitudinal wind, will cause the battery fire plume to tilt. The flow of the ceiling jet and hot smoke layer can be asymmetrical due to the narrow and constrained structure of the tunnel. When the longitudinal wind reaches a certain value, the ceiling temperature distribution is expected to shift downstream. In this work, the evolution law of flame characteristics and ceiling temperature distribution of LIB fires in a tunnel were experimentally studied. Battery fires in the tunnel are a non-stationary process and relevant parameters including ceiling temperature are continuously changing with time. Therefore, the characteristic stage of TR was selected, separately, to analyze the maximum ceiling temperature. Additionally, a modified model to describe the temperature rise beneath the tunnel ceiling was applied. This study provides important knowledge concerning the dynamic evolution of battery fires in tunnels.

**EXPERIMENT**

**Battery samples**

Currently, there are two main battery technology routes in new energy vehicles, i.e. lithium iron phosphate (LiFePO₄, LFP) and ternary lithium (Ni-Co-Mn, NCM) batteries. Due to the different cathode materials, the two mains batteries in the market have their advantages and disadvantages. This is mainly manifested in the LFP battery in terms of its safety, long life, and high-temperature resistance; and in the NCM battery in terms of its light-weight, high charging efficiency, and low-temperature resistance. In this work, the commercial LFP battery and the NCM battery were selected as experimental
cells, respectively. The LFP battery is the 32700-type cylindrical cell, 32 mm in diameter and 70 mm in length; and the NCM battery is the 18650-type cylindrical cell, 18 mm in diameter and 65 mm in length. The two commercial LIBs have graphite anodes, and the cathodes were constructed of LFP and NCM. The electrolytes are ethylene carbonate, ethyl methyl carbonate, dimethyl carbonate, and LiPF6. Table 1 summarizes the physical properties of the batteries.

In this experiment, after activating batteries, LFP and NCM battery samples were all charged to 100% state of charge (SOC) using constant current and constant voltage (CCCV) mode (a 0.5 C rate CCCV charge until the voltage reached the charge cut-off voltage 3.65 V (4.2 V) and the current decreased to the cut-off current 100 mA (30 mA)). Subsequently, all batteries were rested for at least 24 h to ensure stability. As 100% SOC batteries is the most dangerous state, the ceiling temperature rise was studied as the worst case for battery fires in a model tunnel.

Table 1

<table>
<thead>
<tr>
<th>LIBs</th>
<th>Physical properties of the different material used as fuel.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LFP battery</td>
</tr>
<tr>
<td>Size</td>
<td>32700</td>
</tr>
<tr>
<td>Cathode material</td>
<td>LiFePO$_4$</td>
</tr>
<tr>
<td>Anode material</td>
<td>Graphite</td>
</tr>
<tr>
<td>Cell weight (g)</td>
<td>142±3 g</td>
</tr>
<tr>
<td>Nominal voltage (V)</td>
<td>3.2</td>
</tr>
<tr>
<td>Nominal capacity (mAh)</td>
<td>6000</td>
</tr>
<tr>
<td>Internal resistance (Ω)</td>
<td>10±2</td>
</tr>
<tr>
<td>Charge cut-off voltage (V)</td>
<td>3.65</td>
</tr>
<tr>
<td>Discharge cut-off voltage (V)</td>
<td>2.0</td>
</tr>
<tr>
<td>SOC</td>
<td>100%</td>
</tr>
</tbody>
</table>

Experimental setup

As shown in Fig. 1, experiments were carried out in a model tunnel of 8 m (length) × 1.2 m (width) × 1.0 m (height). A fan with a 4 m long rectifier section provided the longitudinal wind to the model tunnel. A hot-wire anemometer with 3 probes (accuracy: 0.01 m/s) was installed near the fire source to measure the crossflow velocity. Cross airflow speeds ranged from 0 to 2.5 m/s with a turbulence intensity of less than 5% [10]. The exit end of the tunnel was open. The ceiling floor and the sidewall which were not used to observe the experimental phenomenon were made of steel brackets. The front glass plate used to photograph flame characteristics was not installed in this experiment for better recording the flame images and to prevent the gas generated during TR from exploding in the confined space.

An electric heater of 2 kW (150 mm length, 125 mm width) was used as the external heating source to trigger the thermal runaway. It was placed on a raised platform covered by a fireproof panel inside the chamber. A steel support was used to hold batteries in a vertical position. A total of 33 type-K thermocouples with a diameter of 1 mm were installed about 2 cm beneath the model tunnel ceiling, as shown in Fig.1(a). The thermocouple directly above the battery fire source is marked as $T_0$. The upstream tunnel and downstream tunnel included 12 thermocouples (0.05 m spacing between upstream tunnel thermocouples $T_{u,1}$ to $T_{u,10}$, and 0.10 m spacing between upstream tunnel thermocouples $T_{u,10}$ to $T_{u,12}$) and 20 thermocouples (0.05 m spacing between upstream tunnel thermocouples $T_{d,1}$ to $T_{d,10}$, and 0.10 m spacing between upstream tunnel thermocouples $T_{d,10}$ to $T_{d,20}$) respectively. The ceiling temperature rise triggered by the heater when there was no battery can be seen in Fig. 1(c). The mass loss during the thermal runaway of LIBs was recorded by an electronic balance with an accuracy of 0.01 g. The flame morphological characteristics were recorded by two digital cameras with 25 fps, 1920 × 1080 pixels in Fig. 1(d).

In the experiment, the battery fire source was 0.5 m from the model tunnel ceiling. At the same time, the cell surface temperature was recorded by attaching a type-K thermocouple to the surface of the
battery, to describe the thermal runaway process. The ambient temperature was approximately 30 ± 5 °C.

![Diagram](image)

**Figure 1**  
(a) Schematic of experimental setup; (b) The wind speed ranges from 0 to 2.5 m/s; (c) The ceiling temperature rise causes by the external heat source (no LIBs); (d) The flame characteristics of two cells.

### RESULTS AND DISCUSSION

**Flame evolution under longitudinal ventilation**

*Flame evolution of 32700-type LFP batteries*  
Fig. 2 and Fig. 3(a) shows typically the flame geometry evolution and surface temperature variation of cells during the entire thermal runaway process on the 32700-type LFP battery fires with increasing crosswind speed (0, 0.5, 1.0, 1.5, 2.0, and 2.5 m/s wind velocity), respectively. From Fig. 2, it can be found that the whole experimental process can be divided into four stages: (a) the continuous heating stage; (b) the gas emission stage (venting), stable combustion; (c) the thermal runaway stage, jet fire; and (d) the attenuation stage. **Stage (a):** the starting point of the first phase was marked by the electric heater starting to heat the test cell and the endpoint was when the cell safety valve was broken. It can also be seen in Fig. 3(a) that the cell surface temperature slowly increases during stage (a). Along with the complex exothermic reaction between the positive electrode, negative electrode, and electrolyte inside the battery, a large amount of gas was generated inside the battery. However, the pressure inside the battery did not reach the safety valve rupture limit, so the gas release process was not observed at this stage. At the start of **stage (b):** the safety valve ruptured with a cracking sound. The gas accumulated inside the battery started to be released and a sudden jet of flame was seen at this point. For example, when the wind speed was 0.5 m/s, at 568.20 s, a bifurcation of the flame was observed. It is important to note that, the main reason for the flame formation of LFP batteries is the high-temperature effect of the electric heater that causes the flammable gas released from the batteries to catch fire. As high-temperature fumes carrying a lot of heat were released into the environment, the safety venting point was recorded as \( T_{\text{vent}} \) in Fig. 3(a). As the exothermic reaction inside the cell was proceeding, the cell continued to produce combustible gas and a relatively stable flame was observed. At wind velocities of 0-0.5 m/s, no significant flame tilt was observed. However, as the crosswind speed increased, the flame was stretched in a downstream direction during this stable combustion phase. The stretch was more...
pronounced at 1.5 and 2.0 m/s wind speeds. This was made possible by the presence of the longitudinal wind which affects the air entrainment and thus contributed to a significant tilting of the battery flame and its plume. For example, at a wind speed of 1.0 m/s, no flame (smoldering fire) was seen in 446.24 s and only a large amount of gas diffusion, which is mainly because the longitudinal wind accelerated the ambient cooling and the battery did not produce enough gas to ignite. Other influences include the fact that the radiative heat of the furnace was slightly reduced after a long period of use. More seriously, at a crosswind speed of 2.5 m/s, there was no flame at all at this stage. Stage (c) can be seen in Fig. 3(a), as a sharp temperature turnaround, which means that the uncontrollable TR moment ($t_{t}$) emerged. For example, in Fig. 2, at 535.20 s and 537.20 s under no wind, a large amount of gas was violently released again, followed by a nonstationary jet fire being ejected. Therefore, at higher wind speeds than 2.5 m/s, jet fires can also be observed. Stage (d) is seen when the internal reaction weakened, the LIB surface temperature was reduced gradually. At this stage, the jet flame became faint and was completely extinguished. Thereafter, the TR battery cooled naturally until the end of this test.

**Figure 2** Flame evolution of LFP batteries under longitudinal ventilation: 0, 0.5, 1.0 m/s, 1.5, 2.0, and 2.5 m/s.

**Flame evolution of 18650-type NCM batteries**

Fig. 4 show the flame geometry evolution of cells during the entire thermal runaway process from the 18650-type NCM battery fires under 0, 0.5, 1.0, 1.5, 2.0, and 2.5 m/s wind velocities, respectively. From Fig. 4, it can be seen that the whole experimental process can be divided into four stages (as for the LFP batterie), here denoted: (I) the heating stage; (II) the venting stage (the gas emission); (III) TR, sparks and jet fire; (IV) the stable combustion and attenuation stage. During the heating phase, there was almost no change in the cell surface. The battery surface temperature slowly increased under the action of the electric heater as seen in Fig. 3(b). In addition, what is not visible is that a complex exothermic reaction began to occur inside the battery under the continuous action of an external heat source to produce a large amount of combustible, toxic and harmful gases. After a large accumulation of these gases inside the cell, a venting phase (stage (II)) occurred when the gases were released into the environment. In this experiment, a TR phase (stage (III)) with a rapid temperature rise rate appeared immediately after venting, unlike past studies where venting was followed by a gestation period [31]. During this phase, flames with combustible materials inside the cell were instantaneously ejected. A brief ceiling jet phenomenon can be observed when a jet fire reached the
tunnel roof as seen in Fig. 4. The jet flame with a wind speed of 0 m/s was vertically upward and had only a slight slope downstream at 2.5 m/s. This is mainly due to the fact that although the NCM battery flames are emitted coming out of the battery cell, the battery fires show an explosive jet during thermal runaway, which makes the battery fires not tilt at higher wind speeds. Finally, the flame was extinguished as the combustible material burned out.

Figure 3 Surface temperature change of cells under longitudinal ventilation: 0, 0.5, 1.0, 1.5, 2.0, and 2.5 m/s wind velocity: (a) LFP batteries, (b) NCM batteries.

Figure 4 Flame evolution of NCM batteries under longitudinal ventilation: 0, 0.5, 1.0, 1.5, 2.0, and 2.5 m/s wind velocity.

Discussion of flame evolution mechanism of LFP and NCM batteries in crossflow

The flame evolution characteristics of TR processes of LFP and NCM batteries are described separately above. Previously, for both cells, the flame characteristics have been studied in the absence of wind. The inertial force introduced by ambient wind interacts with the buoyancy of battery fires in the vertical direction, causes a complex evolution of flame patterns [11]. Therefore, it is necessary to further analyze the evolutionary characteristics of flame morphology under the environmental wind effect. A physical
model of LFP and NCM battery fires on the controlling mechanism in the tunnel under longitudinal ventilation is given in Fig. 5. As shown in Fig. 5(a), the conditions of safe venting and uncontrolled TR for LIBs can be described by [4]:

\[
P_m - P_i > P_{crack} \tag{1}
\]

\[
dT_{b, surface} / dt > \varepsilon \tag{2}
\]

where \(P_m\) is the internal battery pressure, kPa; \(P_i\) is the environmental pressure, kPa; \(P_{crack}\) is the pressure which can be reached by a ruptured battery safety valve, kPa; \(dT_{b, surface} / dt\) is the cell surface temperature rise rate, K/s; \(\varepsilon\) is a temperature rise rate that the battery surface temperature reaches the critical value of uncontrollable thermal runaway, K/s.

In experiments, the cell surface temperature gradually increased under the action of an external heat source seen in Fig. 3. During the initial heating process, the organic solvent inside the closed cells evaporated. The electrolyte reacted with the electrode material or self-decomposed releasing large amounts of flammable gases in Fig. 5(a). The accumulated gases, therefore, increased the pressure inside the battery. When the battery safety valve could no longer handle the higher internal pressure, the safety valve opened and the gas escaped [1]. This can be explained by Eq. (1). As can be seen in Fig. 5(a) and Eq. (2), flammable gases were produced when the battery underwent TR, including the production of CO, CO\(_2\), H\(_2\), CH\(_4\), C\(_2\)H\(_4\), and other gases [17]. In this work, the flame morphologies of LFP and NCM batteries are inconsistently affected by the ambient wind, which is mainly attributed to the difference in cathode materials [1]. Compared to NCM batteries, LFP batteries have better thermal stability [32]. Therefore, the flame of the LFP battery was relatively stable in the experiments. In addition, it is also found that the flame characteristics of LFP batteries under the longitudinal wind were relatively similar to that of gas fires and oil pool fires studied in the past [33-35]. Flame tilt, and flame stretching at stronger wind speeds can also occur in Fig. 5(b). The difference is that the experimental LFP batteries after safety ventilation, even in the absence of wind, will also exhibit a "blow-out phenomenon". Afterward, as the heating process proceeds, the LFP battery will again produce flammable gases and the extinguished flame will reignite. This is mainly related to the characteristics of the thermal runaway process of LIBs. However, the experimental NCM cells have a relatively simple flame pattern, mainly due to larger “fireballs” with cathode material being released during TR in Fig. 5(b). The gas flow rate generated by the cell is crucial to analyze whether the flame is momentum-driven or buoyancy-driven. According to studies by Mao et al. [17], the gas jet model of the battery is divided into three stages: Level 1 (conditions inside the cell), Level 2 (conditions at the orifice), and Level 3 (conditions after a national expansion to ambient conditions), as shown in Fig. 5(b). The jet ejected from the cell is a high-pressure fluid that expands rapidly downstream of the nozzle and equilibrates with the surrounding environment (Level 3) [36]. Therefore, the flame height of battery fires is related to fluid characteristics at the virtual nozzle (Level 3), including the combustible gas flow rate.

In physical terms, the flame morphology (including flame height) of battery fires in a longitudinally ventilated tunnel is influenced by the inertial force of the wind (\(v^2\)) and thermal buoyancy (\(gd\)) of the fire source. Froude number, \(Fr\), can be represented by the following formulas [10]:

\[
Fr = \frac{v^2}{gd} \tag{3}
\]

where \(v\) represents the wind speed, m/s; \(g\) is the gravity acceleration, m/s\(^2\); here, \(d\) replace with battery nozzle diameter, m.

Consequently, in a longitudinal ventilation tunnel, the competitive relationship between thermal buoyancy and inertial force is explained by the \(Fr\). For LFP batteries, when the wind speed is greater than 1.0 m/s (\(Fr > 3.2\)), the longitudinal winds and confined space will accelerate the plume entrainment behaviour resulting in higher wind pressure upstream of the flame than downstream. Hence, the flame tilt is more obvious. With a further increase in wind velocity to 2.0 m/s (\(Fr = 12.76\)), the flame is almost on the ground. Nevertheless, it should be noted that the above-mentioned effect of wind on flame pattern occurs from safe battery ventilation to uncontrollable thermal runaway, depending on the wind and battery type. For example, at 2.5 m/s, the combustible gas was not ignited (smoldering fire period) when
the battery was safely ventilated because the relative stronger wind speed makes the heat dissipation increase and the combustible gas is not ignited. However, during TR phase of the battery, the flame reappeared. This is due to the high temperature of combustible gases during the TR stage. In contrast to LFP batteries, the flame of NCM cells was mainly generated with a large fireball ejected from the TR stage, which evolved into a faint flame of relatively stable combustion. Accordingly, the $Fr$ number is not very applicable to this experimental phenomenon. However, some NCM batteries only eject a large amount of gas-solid mixture and catch fire when they are thermally out of control [22]. In conclusion, cells with different cathode materials exhibit different flame morphologies in longitudinal ventilation tunnels, which have important research value for future tunnel protection [37-39].

![A physical model of LFP and NCM battery fires on controlling mechanism in tunnel.](image)

**Figure 5** A physical model of LFP and NCM battery fires on controlling mechanism in tunnel.

**Ceiling temperature distribution of battery fires under longitudinal ventilation**

*Temperature profile of LFP and NCM batteries in crossflow*

The experimentally measured ceiling temperature profiles of the upstream and downstream of the battery fire source in the tunnel with different wind speed as a function of time are given in Fig. 6 and Fig. 7, respectively. Due to the stronger wind, the bright jet flame was not stretched, and there was only a slight rise in the ceiling temperature. It can be seen that a more obvious feature is the appearance of three peaks about ceiling temperature distribution under no wind in Fig. 6(a). The peak temperatures of the three wave crests are 83°C, 124°C, and 120°C, respectively. Combining Fig. 2 and Fig. 6, this is attributed to the different phases of the cell thermal runaway: the first and third waves are caused by the safe ventilation of the battery and the uncontrollable phase of thermal runaway, respectively. The extinguished battery fire produced a large amount of combustible gas again at about 470 s and was ignited, which is the main reason for the formation of the second peak. However, with the increase in wind speed, the three wave peaks transform into two (88°C, 56°C) at 0.5 m/s wind speed. For higher wind velocities, there is only one or even no temperature rise peak. Moreover, the bifurcated flames can
be observed at 0 and 0.5 m/s wind speeds, which is mainly present in the stable combustion stage (stage (b)). As shown in Fig. 6(d), the flame stretching or "ground-hugging behavior" can be observed at higher wind speeds. However, at 2.5 m/s wind velocity, the battery did not catch fire in stage (b), which is different from the other wind speed. Furthermore, the combustible gases ejected from the battery in the stage (c) were ignited under the high temperature of the heater. Nevertheless, it only lasts for a relatively short time. In summary, for the LFP battery fires, the ceiling temperature rise in the tunnel is mainly caused by the flame in the stage (b) when the wind speed is less than 2 m/s. As the wind speed increases, the ceiling temperature rise in the stage (3) tends towards the ambient temperature due to the dominant effect of ventilation to accelerate heat dissipation.

Figure 6  Ceiling temperature curves of 32700-type LFP batteries at different locations under longitudinal ventilation: 0, 0.5, 1.0, 1.5, 2.0, and 2.5 m/s wind velocity.

Figure 7  Ceiling temperature curves of 18650-type NCM batteries at different locations under longitudinal ventilation: 0, 0.5, 1.0, 1.5, 2.0, and 2.5 m/s wind velocity.
However, unlike LFP battery fires, the ceiling temperature distribution caused by 18650-type NCM battery fires in the tunnel was only one wave peak at different wind velocities, which can be seen in Fig. 3 and Fig. 7. The main reason for the ceiling temperature rise is caused by the spark injection and unstable jet fire during the TR of NCM batteries accompanied by gas-solid mixture ejected [31]. For the steady combustion stage, the weak flame was not enough to cause a temperature rise. In addition, at a higher wind speed of 2.5 m/s, the ceiling temperature distribution near the tunnel fire source was still around 70°C, which is in stark contrast to LFP cell fires. In conclusion, when the wind speed is greater than 1.0 m/s, the temperature rise of the two types of batteries has a relatively similar trend. For the battery fires in the tunnel with two different cathode materials, the lithium iron phosphate fires are easily affected by wind speed. In addition, the ceiling temperature rise of LFP battery fires is controlled by different stages of the thermal runaway process. However, for NCM batteries, the unstable jet fire after safe ventilation is the main risk.

In general, for LIBs in tunnel, the effect of the ambient wind will, on the one hand, accelerate battery heat dissipation and delay the triggering of TR. Furthermore, because there are only exits at both ends of the tunnel, the longitudinal wind will accelerate airflow and provide sufficient oxygen for battery combustion. Thirdly, it will cause a significant tilt in the battery flame and its plume. Fig. 8 and Fig. 9 show that the temperature of each ceiling position and change of the maximum temperature position at the moment of maximum temperature under different wind speeds for LFP and NCM kinds of batteries. It is noted that there is an uncertainty in the direction of the jet flame during TR of LIBs. As shown in Fig. 8(a), for LFP battery fires under 0 m/s wind velocity, even though the location of the maximum ceiling temperature is not directly above the fire source, the upstream and downstream temperatures of the tunnel are largely symmetrical. Moreover, when the wind speed is greater than 1.5 m/s, the temperature at different locations is almost the same without much turnaround. However, as can be seen in Fig. 8(b), the ceiling temperature at different locations on both sides of the maximum temperature location exhibits a decreasing trend. Contrary to LFP batteries, the ceiling temperature near the fire source (± 0.20 m) is about 20°C higher than the ambient temperature even at a strong wind speed of 2.5 m/s. As the wind speed increases, the crash position tends to move downstream as seen in Fig. 9. The difference is that the maximum temperature position of the NCM cells moves upstream first, and then the turning point occurs at 1.5 m/s. In the experiments, the maximum temperature position of the two batteries developed as the average value of the maximum temperature position change of LFP cells and NCM cells are 0.16 m (Upstream) and -0.04 m (Downstream), respectively. In addition, for the maximum ceiling temperature of two cell fires in the tunnel, the temperature differences caused by the maximum and minimum wind speeds were all 90°C. Combined with the effect of longitudinal ventilation in the tunnel on the ceiling crash location and ceiling temperature of battery fires with different cathode materials, the wind velocity had a relatively large effect on LFP battery fires compared to NCM battery fires [32].

Figure 8  Temperature of each ceiling positions at the moment of maximum temperature under different wind speeds: (a) LFP batteries (b) NCM batteries.
Variation of the maximum ceiling temperature positions at different wind speeds: LFP and NCM batteries.

Maximum temperature rise of LFP and NCM batteries in crossflow

It was found that the battery fire in the tunnel is a non-stationary process and the relevant parameters including heat release rate, flame morphology, and ceiling temperature are continuously changing with time, which is inconsistent with past studies of conventional fire sources (e.g. oil pool fires, wooden pallet fires, cable fires, etc.) [31]. The non-stationary battery fire source is mainly determined by two factors, time and space so that the tunnel ceiling temperature can be expressed by the following equation [40]:

$$\Delta T = fcn(t, x)$$

here, $\Delta T$ is a ceiling temperature rise in tunnel; $t$ is a time; $x$ is vectorial observation coordinate. The characteristics of the ceiling temperature variation of battery fires in the tunnel have been described in detail above. It can be summarized that the two characteristic times can be identified during battery fires, i.e. the safe ventilation time $t_{\text{vent}}$ and uncontrollable TR time $t_{\text{tr}}$, which are the key points that caused the tunnel ceiling temperature rise. For NCM batteries, the maximum ceiling temperature rise begins at the moment of uncontrollable TR ($t_{\text{tr}}$) or stage (III). In the case of LFP cells, however, the maximum ceiling temperature rise under the effect of longitudinal ventilation exists mainly during safe ventilation and TR (at the stage (b) and stage (c)). Therefore, the maximum ceiling temperature rise can be analyzed beginning with these two time points [1]. To simplify the analysis, the maximum ceiling temperature can be expressed as a function of time

$$\Delta T_{\text{max}} = fcn(t), \quad t_{\text{vent}} \leq t < t_{\text{tr}} \text{ and } t_{\text{tr}} \leq t$$

Consequently, for LFP batteries, the temperature rise begins to occur after safe ventilation (385 s) in Fig. 6(a). In addition, the first wave is reached almost instantaneously to 356 K. In the time between 385 s and 471s, it is the first small crescendo in the ceiling temperature rise. After this, the ceiling temperature can enter a second wave that lasts until 563 s. It is important to note that the thermal runaway of LIBs is still in the post-safety ventilation phase. Finally, the uncontrollable thermal runaway begins and the ceiling temperature rise enters its final phase. Furthermore, with the increase of wind speed, the ceiling maximum temperature distribution tends to the initial stable flame state of cells. According to Eq. (1), for LFP batteries, the maximum ceiling temperature of several combustion stages under different wind velocities can be summarised as:

$$\Delta T_{\text{max}} = \begin{cases} 356K(t_{\text{vent}} \leq t < 471), & 397K(471 \leq t < t_{\text{tr}}), & 393K(t_{\text{tr}} \leq t), & v = 0 \text{ m/s} \\ 361K(t_{\text{vent}} \leq t < t_{\text{tr}}), & 330K(t_{\text{tr}} \leq t), & v = 0.5 \text{ m/s} \\ 345K \rightarrow 320K(t_{\text{vent}} \leq t < t_{\text{tr}}), & 0.5 \text{ m/s} < v < 2.0 \text{ m/s} \\ \text{Approximate ambient temperature}, & 2.5 \text{ m/s} < v \end{cases}$$

In comparison, the temperature rise curve of NCM batteries is relatively homogeneous. The maximum ceiling temperatures all appear in stage (III) and end in a flash. Therefore, not much attention needs to
be paid to its ceiling temperature evolution characteristics at different wind speeds. In the experiment, the main cause of the first ceiling temperature rise is the safety venting of LIBs. Eq. (1) and Eq. (2) can be used for interpretation. For the same LIBs, the cooling effect on the battery will intensify as the wind speed increases. However, the safe venting time of the experimental LFP batteries did not exactly increase with time. This is also the case for NCM cells in Fig. 7. This is due to the aging of the external heat source equipment and the consistency of the battery itself during the experiment.

According to the above analysis, during the whole process of TR, the maximum ceiling temperature of LFP cells is in the battery stabilization flame stage, while maximum ceiling temperature of NCM batteries is basically in the jet fire stage. Fig. 10(a) and Fig. 10(b) give the maximum ceiling temperature for the two cells at different wind speeds. For LFP batteries, when the wind speed is 0 m/s, the maximum ceiling temperature is highest, at 397 K and the wind speed for the highest maximum ceiling temperature of NCM cells is 0.5 m/s with a value of 471 K. It can be seen that for the LFP batteries as the wind speed increases, the maximum ceiling temperature shows a negative correlation. However, NCM cells are not suitable for predicting the maximum ceiling temperature, which is mainly related to the fact that the experimental cells with a high degree of uncertainty eject a fireball accompanied by a gas-solid mixture.

Taking into account the typical characteristics of a tunnel as a long and narrow confined space and the presence of longitudinal winds, the air entrainment behaviour of battery fires will be accelerated by the inertial force of the wind and the fire plume can be deflected at higher wind speeds. Further, when the cell fire plume hits the tunnel roof, the ceiling temperature development will be affected due to the longitudinal wind accelerating the air dissipation. In summary, the ceiling temperature rise is mainly related to the heat release rate (HRR, \( Q \)) of battery fires and the longitudinal wind. Considering the particular boundaries of the tunnel, the ceiling temperature rise (\( \Delta T \)) of battery fires can be represented by the following function:

\[
\Delta T = fcn(Q, v, d, g, H)
\]

According to the above analysis, the maximum ceiling temperature rise of LFP cell fires at different wind speeds occurs mainly during the steady combustion phase (stage (b)). Therefore, to simplify the analysis, according to the Eq. (4), Eq. (5), and Eq. (6), the maximum ceiling temperature rise can be inferred from:

\[
\Delta T_{\text{max}} = \Delta T_v = fcn(Q, v, d, g, H), t \in (t_{\text{vent}}, t_{\text{tr}})
\]

Using dimensional analysis, Eq. (8) can be manipulated and shown as:

\[
\Delta T_{\text{max}} / T_s = fcn\left(\frac{Q}{(\rho_v C_p T_s g^{1/2} H^{3/2}), v^2 / (gd)}\right) = fcn(\dot{Q}, Fr)
\]

where \( T_s \) is the ambient temperature, K; \( \dot{Q} \) is the dimensionless heat release rate; \( \rho_v \) is the air density, kg/m\(^3\); \( C_p \) is the constant pressure specific heat capacity, kJ/(kg·K); \( H \) is the height of battery fires from the tunnel ceiling, m.

In Fig. 10, the \( \Delta T_{\text{max}} \) gradually decreases as the wind speed increases. The HRR from the fire source in the tunnel is also the main parameter affecting the \( \Delta T \). Therefore, a new parameter, \( \kappa \), is defined to describe the competing effects of HRR and \( v \).

\[
\kappa = \frac{\dot{Q}}{Fr}
\]

Here, no wind is considered, i.e. \( Fr \) is equal to 0. Thus, combining Eq. (9) and Eq. (10), the dimensionless maximum ceiling temperature rise can be expressed as:

\[
\Delta T_{\text{max}} / T_s = fcn(\kappa) = fcn(\dot{Q} / Fr)
\]

In this work, the heat release rate can be calculated using the Eq. (12) [13]:

\[
Q = \chi \Delta H_c \dot{m}_b
\]
Fig.10(c) shows the mass loss, mass loss rate and heat release rate curves with time for LFP cell fires under the 0 m/s wind velocity. Combined with Fig.6(a), the maximum ceiling temperature under no wind corresponds to the peak HRR (3.6 kW) of the stage (b). This method is also used to value the HRRe at other wind speeds. The dimensionless relationship with a power function (the fit coefficient is 0.811) between the maximum ceiling temperature and wind speed is described in Fig.10(d). Considering the absence of wind, the dimensionless ceiling maximum temperature rise of LFP battery fires in this experiment can be showed by the following step function:

$$\Delta T_{\text{max}} / T_\infty = \begin{cases} 1.32, & Fr = 0 \\ fcn\left(1.302(\dot{Q} / Fr)^{0.034}\right), & Fr \in (0.80,19.93) \end{cases}$$

(13)

In addition, experimental battery fires, which blow out to re-ignition and burn less steadily at different wind speeds, introduce a certain amount of data uncertainty.

CONCLUSION

In this work, LFP and NCM batteries were experimentally carried out at different wind speeds in a longitudinal ventilation tunnel, respectively. The flame characteristics and ceiling temperature distribution of two cells in the presence of ambient wind were studied. The main findings are as follows:
1) The combustion processes of both LFP and NCM batteries are divided into four stages in the tunnel, where the safety ventilation and uncontrolled jet fire phases are the two key states of LIB fire. Compared to NCM batteries, it is found that the flame characteristics of LFP batteries under ambient wind are relatively similar to that of gas fires and oil pool fires studied in the past. The flame stretching or “ground-hugging behavior” can be observed at higher wind speeds >2.0 m/s. Furthermore, for LFP batteries, the competitive relationship between the thermal buoyancy and inertial force is well explained by the Fr, where Fr > 3.2, correlates to higher flame tilt of LFP cells.

2) The maximum ceiling temperature of NCM fires is nearly 1.5 times higher than LFP fires at no wind. For LFP batteries, with increasing wind speeds, the three temperature wave peaks transform into two, one, and even almost the same as the ambient temperature at 2.5 m/s. The ceiling temperature distribution is mainly in the stable combustion phase. Unlike LFP batteries, the ceiling temperature caused by NCM battery fires is only one wave peak at different wind velocities. In addition, at a higher wind speed of 2.5 m/s, the maximum ceiling temperature is still around 70°C. The average value of the maximum temperature position change of LFP cells and NCM cells are 0.16 m (Upstream) and -0.04 m (Downstream), respectively. In summary, LFP battery fires are more easily affected by the wind speed.

3) A time-dependent segmentation function was developed to describe the maximum ceiling temperature of battery fires in the tunnel. It can be concluded that the times of safe venting (t_{vent}) and uncontrollable TR (t_{tr}) are the key points that caused the tunnel ceiling temperature rise. In terms of LFP batteries, the maximum ceiling temperature shows a negative correlation with increasing wind speed. Compared to LFP batteries, the maximum ceiling temperature of NCM batteries at wind speeds below 2.0 m/s is basically above 127°C, which is already higher than the maximum temperature of LFP cells in no wind. Further, for the maximum temperature of LFP and NCM cells in the tunnel, the temperature differences caused by the maximum and minimum wind speeds are all 90°C, respectively. In the experiments, the relationship between the dimensionless maximum ceiling temperature rise and the longitudinal wind can be expressed as a power function due to the relative stability of LFP battery fires.

Finally, LIBs generally exist in battery packs. In the future, further experiments are needed on flame characteristics (flame height, flame inclination, and horizontal length), and temperature variation in tunnels caused by TR propagation of multiple cells and different SOCs.

REFERENCES


[16] Huang Z, Shen T, Jin K, Sun J, Wang Q, Heating power effect on the thermal runaway characteristics of large-format lithium ion battery with Li(Ni1/3Co1/3Mn1/3)O2 as cathode, Energy, 2022;239: 121885.


Hydrogen Tunnel Risk Assessment – numerical study of selected hydrogen incidents and implementation in the Austrian Tunnel Risk Model

Oliver Heger\textsuperscript{1}, Regina Schmidt\textsuperscript{1}, Daniel Fruhwirt\textsuperscript{2} & Martin Aggarwal\textsuperscript{3}
\textsuperscript{1}ILF Consulting Engineers, Graz, Austria
\textsuperscript{2}Graz University of Technology, Graz, Austria
\textsuperscript{3}Hydrogen Centre Austria Ltd., Graz, Austria

ABSTRACT
With an increasing share of alternative propulsion energies, potential effects of these systems on tunnel safety become an important issue. This is in particular the case for hydrogen used as energy carrier, where the nature of fire incidents might completely change due to explosions and temporary but violent jet fires. In order to investigate the potential impact of hydrogen incidents on tunnel safety the Austrian Federal ministry for climate action, environment, energy, mobility, innovation and technology launched a dedicated research project – the HyTRA project. Based on a qualitative event-tree analysis considering the reviewed research findings, five hydrogen scenarios were derived. With respect to latest research findings on hydrogen incidents in tunnels and based on available engineering tools, consequence models have been developed and implemented in the Austrian tunnel risk model. The resulting consequence numbers indicate that hydrogen incidents can lead to significantly higher consequences than conventional tunnel fires in modern unidirectional road tunnels. The results strongly depend on the relation between incident time line and emergency response. A realistic and precise treatment of the emergency response time line in a tunnel risk assessment of an actual tunnel is therefore critical, if hydrogen vehicles become relevant in the future.

KEYWORD: hydrogen jet fire, hydrogen release, tunnel risk model, numerical investigations

INTRODUCTION
Automotive propulsion is mainly based on the burning of fossil fuels. This concept represents a well developed and feasible technology. However, its consequence is the release of green house gases that in the end lead to well known effects of global warming, climate change and increase in frequency of extreme weather events. For this reason new technologies have been developed in order to replace the conventional system. Hydrogen seems to represent one promising alternative, as its gravimetric energy density (33.3 kWh/kg) enables similar driving distances as gasoline and diesel driven vehicles \cite{1}. Nevertheless, its low volumetric energy density (2.98 kWh/Nm\textsuperscript{3}) requires hydrogen to be storred liquified at very low temperatrures (-253°C) or as a pressurized gas at high pressure levels. Currently, the gasseous storage is more common than the liquid storage. The typical storage pressures are 35 MPa for buses and trucks and 70 MPa for passenger vehicles. The hydrogen inventory of a single tank (64 – 152l) is typically in the range of 3.2 – 6.2 kg \cite{2}. While the use of hydrogen bears promising advantages from a pure technological point of view, it also poses special risks in case hydrogen-propelled vehicles are involved in incidents. The potential consequences might be particularly critical, if the incident happens in an enclosed environment like a tunnel. Therefore, several research projects investigated the physical consequences in case vehicles with alternative energy carriers like hydrogen, are involved in a tunnel incident - in particular in a tunnel fire. In the HyResponse project, for instance, special training programs for first responders reacting on hydrogen incidents were developed \cite{3}. The INERIS – DRIVE project as well as research activities carried out by the Swedish research institution RISE are other examples. There, the potential consequences were
Specific risks are associated with the high storage pressure of compressed gaseous hydrogen, typically used in the transportation sector. If a hydrogen-propelled vehicle is involved in an incident that leads to a rupture of the tank, harmful and even lethal overpressures in the surrounding of the vehicle and also along the tunnel might occur. To prevent intolerable pressures in the tank, hydrogen systems are equipped with pressure relief devices (TPRDS). These devices are thermally triggered. In case of high temperatures, a thermal fuse opens a flow path to release the hydrogen from the tank and consequently prevents the tank from bursting. In the case of a TPRD malfunction in combination with sufficient external heat, the hydrogen tank pressure may exceed the burst pressure which can finally leads to a tank rupture. In such a case, a blast wave which propagates along the tunnel, will cause
severe damage on the tunnel equipment and serious consequences for humans that may lead to lethal effects. A tank rupture can also lead to thermal effects in the form of a fireball in addition to the mechanical stresses. If, on the other hand, the pressure-relief device is working properly and the bursting of the tank is prevented, hydrogen is released with very high velocities due to the high storage pressure and the small opening. This can lead to jet-flame formation, if the released hydrogen is ignited. It is most likely that this hydrogen jet will ignite, as the required ignition energy for H\textsubscript{2} is only 0.017 mJ as well as due to the underlying fire that caused the triggering of the TPRD. Such hydrogen jet fires represent another type of hazard. The direct contact can cause serious injuries and severe pain, as the stoichiometric combustion temperature of 2130°C is significantly higher than flame temperatures of typical hydrocarbon fires. In addition, hydrogen flames are also difficult to detect because of its missing electromagnetic radiation in the visible spectrum. In case hydrogen is released unignited from the pressure release device or any other part of the storage system, a gas cloud forms, which is then propagating along the tunnel. With a lower flammability limit of 4Vol % and an upper flammability limit of 76%, there is a high possibility for such a gas cloud to form a flammable or even explosive mixture inside the tunnel and cause a so called vapor cloud explosion, if being exposed to a sufficient ignition source. Following this line of thought three scenario types are associated with hydrogen incidents in tunnels:

**Tank rupture, hydrogen jet flame and hydrogen vapor cloud explosion.**

To estimate how critical such incidents can become in terms of passenger safety, a detailed knowledge about the boundary conditions e.g., the scenario timeline, under which such incidents are most likely to happen, have to be known. To work out the relevant scenario boundary conditions as well as incident timelines, a simplified event-tree analysis has been applied. In this analysis, relevant incident causes as well consequence factors, affecting the potential damage of a hydrogen incident, have been considered. All resulting scenarios have been assessed qualitatively with respect to their probability of occurrence and their potential consequences on tunnel users in the scope of an expert workshop. To estimate the likelihood of occurrence as well as the potential consequences, results from research projects mentioned before, as well as known physical properties of hydrogen and the hydrogen storage system, have been taken into account. Twelve scenarios have been identified as relevant for tunnel safety. Five of these twelve relevant scenarios have been categorized with high priority and are further considered in the scope of the HyTRA project together with the conventional scenarios of a full vehicle fire (vehicle body + energy carrier) and a vehicle-body fire see Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Scenario description</th>
<th>Hazard type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Full conventional vehicle fire (vehicle body + energy carrier)</td>
<td>Conventional vehicle fire (for comparison to H\textsubscript{2} scenarios)</td>
</tr>
<tr>
<td>2</td>
<td>Vehicle-body fire</td>
<td>Vehicle-body fire</td>
</tr>
<tr>
<td>3</td>
<td>Vehicle-body fire of a hydrogen-propelled vehicle with hydrogen release through TPRD and immediate ignition of the hydrogen cloud</td>
<td>Vehicle-body fire + hydrogen jet fire</td>
</tr>
<tr>
<td>4</td>
<td>Vehicle-body fire of a hydrogen-propelled vehicle and tank rupture due to a malfunction of the TPRD</td>
<td>Vehicle-body fire + tank rupture</td>
</tr>
<tr>
<td>5</td>
<td>Collision of a hydrogen-propelled vehicle with immediate tank rupture</td>
<td>Tank rupture</td>
</tr>
<tr>
<td>6</td>
<td>Release of hydrogen through a leakage of the tank system with delayed ignition</td>
<td>Gas cloud explosion</td>
</tr>
<tr>
<td>7</td>
<td>Vehicle-body fire of a hydrogen-propelled vehicle with hydrogen release through TPRD and delayed ignition of the hydrogen cloud</td>
<td>Conventional vehicle-body fire + gas cloud explosion</td>
</tr>
</tbody>
</table>

*Table 1 Basic scenarios for further consideration in the quantitative consequence analysis*

Consequences of hydrogen jet-fire- and tank-rupture scenarios have already been quantified and are presented in one of the later sections. Consequences of vapor cloud explosions are still under
consideration. The numerical models used to estimate the potential consequences of the selected hydrogen scenarios are discussed in the following.

**CONSEQUENCE MODEL FOR CONVENTIONAL TUNNEL FIRES**

The present paper focuses on hydrogen incidents. A consequence model for conventional vehicle fires is however necessary in order to be able to estimate consequences of conventional vehicles for comparison (Scenario 1 in Table 1), and also to estimate consequences related to the fire of the hydrogen-propelled vehicle body (Scenarios 2-4 in Table 1). Fire curves for conventional vehicles to be used in the context of the Austrian tunnel risk methodology are defined in the respective guideline [11]. The fire curves are thereby defined by time-dependent functions of the heat release rate and normalized fire gas emission rates, which are given in units of emitted gas mass / released thermal energy. These standard fire curves include the released thermal energy related to the conventional energy carrier as well as the vehicle body. To estimate fire curves of the vehicle body only, the standard fire curves have been adapted in such a way that the overall released thermal energy is reduced by the calorific content of 50 liters of petrol and 480 l of diesel, for passenger car fires and bus fires, respectively, while the same HRR time development is used as for the conventional vehicles. The standard fire curves and modified vehicle-body fire curves are shown in Figure 1. For consequence modelling a one-dimensional microscopic evacuation model is used, in which tunnel users are represented by a set of evacuating agents with different walking speeds and physiological properties. For the assessment of fire consequences the FED/FIC approach according to the work of Purser [12] is used. This approach aims to model the physiological impact of fire hazards on the human body, taking the effect of reduced visibility, toxin- and temperature dosage intake as well as respiratory and visual irritancy into account. The degree of intoxication is determined based on the concentration of pollutants along the escape route of an evacuating person as well as on the exposure duration. In each time step, the "Fractional Effective Doses" (FED) with regard to asphyxiation and hypothermia, as well as the "Fractional Incapacitation Concentration" (FIC) are determined. An evacuee is assumed as incapacitated if one (or more) of the FED- or FIC values equals or exceeds a threshold value of 1.0.

**CONSEQUENCE MODEL FOR TANK RUPTURES IN TUNNELS**

A hydrogen VCE following a tank rupture can result from two initial events. First, the tank can burst due to overheating from being exposed to a fire of the hydrogen car body with the TPRD not working properly or the pressure rising faster than it can be relieved via the TPRD (scenario 4 in Table 1), or second, it can burst because of mechanical stress following a collision (scenario 5 in...
In the latter case the explosion is assumed to take place directly after impact. For tank rupture due to overheating Molkov et al. estimated fire resistance ratings for various heat release rates per fire area [13]. This relation is shown in Figure 2. Following this relation, a fire resistance rating of 8 minutes can be assumed for a heat release rate per area of 0.74 MW/m² related to the passenger car vehicle-body fire curve shown in Figure 1. Therefore, a time delay from fire ignition to tank rupture of 8 minutes is used for hydrogen passenger car fires. During this first 8 minutes, the total released heat results to be 1.270 GJ according to passenger car vehicle-body fire curve presented in Figure 1. For the bus vehicle-body fire curve shown in Figure 1, the same released total heat is achieved after 159 seconds (roughly 2 and a half minutes), which is consequently used as time delay from fire ignition to tank rupture for the hydrogen bus fire. The estimated times until tank rupture are based on current knowledge and are therefore considered as plausible. Given the coarse model assumptions, they can, however, be assumed only to be rough estimations at best. In reality, actual delay times until rupture of a hydrogen tank depend on many parameters e.g., the fire curve, and represent therefore rather a range than a single sharp value.

![Figure 2: FRR as a function of HRR/A from (Molkov et al. 2021) and the HRR/A value related to the 2.98 ME fire curve of Figure 1](image)

Independent of the initial cause or the tank-rupture time, two major hazards occur in case of hydrogen tank rupture followed by a hydrogen vessel explosion. First, the instant release of the stored pressure together with the pressure rise due to the explosive combustion of hydrogen leads to a pressure wave that propagates longitudinally along the tunnel. Second, the combustion of the released hydrogen also leads to a fireball, which also extends in longitudinal direction. To estimate the overpressure hazard area, the relationship between overpressure and distance from the origin of the detonation corresponding to explosions of different sizes of hydrogen tanks has been used [14]. To obtain this relationship, the overpressure of a hydrogen tank explosion in the tunnel was investigated both numerically and experimentally, and a correlation between the dimensionless peak overpressure ($\bar{P}_T$) and the dimensionless distance from the detonation origin ($\bar{L}_T$) was found by the authors of mentioned paper, see Figure 3. Details about the model, and in particular the definitions of $\bar{P}_T$ and $\bar{L}_T$ are given therein. This model can be applied to arbitrary tunnels as geometric tunnel properties, like aspect ratio, hydraulic diameter and tunnel cross-section, are taken into account in the calculation of $\bar{L}_T$. Different $\text{CGH}_2$ systems have been used in the calculation of the mechanical expansion work based on storage pressure and volume. Therefore, this engineering tool is applicable for the consequence analysis of hydrogen pressure vessel explosions a danger zone associated with
overpressure. The hazardous range can be obtained by calculating the distance from the detonation origin, where an overpressure of at least 1 bar – fatality threshold value according to [15] – is reached. This distance can be compared with person densities in the evacuation and survivability model [7]. To account for the hazard of a fast expanding fire front inside the tunnel, resulting from the combustion of the released hydrogen during a VCE, an empirical relation between the amount of hydrogen in the tank and the fireball diameter is used [16]. The fireball volume resulting from a hemispherical fireball shape is then applied to the tunnel geometry to calculate the associated hazard zone. It is however acknowledged, that according to analytical and numerical investigations based on experimental data a hemispherical shape of the fire ball may not be applicable in a tunnel environment and that the resulting hazard zone related to the hydrogen fire ball is therefore rather conservative.

![Figure 3 Relationship between dimensionless overpressure and dimensionless distance from [14]](image)

**CONSEQUENCE MODEL FOR HYDROGEN JET FIRES IN TUNNELS**

Jet flame formation can be observed if the pressurized hydrogen is relieved through a small valve (e.g., TPRD). Hence, in a tunnel fire event that triggers the TPRD of a hydrogen tank, most probably a hydrogen jet will be generated (scenario 3 in Table 1). In the consequence model for hydrogen jet fires an initial conventional fire according to the fire curves shown in Figure 1 is assumed. Therefore, two different mechanisms must be taken into account to estimate the consequences of a jet-fire scenario:

- The conventional hazards of the vehicle-body fire – like toxic gases, high temperatures and reduced sight, and
- The hazard related to the high temperature of the hydrogen jet flame itself.

The conventional hazards are modelled with the Fire Dynamics Simulator (FDS) software in combination with the FED/FIC approach already discussed in one of the previous sections. In the CFD simulation, in addition to the distribution of the pollutants, also the gas temperature is evaluated. In discussing the above defined scenario 3, it is assumed that, as soon as the TPRD is activated a jet-fire is formed, either due to the hydrogen being immediately ignited because of its physical properties (low required hydrogen ignition energy) or due to the underlying already existing fire. The resulting jet flame is not treated directly in the CFD model but by estimating a certain “danger zone”, which represents a fatal area for evacuating persons, in the already discussed linear one-dimensional egress and survivability model.
Three general parameters determine the potential consequences of the jet fire itself:

- The TPRD activation time,
- the duration of the jet fire, and
- the special extension of the hazardous zone associated with the hydrogen jet.

A typical TPRD activates when the temperature fuse inside the TPRD reaches a temperature of 110°C. The temperature of the device is increased by convective heat transfer from the hot air, radiative heat transfer from the flame and conductive heat transfer through other parts of the vehicle. If radiative heat transfer and conductive heat transfer are neglected, due to the assumption of the TPRD being shielded from the flame and because of the long time scale on which conductive heat transfer happens, the time to TPRD activation can be modelled according to a simple temperature-response relation [17]. Equation 1 shows the infinitesimal temperature increase of the TPRD following the temperature response relation for sprinkler, with \( T_{TPRD} \) being the the actual TPRD temperature at time \( t \), \( T_{gas} \) being the actual gas temperature at time \( t \), \( u \) being the longitudinal flow velocity at time \( t \) and \( RTI \) being the response time index of the TPRD.

\[
\frac{dT_{TPRD}(t)}{dt} = u^{0.5}(t) \frac{RTI}{RTI} \left( T_{gas}(t) - T_{TPRD}(t) \right)
\]

**Figure 4** TPRD Temperature, gas temperature and resulting TPRD activation time for passenger-car vehicle-body fire curve according to Figure 1

**Figure 5** TPRD Temperature, gas temperature and resulting TPRD activation time for bus vehicle-body fire curve according to Figure 1

134
Figure 4 and Figure 5 depict the TPRD temperature (solid line) as a response to the measured gas temperature (dotted line), for the passenger car vehicle-body and bus vehicle-body fire models, respectively. The strong fluctuations of the gas temperature, which is measured 1.6 m above the road surface, stem from turbulences in the hot smoke layer. Figure 4 and Figure 5 also show the resulting time until TPRD activation according to Eq. (1) (dashed line), where a response time index of 25 m$^{0.5}$ has been assumed. This value for the response time index is presented in [17] for fast responding automatic sprinklers. This approach results in TPRD activation times of 206 seconds for the 2.98 MW fire curve and 134 s for the 18 MW fire curve. The activation mechanism of automatic sprinklers and TPRDs are similar, however, the estimation can be improved if a response time index of an actual hydrogen-tank TPRD is used in future applications. As an alternative to equation x, the gas temperature itself has been used to determine TPRD activation times in the past [7]. The neglection of the convective heat transfer to the TPRD and the resulting temperature response of the TPRD leads to significantly earlier activation times (dotted-dashed lines). The later activation times related to the actual TPRD temperature instead of gas temperature are considered to be more realistic, however, the predicted TPRD temperature development depends on rough modelling assumptions (e.g., the RTI or the applied fire and CFD model).

The duration of the jet-fire depends on the hydrogen pressure inside the tank as well as the tank size and can be read off from tank blowdown nomograms [2]. Tank sizes as well as TPRD orientations are different for different vehicle types and regulated via various standards, such as ISO 23273:2013, ISO 15916:2015 and ECE R134. Therefore, orientation as well as dimension of the jet flame depend on the type of involved vehicle [7]:

- **Passenger cars** typically use hydrogen tanks with an operating pressure of 700 bar. The TPRD is situated in the back and discharging in backwards direction with a horizontal angle of 45° downwards.

- **Busses** use hydrogen tanks situated on the top of the vehicle, with the TPRD being assumed oriented upwards. The tanks operating pressure is 350 bar.

For passenger cars the danger zone has been estimated based on the numerical findings for hydrogen jet fires from a thermally activated pressure relief device in a naturally ventilated covered car park [18]. In this reference, the behavior of hydrogen free-jet fires, due to a triggered TPRD with different outlet directions in underground car parks, was investigated. The analyzed hazard zone or the area in which persons cannot survive due to the free-jet fire could be set to 6.5 m for a car with TPRD opening diameter of 2 mm and blow-out direction in 45° to the rear, in the longitudinal direction. To estimate consequences for bus jet fires, the results from [19] have been utilized. There, the tank parameters of a hydrogen bus in combination with an upwards TPRD orientation results in tenable conditions below a height of 2.0 m above the tunnel floor. Therefore, no additional hazard in form of a danger zone has been taken into account for bus jet fires (see Figure 7).

---

**Figure 6 Dangerous zone according to car jet flame for a storage pressure of 700 bar [18]**
HYDROGEN DISPERSION IN TUNNELS

An unignited hydrogen release after TPRD activation will cause the hydrogen to accumulate beneath the ceiling. Ultimately, this will lead to hydrogen cloud formation. If the hydrogen volume fraction is within the flammability limits \((4 - 76\text{Vol}%)\), a contact to an ignition source (e.g. lights, fans, etc.) may result in a gas cloud explosion causing a destructive blast wave to propagate throughout the tunnel. Although an unignited hydrogen release is considered to be unlikely the serious consequences from a gas cloud explosion have encouraged researches to assess this scenario both in experimental [20] as well as in numerical [21] investigations. In the course of the Austrian research project HyTRA hydrogen dispersion after an unignited release was investigated with special focus on the Austrian ventilation strategy as it is defined in guideline RVS 09.02.31 [22]. According to this guideline a target supply air velocity of \(1.75 \pm 0.25 \text{m/s}\) in a unidirectional traffic mode and \(1.25 \pm 0.25 \text{m/s}\) in bi-directional traffic have to be generated by the mechanical ventilation system. Thus, the supply air velocity can be expected within the interval of \(1 \text{m/s}\) to \(2 \text{m/s}\). Hence, both limits have been considered as boundary conditions in 3D CFD simulations of a longitudinally ventilated tunnel in the scope of the HyTRA project. In addition, a third scenario has been assessed based on a supply air velocity of \(0.01 \text{m/s}\). The 3D CFD simulations of a hydrogen release from a passenger car tank aimed to determine the hydrogen concentration in the tunnel and to identify the tunnel regions at risk.

Ansys Fluent was employed as the 3D CFD solver. The CFD model was based on the pressure-based solver. In order to model the turbulent flow a Reynolds Averaged Navier Stokes approach was employed, where a k-omega SST turbulence model was selected in order to close the set of equations. The release of hydrogen required the consideration of species transport. For this reason a non-reactive transport of a fluid-mixture was enabled and the gas behaviour was approximated by the real gas Redlich-Kwong model. Pressure-Velocity coupling was done using the SIMPLE algorithm. The second order implicit formulation was employed for the spatial discretization of pressure, density, momentum, turbulent kinetic energy, specific dissipation rate, hydrogen concentration and energy. In addition, an underrelaxation was applied using an underrelaxation factor of 0.4 for momentum and 0.5 for turbulent kinetic energy and specific dissipation rate respectively.

The computational domain comprised a 280 m tunnel section and a car body of 1.6 m height, 1.8 m width and 5 m length that was situated 100 m from the tunnel inlet. The hydrogen release through the TPRD was considered towards the road surface under an angle of 45°. The horseshoe profile tunnel had a cross section area of 62 m² and a circumference of 27 m (standard Austrian double-lane tunnel). In order to reduce the computational effort a symmetry plane was added, which divided the tunnel in two halves. For this reason, the car body was situated central within the tunnel. The mesh included three different regions for which different limits for maximum cell size were defined. Figure 8 depicts the generated mesh in the vicinity of the car body. The spatial resolution was defined by tetrahedrons with a maximum size of 6 cm (Mesh A), 40 cm (Mesh B) and 80 cm (Mesh C). In addition, six inflation layers were added at the boundary to the tunnel lining. For the simulation of hydrogen dispersion in a tunnel [21] considered an enlargement of the TPRD diameter, in order to achieve feasible simulation times. This advice was taken into account by considering an enlargement factor of 10 compared to the nominal TPRD diameter. The spatial discretization of the TPRD was done by a maximum cell size of 0.3 cm.
The hydrogen blowdown model (see Figure 9) was derived from that available in [23] where a 125 l tank at 70 MPa storage pressure and a TPRD diameter of 2.25 mm were considered. The hydrogen release was considered against the main flow direction (45° angle) of supply air. The results of the set of simulations are illustrated in Figure 10. This figure shows a comparison of the hydrogen mole fractions on the symmetry plane for supply air velocities of 0.01 m/s, 1 m/s and 2 m/s and at different points of time within a total period of 100 s after TPRD activation. In this comparison red areas define regions in which the hydrogen concentration is higher than 4 Vol%, thus above the lower flammability limit. One can see that a supply air velocity of 2 m/s seems sufficient to keep the hydrogen concentration below the flammability limit in this case. In addition, hydrogen propagates only downstream of the car. A reduction of the supply air velocity to 1 m/s leads to short (~15 m) backlayers. However, the hydrogen concentration still stays below 4 Vol% for nearly the entire period of 100 s. In the third scenario, the reduction of supply air velocity down to 0.01 m/s results in a significant longitudinal extension of the hydrogen cloud. In addition, in some small layers (~25 cm) the hydrogen concentration exceeds the lower flammability limit.
CONSEQUENCE ANALYSIS RESULTS

The discussed consequence models can in general be implemented in any risk model and thereby allow to include hydrogen scenarios in any assessment methodology. The HyTRA project is, however, focusing on the effects of hydrogen-propelled vehicles on tunnel safety in Austria. Therefore, the consequence models have been applied to a comparison tunnel with design- and operation parameters typical for Austrian tunnels and for emergency-response timelines typically used in the Austrian tunnel risk assessment methodology. The parameters for the comparison tunnel together with the assumed emergency-response timeline are summarized in Table 2.

<table>
<thead>
<tr>
<th>Tunnel Parameter</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel system</td>
<td>2.0 km long unidirectional tunnel tube without inclination and a horseshoe cross section of 63 m²</td>
</tr>
<tr>
<td>Cross-passage distance</td>
<td>500 m</td>
</tr>
<tr>
<td>Traffic</td>
<td>20'000 veh./day per tube with 85% passenger cars, 14.5% heavy-goods vehicles and 0.5% busses</td>
</tr>
<tr>
<td>Ventilation</td>
<td>Longitudinal ventilation with jet fans, target airflow velocity in fire mode 2.0 m/s</td>
</tr>
<tr>
<td>Emergency response</td>
<td>Ventilation activation 120 s after fire start, evacuation initialization 150 s after fire start</td>
</tr>
</tbody>
</table>

Table 2 Comparison tunnel parameters for the consequence analysis

Passenger car incidents
The resulting consequence numbers for passenger-car incidents are shown in Figure 11. The estimated consequence numbers for all passenger-car incidents are low on an absolute scale, in particular below 1.0 fatality per event. The non-integer consequence numbers stem from the used microscopic evacuation model, where each person inside a tunnel is represented by a set of so-called evacuating agents with different evacuation behaviors and physiological properties. One agent thereby represents
a certain share of one actual evacuating person and consequently is associated to a number of persons smaller than 1.0. Consequence numbers for conventional fires – either for full conventional vehicle fires (vehicle-body + conventional energy carrier) or for the vehicle-body only – are very close to zero. This implicates that the applied ventilation strategy is sufficient to mitigate the consequences of conventional passenger car fires completely, as one would expect for a modern road tunnel. The remaining consequences are related to a small share of agents in the direct vicinity of the fire, that do not leave the fire site, either because of wrong behavior or because of being unable to evacuate. In the Austrian tunnel risk model, a share of 3% of all evacuees is assumed to show this behavior. In fact, all consequences related to passenger-car fires are associated with this small group of non-evacuating agents, as the TPRD activation as well as tank rupture due to fire happens considerably later than the evacuation alert, see Table 3 and persons therefore have enough time to leave the hazard zone before the hydrogen-incident takes place.

<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire ignition</td>
<td>0 s</td>
</tr>
<tr>
<td>Tank rupture due to mechanical incident</td>
<td>0 s</td>
</tr>
<tr>
<td><strong>Start of evacuation</strong></td>
<td><strong>150 s</strong></td>
</tr>
<tr>
<td>TPRD activation for passenger car fire</td>
<td>206 s</td>
</tr>
<tr>
<td>Tank rupture for passenger car fire</td>
<td>460 s</td>
</tr>
</tbody>
</table>

*Table 3 Incident timeline for passenger car fires*

For conventional fires, only persons located directly at the location of the fire are affected. For hydrogen jet fires, also persons in the close vicinity of the fire (6.5 m upstream of the fire) are affected.
which increases the number of consequences, even though the numbers are still very small on an absolute scale. For tank-rupture scenarios, however, consequence numbers increase significantly, to roughly 0.2 fatalities per event, if rupture of a single tank is assumed (filled area in Figure 11), and to roughly 0.35 fatalities per event, if simultaneous rupture of all three tanks is assumed (dashed areas in Figure 11). This increase, compared to jet fires and conventional fires, is related to the significantly larger hazard zone related to tank-rupture incidents. The hazard zones resulting from the consequence models described in the sections before are shown in Figure 12 for scenario 3 – hydrogen jet fire (left), scenario 4 – car fire & hydrogen tank rupture (center) and scenario 5 – collision & hydrogen tank rupture (right). In addition, also the traffic densities at the time of the incident (TPRD activation / tank-rupture) are shown. For the fire events – scenario 3 and 4 – the hydrogen incident starts significantly after the initial traffic interruption, which is related to the conventional vehicle-body fire. Therefore, vehicles downstream of the fire have already left the hazard zone. Upstream of the fire, a vehicle queue has formed. This is indicated by the high traffic density between 1000 m (incident location) and approximately 900 m, and zero traffic density elsewhere in the tunnel for scenario 3 and 4 in Figure 12. For scenario 5 in Figure 13, the tank rupture is triggered immediately due to the collision. Consequently, the hydrogen incident happens during free-flowing traffic. Therefore, the traffic density is much lower and in particular homogeneous along the tunnel. As can be seen, the traffic density within the hazard zone is much larger for scenario 4 than for scenario 5. Nevertheless, the consequence numbers are approximately the same. The reason for this is that for scenario 4, where tank rupture is estimated to happen 8 minutes after fire ignition, the majority of persons have already left their vehicles and therefore the hazard zone successfully. Only the assumed 3% of persons, who do not leave their initial position is affected. For scenario 5, which happens during free-flowing traffic, the traffic density within the hazard zone is much smaller, but passengers have not started to evacuate yet. The larger traffic density within the danger zone together with the smaller share of persons located at the location of their vehicle during the incident leads to approximately the same number of affected persons as a lower traffic density within the hazard zone and the assumptions that all persons (all considered agents) in the vehicle are affected.

**Bus incidents**

The resulting consequence numbers for bus incidents are shown in Figure 13. The consequences of conventional bus fires and bus vehicle-body fires (scenario 1 & scenario 2) are small on an absolute scale but higher than for passenger car fires, due to the higher heat release rate. Consequence numbers for hydrogen jet fires on buses (scenario 3) are exactly the same as for bus vehicle-body fires, because no additional hazard in form of a danger zone has been assumed, according to the discussion presented in the consequence modelling section. For hydrogen tank rupture following a bus collision (scenario 5) consequence numbers are increased compared to the respective passenger car incident, in particular, if the whole tank system is involved (shaded area in Figure 13) because of the higher amount of involved hydrogen mass. It has to be mentioned that bus parameters have been used for the modelling of the hazard zone and fire event, but no actual bus has been considered at the incident location in the evacuation model. The reason is that the Austrian tunnel risk model utilizes a continuous traffic model, where all types of vehicles are considered at every location in the tunnel (also the incident location) with a probability related to their respective share on the overall traffic. For an actual bus incident, where a large number of persons is located below the exploding tank, consequences could be significantly larger, if the incident vehicle is considered explicitly in the evacuation model. From all investigated bus scenarios, the tank rupture following a bus fire results in the highest number of consequences (scenario 4). The reason for this considerable increase compared to all other scenarios is the early time of tank rupture estimated for the bus vehicle-body fire. With a time to tank rupture of 159 seconds and an evacuation starting time of 150 seconds only passengers who need 9 seconds to leave the hazard zone will be able to survive. Given the length of the hazard zone in upstream direction (approximately 40 m) and an assumed walking speed of approximately 1.0 m/s a significant number of persons is not able to leave the hazard zone before tank rupture, in addition to the assumed 3% of persons who do not evacuate anyway.
Table 4 Incident timeline for bus fires

<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire ignition</td>
<td>0 s</td>
</tr>
<tr>
<td>Tank rupture due to mechanical incident</td>
<td>0 s</td>
</tr>
<tr>
<td>TPRD activation for bus fire</td>
<td>134 s</td>
</tr>
<tr>
<td><strong>Start of evacuation</strong></td>
<td><strong>150 s</strong></td>
</tr>
<tr>
<td>Tank rupture for bus fire</td>
<td>159 s</td>
</tr>
</tbody>
</table>

Figure 13 Consequence numbers associated with hydrogen incidents of passenger cars

Figure 14 Traffic density at the time of tank rupture (solid line) and hazard ones with single-tank involvement (dashed lines) and involvement of the whole tank system (dotted lines) for bus incidents

CONCLUSIONS
A set of hydrogen scenarios relevant for tunnel safety in terms of potential consequences and likelihood of occurrence has been selected based on a qualitative event-tree analysis. Consequence models, which have been developed from engineering tools and latest research findings regarding hydrogen incidents in tunnels, have been developed for this set of scenarios. These consequence models, together with state-of-the consequence models for conventional tunnel fires, have been applied on the selected set of scenarios. Thereby, consequence numbers for conventional fires, vehicle-body fires, hydrogen jet fires and hydrogen tank ruptures have been computed. In addition, also a numerical analysis of hydrogen gas cloud formation has been performed. The results show that consequences during conventional tunnel tunnel fires are very efficiently mitigated in modern road tunnels due to the unidirectional operation and efficient ventilation strategies. Thereby, hazardous smoke in the area of evacuating persons can be avoided. For hydrogen incidents, however, a space-like separation of hazard zone and evacuating persons is not possible anymore, as the jet fire as well
as the pressure wave following a tank rupture or a VCE also extend in upwind direction. This can lead to significantly higher consequences compared to conventional fires. A way of separating evacuees and hydrogen hazards is to give evacuees enough time to leave the hazard zone before the hydrogen incident, i.e. jet flame, tank burst or VCE, occurs. This is also visible in the obtained results. For passenger cars, where the assumed alert time was significantly shorter than the estimated time to TPRD activation or tank burst, consequence numbers where of the same order of magnitude as for conventional vehicle fires. For bus incidents on the other hand, where tank burst can happen earlier due to the larger fire size, consequence numbers in the range of approximately 1 to 10 fatalities where obtained. The consequences of hydrogen vapour cloud explosions have not been computed in such detail, as feasible engineering tools have not been developed so far and because of the unlikelihood of such an event. Instead, 3D CFD simulations to obtain information about the impact of mechanical ventilation on the hydrogen dispersion in an unignited hydrogen release scenario have been performed. The results gained indicate that an increase of supply air velocity leads to an improvement related to the hydrogen cloud formation and the hydrogen concentrations, respectively. However, the performed simulations were based on only one available blowdown model that itself refers to a TPRD diameter of 2.25 mm. Larger TPRDs would result in higher hydrogen release rates. Hence, hydrogen cloud formation and concentrations above the lower flammability limit can not definitely be ruled out. In general, the results present a first attempt in calculating consequence numbers for hydrogen- incidents in tunnels with respect to realistic tunnel-operation conditions, in particular for Austrian tunnels. The results are based on several model assumptions and are strongly influenced by the assumed emergency timeline. Absolute numbers should therefore be interpreted with care. Results may change as underlying models are being improved and better knowledge about incidents of hydrogen-propelled vehicles is obtained in the future; however, the consequence numbers already show the importance of incident- and emergency timeline for the actual consequences that might occur during a hydrogen event. At the moment, hydrogen scenarios, like jet flames, tank ruptures and vapour cloud explosions, even though extremely unlikely, cannot be prevented completely, but it seems that consequences of hydrogen incidents can be reduced significantly (below 1 fatality per event) if fast emergency response can be achieved.

ACKNOWLEDGEMENT

The project “HyTRA – Hydrogen Tunnel Risk Assessment” is funded by the Austrian Research Promotion Agency (FFG), representing the Federal Ministry Republic of Austria for Climate Action, Environment, Energy, Mobility, Innovation and Technology, as well as the “Autobahn and highway financing stock corporation (ASFINAG)”. We thank Peter Sturm, (Institute of Thermodynamics and Sustainable Propulsion Systems, Graz University of Technology) and Nikola Kapralov (Karl Franzens University of Graz) for their contribution to the HyTRA project.

REFERENCES


Life-safety targets in underground stations

Johan Lundin¹, Bo Wahlström¹, Erik Hall Midholm¹, Oskar Jansson²
¹ Brandskyddslaget AB, Sweden
² RiskTec Projektledning AB, Sweden

ABSTRACT

The Swedish Transport Agency and the Swedish Transport Administration have completed the R&D project ‘Common life safety targets in traffic tunnels’ in which a common life-safety target was formulated for users of road, rail, tramway and subway tunnels. As a logical continuation of this work an additional project was initiated to investigate the potential to express a safety target for underground stations connected to tunnels. This effort makes the design regulations with technical requirement more complete for this type of structures. It also provides risk control in an essential part of the construction works related to the transport system for which the Swedish Transport Agency has a mandate to formulate requirements in regulations and general recommendations.

KEYWORDS: underground station, submerged platform station, safety target, risk analysis, life-safety, severe accident, dangerous goods, fire.

INTRODUCTION

Background

The Swedish Transport Administration and the Swedish Transport Agency has initiated a project to study the prerequisites and the potential for formulating a harmonized safety target for the space surrounding underground platform stations. The safety target should be applicable to different modes of transport regarding underground/covered platform stations, such as railroad-, tramway and metro-stations, bus stops and bus terminals. Such a target needs to and facilitate the balance between risk and economic effectiveness to be operational in both regulations and design. The work is a continuation of previous research conducted in tunnels where two reports from the R&D projects “Life-safety objectives for road, rail and metro tunnels” has been previously presented. The first report in 2016 [1] showed that it is possible to formulate a common life-safety target, with a clear link to public benefit for users of road, rail, metro and subway tunnels. The second report in 2019 [2] continued the work, developing and verifying the conclusions of the first report and forming a basis for forthcoming national legislation. In these reports delimitations were made as to exclude railway, subway, and tram underground stations and limiting the proposals for life-safety targets to apply only to new tunnels.

The current regulations set detailed requirements for the design of safety measures in underground stations and, to a certain extent, requirements for risk analysis to be performed as a completion during certain conditions. However, no safety targets are stated to assess the risk which were previously also the case for tunnels. The basis of this is that safety targets for the design of safety concepts in underground stations are either lacking or too general and formulated on a highly hierarchical level in the regulations. As a consequence, unambiguous safety targets on a lower hierarchical level suitable for design work are also lacking. This provides a risk for different interpretations and uncertainties about the goals and objectives to be achieved. The result may be different risk levels in different projects and for different modes of transport. Another result can be that the approval process becomes difficult and/or that the safety level can either be too low or too high, i.e. expensive.
Optimising safety in a specific tunnel, however, relies on some form of generally accepted level for acceptable safety – a common life-safety target. This has been lacking in current rules and regulations, which risks different interpretations in relation to planning and administration when cost is weighed against public benefit. Without such a target, it is difficult to determine whether the functional requirements in the current legislation have been fulfilled.

Another issue is that the current rules and regulations for road and railroad tunnels do not address the risks that are specific to underground stations which might have severe consequences in case of an accident, including, among other things, fires and events involving dangerous goods.

With this background the Swedish Transport Agency (authority having jurisdiction) and the Swedish Transport Administration (infrastructure manager) were curious to explore the opportunity to embrace underground stations as a complement to the efforts made with tunnels and align this work with the ongoing development of the tunnel regulations.

The project results will be used by the Swedish Transport Agency as a basis for creating national requirements and issuing general recommendations and accompanying impact assessments in the coming draft of regulations pertaining to tunnel safety, underground stations included. Regarding implementation phases, the expected result is that the safety requirements in tunnels will become improved. This will reduce arbitrary interpretations and ensure that the requirements concerning risk assessment, are well-balanced, based on societal benefit, and harmonised with the national standards for other transportation infrastructure. Distinct life-safety targets lead to more efficient building processes since correct measures can be applied during planning and construction, and tunnel managers can apply efficient, risk-based working methods. This paper is reporting on some of the results from the project documentation [3].

**Purpose and objective**

The purpose of the work is to form a base for a forthcoming national legislation in Sweden and to improve the regulatory risk control in the current regulations. The objective is to investigate whether it is possible to propose a well-balanced safety target and suitable verification method or concept in a similar way as for tunnels. Based on experience it has been found relevant to describe how both accidents with few casualties, e.g. suicides or fall accidents, and very unlikely accidents with very large consequences, e.g. accidents involving dangerous goods or large and rapid fires, can be assessed within tunnels.

**Delimitations**

In this paper underground station and platform station refer to the space adjacent and/or between tunnels entering an underground station area. The space for which the safety target is derived consist of the concurrent part of the traffic system together with the underground platform station, see examples in Figure 1 and Figure 2, i.e. defined by the platform floor, the side walls, the platform ceiling and interfaces to other parts of the station facility located in the same fire compartment (“plattformsrum” in Swedish). This mean that the safety target does not cover areas as shopping facilities, restaurants, interchanges above ground or ticket offices located in other parts of the station. It does not cover the safety in areas above the station potentially used for other purposes.
The project includes safety targets for travellers in underground stations according to the Swedish Transport Agency regulatory authority according to the Planning and Building Act [1]. The ambition is to contribute and clarify how to fulfil the technical essential requirements on a detailed level, i.e. regulations or general recommendations. The safety targets are not intended to be used to demonstrate fulfilment of all safety requirements covered by other legislation i.e. railway technical systems, work environment, antagonistic threats, poor air environment, etc.

Method
The work of investigating and proposing safety targets began with a literature review and a description of the regulations regarding life safety in underground platform stations and/or underground interchanges. In addition, if the approach suggested to control and design life safety measures in tunnels also can be applied on underground stations, the risk control approach in the regulations can cover a larger part of the transport system. An important complementary part of the work was to account for how safety goals are expressed for existing facilities and in ongoing projects and also to propose input to a prescriptive standard forming the base for the safety requirements. Another important input is to study and analyze the risk analysis output from various ongoing and recently completed underground station projects.

Since this work is a continuation of previous research conducted in tunnels let us begin with a reminder on what have been done. Many of the conclusions made in previous research can be useful.

LIFE-SAFETY TARGET FOR TUNNELS

General remarks
The regulation of the safety level of a tunnel can be considered as being the desire of society to ensure that the risk levels of tunnels in general do not exceed acceptable limits. Risk exposure measures used to define targets can be formulated in many different ways. In international literature, e.g. [3], the predominant risk measures for describing individual and societal risk in traffic systems are PLL (Potential Loss of Life) values and F/N (frequency-number) curves. F/N curves appear to be a relevant measure for establishing a risk profile in order to evaluate individual facilities. Other measures, such as PLL values, describe the expected total number of fatalities – which does not provide any additional information to that provided by an F/N curve.

Exposure measures constitute an important aspect of the formulation of a common life-safety target. These are the units of measurement against which risk is standardised. In the context of risk assessment, it is common for risk to be expressed per year, per worked hour, per vehicle-km, per
tunnel-km, etc. One problem with standardising e.g. an F/N graph for a tunnel against year is that as many fatalities per year are “allowed” for a long, very busy tunnel as for a short, less busy one. Other units of measurement include vehicle-km, tunnel-km, etc.

During previous comparisons of different projects, the best concordance was reached through standardisation against person-km. Person-km is also an exposure measure that provides a natural connection to the public benefit of the facility by take into consideration large amounts of people that often occur in new facilities and at the same time be applicable on less complex facilities. Person-km is therefore the proposed measure.

**Proposed common life-safety target for tunnels**

As a starting point the result from previous research is presented. The overall target that was proposed was formulated as:

> ‘The risk during transportation in road, railway, subway, and tramway tunnels shall be equal, expressed as risk of fatality per person-km.’

To be able to assess whether the overall target is fulfilled a quantitative criterion based on societal risk was formulated. The quantitative criterion is meant to assess risks that either are exclusive to tunnel environments or general risks which consequences could become more severe if they occurred in a tunnel compared to above ground. Based on this limitation a quantitative risk analyses should cover accidents such as fire and accidents with dangerous goods. Risks with fewer casualties, e.g. derailment or traffic accidents, are not exclusive for tunnels and the consequences do not aggravate if they occur in a tunnel. Risks with fewer casualties can be met according to detailed prescriptive requirements (in the report named ‘basic standard’). This can be done without further quantitative risk analysis, but must be complemented with analysis comparing available safe egress time (ASET) with required safe egress time (RSET).

The proposed common life-safety target is presented in Figure 2. As regards the upper acceptance limit (A), lower acceptance limit (B), and limit for low number of fatalities (D), this corresponds to the proposal in the first ‘Life-safety targets in tunnels’ report. Regarding unlikely accidents, however, no limit was proposed.

The curve can be said to be formed in such a way that the upper acceptance limit, which may never be exceeded, constitutes the common life-safety target for tunnels in different types of transport systems. Delimitations regarding the lower acceptance limit and ‘low number of fatalities’ constitute support for analysis, rather than actual requirement limits. This can be summarised as follows:

a. The risk may not exceed the upper acceptance limit.

b. Further risk-reducing measures do not need to be analysed for risks that fall below the lower acceptance limit.

c. Further measures targeting risks between the upper and lower acceptance limits shall be evaluated. Measures should be introduced if these can be demonstrated to be cost-efficient from a socio-economic perspective.

d. Accidents with fewer than three fatalities can be excluded from the quantitative risk analysis.

e. The upper acceptance limit has a fictional starting point of $F=1\times10^{-4}$ per million person-km at $N=1$ and a slope of -1.

f. The lower acceptance limit has a fictional starting point of $F=1\times10^{-7}$ per million person-km at $N=1$ and a slope of -1.
The reason for the choice of upper acceptance limit is that either lowering or raising it are assessed to have unwanted consequences. A lowering of the limit results in:

- several new or ongoing projects having great trouble fulfilling the criterion, making it difficult or impossible to demonstrate that the criterion is fulfilled,
- increased costs as compared to the present situation, and
- the position that the safety levels of new tunnels or ongoing tunnel projects will not be considered to be satisfactory in the future.

CURRENT SITUATION FOR UNDERGROUND STATIONS

Risks in underground stations
The life-safety targets must include risks that may affect life-safety in underground stations. Which risk categories are relevant to consider is partly dependent on the mode of transport in each station. Accidents with small consequences (occasional fatalities or injuries) on platforms/waiting areas and access roads are also usually not specific to underground stations in particular but depend on the infrastructure itself. These accidents will probably have the same consequences if they occur on an outdoor platform, and the requirement should be covered by other legislation. The different modes of transport have in common that fire accidents are the accident category that primarily may lead to several fatalities. Derailments and collisions at, or adjacent to, a platform station generally entail a lower probability of major consequences than if the corresponding accident occurs in the tunnel. This is partly because the consequences of these accidents depend on the possibility of evacuation and rescue efforts, which is significantly better at a underground stations than in a tunnel, and partly because underground stations and lower speeds reduce the probability that a derailment will lead to carriages overturning.
The presence of dangerous goods transport can lead to very extensive and rapidly growing fire scenarios, explosion scenarios and the release of, for example, toxic gases. The probability of a dangerous goods accident is relatively very low partly because dangerous goods make up a small part of the traffic, and partly because there are detailed rules for how dangerous goods must be packaged and handled during transport to limit the likelihood of an accident.

**Accident statistics**
The accident statistics compiled in Sweden give a fragmented picture of the situation for platform stations. Major accidents with several fatalities have not been identified in the statistics. According to statistics for injured and deceased persons in the various modes of traffic in Sweden between the years 2014-2019 (Trafikanalys, 2020) railway and subway suicides account for approx. 80% of the total number of deaths. The number of fatalities on the platform accounts for less than 1% of the total number of fatalities. Accident statistics for road traffic 2003-2019 [6] show that 46 people out of a total of 5 841 deaths in road traffic, connects to the mode of transport by bus, i.e. less than 1%. However, it is not clear from the statistics where in the road infrastructure these accidents occurred.

**Standards, regulations and investigations**
The criteria that have been identified regarding the evacuation of underground stations are mainly related to a specific time for evacuation to be completed or comparisons with time for critical conditions in case of fire. Quantitative criterion in terms of a safety target has been identified for railway tunnels in the Swedish transport agency’s guidelines [7]. A Nordic collaboration [5] proposes quantitative criteria for verifying fire assessment for buildings where many people live. But overall, no quantitative criteria that are directly applicable to underground stations have been identified in regulations in Europe and United States in the review.

**Safety in existing facilities and ongoing projects**
The research project created an inventory of existing underground stations and current and planned projects. Inventory is mainly limited to Swedish projects. Among the identified projects, we found two examples where a quantitative social risk analysis was conducted, namely the Slussen bus station and the overbuilding (decking) of Stockholm Central Railway Station. The two projects are characterized by the presence of gas buses at the bus station and the unrestricted rail transport of dangerous goods passing the railway station. Overall, the review does not indicate that clear practices have been established, and there are few examples of quantitative risk analyses being conducted where societal risk has been studied.

**ASSESSMENT OF APPROACHES TO DERIVE A SAFETY TARGET**
The starting point for this work was to investigate in what way a safety target for an underground station could be derived and if it is suitable to described in a similar way as for tunnels was one of the major aspects to investigate in the project.

One conclusion from the inventory given in the previous section (Current situation for underground stations) is that it is not possible to derive safety targets for underground stations with the same approach as for tunnels. There are not enough references to develop general life safety targets covering all transport modes. Therefore, different rationales for deriving safety goals should be thoroughly considered. Such a review was conducted based on the alternatives proposed by Lundin [8].

**Analysis of different safety targets and safety levels**

*Common practice*
Common practice for risk assessment is not static and therefore it is not possible to look way too far back to estimate what is the current practice. What is clear is that it is a common practice, both in Sweden and several other countries, that in case of fire the time to evacuate the platform must subseed the time to critical conditions. This practice is regulated by e.g. Swedish Transport Agency regulations TSFS 2017:119 for subways and tramways [5] and the National Board of Housing,
Building and Planning [6]. Other aspects of safety targets and measures vary significantly, e.g. how to address suicides, fatalities on platforms, etc.

Comparing the safety targets in two different projects, the underground stations in the railway tunnel Citybanan and the Slussen bus terminal, both in Stockholm, it can be concluded that they are derived with different methods. The life-safety targets for the underground stations of Citybanan are based on previous projects and the Swedish Transport Administration’s requirements for safety levels in tunnels, etc. The targets for the Slussen bus terminal on the other hand are based on comparisons to other transport systems and to the general risk level of commuting. As for new subway stations, an overall assessment is made according to regulations of Swedish Transport Agency [5], which is based on yet another approach, where the safety life-target level is not defined for platform stations.

In summary, there is no common practice for risk assessment of this type of facility present.

Analysis of accident statistics
Specific accident statistics connected to underground stations and platform stations are limited. The statistics in Sweden that, to some extent, can be sorted out to apply to railway stations are limited to only include people who have died on the platform as a result of trains in motion, i.e. single deaths. This is only a part of the risks that exist in platform stations and does not cover risks with multiple fatalities, such as fire or dangerous goods.

For subway stations, it can be stated that people being hit by subway trains, including suicides, are dominant, and strongly linked to stations in relation to the subway network in general. Accident statistics for dangerous goods are very limited because accidents occur so rarely. Faveo has made an attempt to describe the probability for dangerous goods accidents in a previous report [10].

The Swedish Transport Administration used accident statistics as a basis for its first report regarding safety assessment/risk analysis in tunnels, BVH 541.3 [8]. The life-safety target in BVH 541.3 was set so that a slightly higher safety would be achieved than what the statistical outcome had been. In this way, they sought to create a contribution to increase safety.

Comparisons to other life-safety targets
The life-safety target and acceptance limits that are undeniably the closest to hand to compare with are those proposed in previous reports on safety goals in tunnels [1] and [2]. In these two reports, comparisons were made between various examples and reference cases where it turned out that risk curves from a several large number of tunnel projects coincide relatively well. Which is why it was deemed appropriate to use these reference cases as a basis for formulating a life-safety target for tunnels.

The proposal is described in the chapter ”Proposed common life-safety targets for tunnels” and illustrated in Figure 2.

The proposal is that the life-safety target should be verified with quantitative analysis for longer tunnels, while for shorter tunnels it is deemed that the safety targets can be met according to detailed requirements (in the report named basic standard), without further analysis. As for risk levels within ALARP, socioeconomic values such as ASEK should be used to evaluate different measures.

The proposal to life-safety targets in [2] do not include criteria for individual risk, since this risk measure is deemed to have a limited contribution to the risk assessment in addition to societal risk. However, it is highlighted that individual risk is a possible complement to the life-safety targets.

The proposal do not include a limit regarding very unlikely accidents, though the first report [1] highlights a need for further investigation of principles and safety targets for managing disaster scenarios.
Underground platform stations are, at least for railway stations, according to the definitions of Swedish Transport Administration part of the railway tunnel. The stations should therefore at least reach the life-safety targets for tunnels. For subways and trams, it is close at hand to compare with the railway’s view of underground stations. Underground stations within road infrastructure, such as bus terminals, can be a completely independent facility and the connection to life-safety targets for tunnels given in [2] is not as obvious.

Comparisons to background risk levels
The quantitative criteria for verifying fire assessment proposed by the Nordic collaboration mentioned in the paragraph ”Standards, regulations and investigations” [5] are proposed based on comparisons to background risk. The acceptance level for individual risk is set to $10^{-6}$ per year, which equals one tenth of deaths due to fire accidents in the Nordic countries.

The proposal of acceptance criteria for individual risk given in 1997 by The Swedish Civil Contingencies Agency (MSB) [12] are also based on comparisons to background risk, for example, the risk of being struck by lightning or the risk of dying in natural disasters.

The different acceptance criteria for individual risk described above apply to continuous presence in a given location. This means that they are not directly applicable to, for example, travellers or staff where the impact of a specific risk source will not be continuous. If the individual risk level considers a non-continuous exposure, the acceptance criteria also should be adjusted with regard to the corresponding parameters.

For societal risk, it is not as easy to base the risk assessment on comparisons to matching background risk levels in the same way as for individual risk. This is one of the reasons why studying both societal risk and individual risk, i.e. these risk measures complement each other with respect to the factors they highlight.

Extract life-safety targets from reference cases
Extracting a quantitative life-safety target from different reference cases assumes that there are existing acceptable systems which are similar to the actual system. This basis was used to extract a life-safety target for tunnels [1].

There are existing underground stations with platforms, but few risk analyses have been carried out and the conditions vary both in terms of analysed accidents as well as different risk levels between different modes of transport. Studying possible reference cases, observations have been made regarding e.g. variations in analysed accidents and accounting exposure factors. For instance, these variations lead to a calculated individual risk for the stations of Citybanan to be less than 1 000 times lower than the specified safety target. The calculated individual risk accounts exposure factors, but the safety target doesn’t. Furthermore, the individual risk calculated for the stations of Citybanan is limited to only include train fire within, or close to, the underground platform station.

A conclusion from the inventory of identified reference cases is that it is not feasible to conduct a safety target for underground stations using their risk levels since the data is too insufficient. There are simply not enough reference cases to conduct a common life-safety target.

However, it is shown that platform stations, to some extent, can be compared to tunnels. At least as far as rail tunnels are concerned. A platform stations that connects to a tunnel becomes a natural extension or part of the tunnel. Because of this, it should be appropriate to conduct a life-safety target for platform stations that is at least equivalent to the safety target for tunnels.

Cost-benefit analysis
Cost/benefit analysis can be used to calculate an acceptable risk level. It requires that the value of a statistical life is determined. Though it is difficult to implement cost-benefit for several different reasons, which is highlighted in the report "Use of risk acceptance criteria in Norwegian offshore
industry: Dilemmas and challenges” [14]. The analysis has its greatest practical use when considering and comparing separate measures, e.g. risk level within ALARP. It is neither practical nor appropriate to only base an acceptance criteria or life-safety target on cost-benefit analysis alone.

Conclusions from assessment
None of the separate basis described above are deemed to work as a sufficiently acceptable basis for life-safety targets for platform stations. However, it could be possible to conduct parts of a safety target using different basis and, in that way, create a relatively comprehensive common life-safety target.

It is common practice that in case of fire all persons must be able to evacuate an underground platform station before critical conditions arise and this needs to be verified by fire and evacuation calculations.

Accident statistics connected to underground platform stations are limited and there are no statistics for accidents with high consequences, which means a limited possibility to draw conclusions based on recent risks.

A comparison with acceptance criteria and safety targets in tunnels seems appropriate when platform stations become a natural extension or part of the tunnel, such as railway and subway tunnels. Underground stations within road infrastructure, such as bus terminals, can be a completely independent facility and the connection to life-safety targets for tunnels is not as clear.

Background risk levels could be used to conduct acceptance criteria for individual risk. Cost-benefit analysis could be used as a basis and part of the management of safety targets.

DESIGN OF A SAFETY TARGET FOR UNDERGROUND STATIONS

Alignment of safety targets for underground stations
The initial assessment is that what applies to safety targets for tunnels is in principle applicable to platform stations. This includes the use of a prescriptive solutions for simpler underground facilities. It may be possible to use the safety targets for tunnels without modifications, but probably this will not provide a sufficient or desired safety. Suitable adjustments could be:

- Practice of verifying fire and evacuation safety so that evacuation can take place before critical conditions arise.
- Given the uncertainty of what is acceptable risk in underground platform stations ALARP should be applied more extensively. In principle, ALARP constitutes the entire area below the upper acceptance limit.
- Given the uncertainty what is acceptable regarding risks with multiple fatalities, such as fire or dangerous goods, additional basis may be needed beyond a straight comparison of cost and benefit. Using a cost/benefit ratio B - C > 0 to assess if the measure is reasonably practicable or not may need to be re-evaluated.
- Complete the safety target with acceptance criteria for individual risk.

The establishment of prescriptive solutions should be sufficient for the majority of facilities and more extensive analysis and verifications against quantitative safety targets then needs to be done for a smaller number of underground stations. Inspired by the results from previous projects, an adapted model could be used to propose measures for platform stations, Figure 3. At least until specific acceptance criteria are developed. In order to, in the long term, establish feasible safety targets and requirements for underground stations based on their conditions instead of comparison with tunnels, the Swedish Transport Agency should continuously do follow ups on statistics and experience from
ongoing projects. This is one important motive to wait until a lower boundary for the ALARP-area is introduced.

In railway and subway projects, it is normally viewed as a malfunction if trains stop in the tunnel in case of a fire. The routine is to, if possible, drive the train to the nearest station, or out of the tunnel, for evacuation. At underground stations, it is therefore standard procedure for trains to stop in case of fire. Compared to the tunnels, this places higher demands on evacuation safety within the platform stations. Verifying fire and evacuation safety should therefore, in accordance with practice, be a part of the prescriptive solutions for platform stations.

![Diagram](image)

*Figure 4. Proposal for process image - decision on measures, underground platform station.*

As the platform station often are seen as a part of a tunnel, the safety level for platform stations should be at least as high as for tunnels, probably higher. Though there are currently not sufficient amount of reference cases to use as basis on how much higher the safety should be. For now, the proposal is that regardless of where the risk level is below the upper acceptance limit, cost/benefit analyses should always be carried out, i.e. ALARP is extended. Eventually a practice will be established for a lower acceptance limit, where it does not make sense to analyse whether further measures are reasonably practicable. Due to insufficient reference cases, it is difficult to determine a lower acceptance limit for now.

Furthermore, special additional assessments must be done for disaster scenarios, such as accidents with dangerous goods, and a basis for that assessment must be conducted. For example, there may be reasons to implement measures for such risks even if the cost/benefit ratio is not $B - C > 0$.

In quantitative risk analyses, both societal risk and individual risk are often used as the risk measures complement each other in describing the level of risk and thus provide an expanded basis for risk assessment. For platform stations, however, it is considered that individual risk could be a necessary complement to describe the extent of the risk.

**Assessment of Accidents with low probability and high consequence**

Accidents with, for example, dangerous goods could result in a mass casualty situation if they occur within, or close to, platform stations where large number of people are staying at the same time.
It is not feasible to evaluate such disaster scenarios for specific platform stations without considering the impact on society as a whole. Generally, accidents that could lead to such disaster scenarios with thousands of casualties are seen in society as unacceptable and should, as far as possible, be avoided. However, the knowledgebase on how to assess this design dilemma is weak at present [15].

Underground platform stations with high traffic in combination with transportation of dangerous goods or large fire scenario (e.g. heavy goods train), still means that this kind of risks have to be managed. Transportation of dangerous goods is a factor that normally means that a prescriptive solutions is not enough, but further assessment including a quantitative risk analysis is required.

Dangerous goods also means that an investigation of disaster scenarios must be carried out. The evaluation of disaster scenarios should be made considering an even more elaborate basis. Since there is no common practice and documentation regarding the analysis needed for evaluating disaster scenarios it is proposed that an overall safety target should be conducted. The proposal is that if the consequences may exceed 1 000 casualties, following analysis should be considered:

- A quantitative risk analysis must be carried out that includes societal risk and individual risk for the underground platform station. The risk analysis should primarily include risks and scenarios that are not handled through the basic standard.
- The quantitative risk analysis should include an inventory of factors that primarily affect societal risk and/or individual risk.
- The risk analysis should also describe a comparison of risk in relation to the current situation/zero alternative.
- The risk analysis should specifically highlight so-called disaster scenarios (scenarios with very large consequences) and which factors contribute to the extent of these scenarios.
- The risk evaluation and compilation of measures should specifically address the general principle of avoiding disasters.
- The risk analysis should include a systematic analysis of inherent uncertainties. If uncertainties have a major impact of the results of the risk analysis, this needs to be taken into account.
- A specific analysis of identified measures, describing all conceivable measures and possible opt-outs, justified by the fact that the measures are not reasonably practicable. The analysis should highlight certain aspects concerning cost and benefits.

**PROPOSED COMMON LIFE-SAFETY TARGET**

Based on the statistics described earlier (see “Accident statistics”), a couple of risks dominate in terms of contribution to the risk level, e.g. suicides, people being hit by trains or vehicles, fire and accidents with dangerous goods. Managing these risks in a good way could lead to an acceptable safety level.

To derive an acceptance criterion for societal risk in platform stations based on accidents statistics is not possible as there is a lack of sufficient basis. However, the safety in underground stations should at least meet the proposed upper risk level according to "Safety targets for tunnels" [2]. For platform stations the proposal is that assessment of safety measures should also be carried out if the risk level is below the proposed ALARP for tunnels.

Fire is a serious accident in underground stations and can provide a large risk contribution. The risk is included in the societal risk, but it is also proposed that requirements be set specifically according to
the practice that has been developed. This means that a functional requirement is set that evacuation of the platform station must be able to take place before critical conditions arise for design scenarios.

Disaster scenarios such as accidents with dangerous goods in the form of, e.g. explosives are very unlikely, but can lead to extremely large consequences. The risk is included in the societal risk, but it is also proposed to be investigated and evaluated specifically. This means that a proposal should state which investigations and analysis should be the basis for decisions of measures.

Individual risk is proposed to be expressed in a quantified safety target. It is considered essential that underground stations are and can be demonstrated to be safe for the individual traveling and that the probability of an accident is not higher in the platform station than in other parts of the infrastructure system. Individual risk complements societal risk for an expanded basis for risk assessment.

As several different measures are often identified for dealing with risks within the ALARP zone, all should be evaluated in a structured manner using a simplified analysis prior to choosing whether to introduce or leave out any measure and performing in-depth studies. In Figure 3, a proposal for a methodology and procedure for a simplified method is summarised. There is a connection between the assessment of risk and ALARP here, and at the same time the assessment criteria have similarities to those of socio-economic analyses. The assessment below can be performed at two levels; either as a comparison between different options with a qualitative gradation, e.g. much worse, worse, equal, better, and much better, or using an assessment of real costs according to supporting texts.

**CONCLUSIONS**

Safety targets for underground stations can be derived based on the safety targets for tunnels that have been developed previously with some modifications. This is based on the fact that underground stations usually form part of the tunnel system and should have at least the same safety. Even though the work carried out so far has not been able to find sufficient data to develop a safety target for underground platform station based on statistics a strategy to be able to do so has been proposed.

- Defining which risks should be included in a quantitative risk analysis to enable a sufficient evaluation with safety targets.
- Basic standards need to be developed for railway and road/bus terminals. Specific basic standards for each mode of transport are recommended.
- The basic standard is proposed to include requirements for evacuation in case of fire. In this, dimensioning parameters such as dimensioning fire scenario and dimensioning number of people etc. should be specified to increase uniformity.
- In order to, in the long term, establish safety targets and requirements for underground stations based on their conditions instead of comparison with tunnels, the Swedish Transport Agency should continuously do follow ups on statistics and experience from ongoing projects.
- Acceptance criteria for societal risk should be complemented with a lower limit when enough basis has been collected. In the future this means a limited need for cost-benefit analyses.
- Methods for cost-benefit analysis should be adapted for safety targets in underground platform stations.
- Regarding disaster scenarios, the Swedish Transport Agency should consider whether it is suitable to introduce general requirements for measures to significantly reduce the risk level, e.g. time control of freight transport in railway facilities. More analysis needs to be done regarding how to actually reduce disaster scenarios if such are to be allowed.
According to the investigation, safety targets for platform stations need to be developed and adapted in relation to what is stated in "Safety goals for tunnels" [2], but some major improvements are proposed. The main concerns are:

- The ALARP area need to cover the entire area below the upper acceptable level of risk mainly due to limited design experience for the prescriptive regulations.
- An individual risk level is included in the proposal.
- More emphasis needs to be put on disaster scenarios and severe accidents, which might also need to be considered in more detail for tunnels too.
- Methodology for cost/benefit analyses and disaster scenarios are to be applied but requires additional guidelines.

In addition to the above conclusions related to safety targets, another conclusion is that mandatory underground platform station requirements, i.e. prescriptive requirements, should be established for each mode of transport. This is because both the current design methodology and the legal framework are based on mandatory standards covering the requirements of common single-fatal safety measures. This standard is sufficient to ensure safety in the event of multiple deaths in a simple, non-risky underground station. However, basic standards should be used for any type of underground platform station. For more complex underground platform stations and special risks, safety targets are required that include both individual and societal risk measures.

Disaster scenarios, such as accidents involving explosives or other hazardous materials, are extremely rare, but when they do occur, they can have very serious consequences. A similar scenario can occur in the event of a large and rapid fire under unfortunate circumstances, e.g. escape routes being blocked. The risk contribution from severe accidents, which is included in the social risk level, is proposed to be specifically investigated and evaluated as a result of this study. This sets the requirements for what project specific investigation to be made as a basis for decision-making from a risk perspective. It should then be formulated with a balanced assessment in relation to existing benefits and advantages.

Finally, it was concluded that the concept of verifying safety targets using risk analysis in a manner similar to tunnels is feasible. The proposal also has the potential to provide a new user-friendly basis for assessing the economics of tunnels and underground stations and optimizing safety measures. The transport sector's safety goals and objectives are supported by the proposal. Addressing quantitative targets with clear socioeconomic reference provides a basis for consultation with authorities and decisions based on rational factors.

ACKNOWLEDGEMENTS

This work was funded by the Swedish Transport Agency (Transportstyrelsen) and the Swedish Transport Administration (Trafikverket). Their support is gratefully acknowledged.

REFERENCES


Risk evaluation of road and railroad overbuilds

Erik Hall Midholm, Rosie Kvål & Johan Lundin
Brandskyddslaget AB, Sweden

ABSTRACT
Railroad and road overbuilds are a kind of substructures that involves large costs which often leads to a need for increased land use close to and on top of the overbuild. If the transportation network which is overbuilt includes transportation of dangerous goods, the risk situation will be complex related to rare events with a potential to cause substantial damage, e.g. collapse of buildings on the over site development.
In Sweden there are at present no national or regional rules or guidelines showing how to address or evaluate this risk situation. The lack of guidelines leads to difficulties in implementing this type of project.
Brandskyddslaget has developed a proposal for what the basis for such risk assessment decisions might look like. We believe that a cost/benefit analysis will make an important piece of the puzzle in the decision-making basis for the selection of dimensional explosive load and thereby accepting the resulting residual risk, as it gives a more complete picture of the actual risk-reducing effect which leads to a less subjective risk evaluation. This can serve as one of several perspectives addressed in risk-informed decision making.

KEYWORDS: overbuild, decking, capping, tunnel risk analysis, cost-benefit, accidents, dangerous goods, explosion, spatial planning.

PURPOSE AND OBJECTIVES
The purpose with this paper is to clarify the challenges with railroad and road overbuilds and risks that can lead to catastrophic consequences. As the research within this area is quite sparse, we find it urgent to start an international debate and inform the research community of the need to pay more attention to this issue in order to facilitate sustainable development of crowded cities with transportation networks through densely populated areas. This paper aims to describe the challenges and present a feasible method for risk evaluation that facilitates decision-making concerning overbuilds and the associated risks.

INTRODUCTION
Background
In Sweden and other countries an increasing need for housing and recreation areas, as well as accessibility to infrastructure compete with an increasing claim for military defense and food supply, climate change etc. over, for instance, accessible land. The Swedish government addresses this issue by assigning a special investigation on national spatial planning [1]. Despite a small decrease during the pandemic, many factors still point to further urbanization [2] and thereby additional need for accessible land in cities.

Due to the lack of accessible urban land, railroad and road overbuilds, i.e. capping or decking, is considered more often, in Sweden, as in other countries.
This type of development connects to sustainability in several ways. For one thing, the infrastructure in question does usually have a vital societal function and is critical to the maintenance of the national public transportation network and the impact on this function and the conditions for traffic are hence very important. The climate change is also an important factor that affects the need to overbuild infrastructure, especially railroads, since a higher density in population close to public transportation nodes decreases car traffic. In combination with large construction costs for this kind of substructures this often results in a need for development close to and on top of the overbuild.

Railroad and road overbuilds bring challenges linked to risks that can have consequences exceeding a few fatalities and where the damage outcome can be more extensive compared to a corresponding accident above ground, e.g. major fires or accidents with dangerous goods [3] [4] [5]. The largest impact will occur underground, and the damages can largely be equated with damages due to major accidents in e.g. road and rail tunnels for which there are regulations and accepted methods for performing risk assessment (e.g. [6]). The main difference though is that the impact outside of a road or rail tunnel will be limited due to a low population density whereas overbuilds mostly are planned in areas with a high density of population. Hence the damage outside the overbuild has a high contribution to the overall risk. For spatial planning outside a tunnel or overbuild there are guidelines of how to assess and evaluate risk but for land use on top of an overbuild there are no regulations or established guidelines. Also, common practice is sparse and relies on a weak knowledge base. Hence risk assessment concerning those areas is uncertain and complex.

If an accident occurs below the deck in a location where the population density is high, the consequences could, under certain circumstances, be very high, even disastrous. Even though the accidents primarily will affect safety below the deck there are certain accidents, especially associated with dangerous goods and detonations, which can cause impact on surrounding buildings on top of, or close to, the overbuild. At the same time the substructure can reduce the impact on the surroundings by limiting the damages of a number of other types of accidents.

The challenges with combining urban land use very close to, or on top of, infrastructure with transportation of dangerous goods is numerous and have been described previously [7], including the difficulty to handle changing conditions accordingly and the lack of measurement of the actual risk – particularly regarding a certain aspect of risk impact. Overbuilding roads and railroads assigned for transportation of dangerous goods introduces a particular challenge related to rare events, such as dangerous goods accidents in tunnels, with a potential to cause substantial damage, e.g. collapse of structures and buildings on the over site development. Since there are no guidelines as how to handle those catastrophic scenarios which is often inevitable in such projects if additional development is the driver.

**Risk assessment on catastrophic scenarios**

Generally, accidents that could lead to catastrophic scenarios with thousands of casualties are seen in society as unacceptable and should, as far as possible, be avoided. However, the knowledgebase on how to assess this risk is weak at present [7]. Completely eliminating such risks could either lead to restrictions that will cause unacceptable limitations in the use of the infrastructure or obstruct the overbuild project due to insurmountable costs or insufficient exploitation volume.

Risk assessments are often based on a comparison of the results of a risk analysis and criteria for risk acceptance. The acceptance criteria are often presented in regional or national recommendations or guidelines and forms the base for decision making. Even though there are guidelines and practices regarding risk assessment for developments close to risk objects such as railroads and roads with transportsations of dangerous goods, there are still some issues about how to treat different risks. E.g. the suggested criteria for societal risk signed DNV on behalf of Swedish Civil Contingencies Agency [8], which for long has been a practice in rural development, is based on ALARP-methodology. However, there are no guidelines or practices on how to actually evaluate whether measures are considered reasonably practicable or not when the risk level is sought to be ALARP. This means that
decisions based on a comparison of the calculated risk level and applied acceptance criteria may be based on insufficient information of the proposed measures.

There are also issues about how to treat catastrophic scenarios. For instance, most criteria for societal risk, has an upper limit on 1,000 casualties. It is not given that an extrapolation of the criteria beyond this point is equal to an acceptable risk. The suggested criteria mentioned above doesn’t include an upper limit, however the report highlights the importance of not basing the risk assessment beyond 1,000 casualties merely on quantitative risk analysis. The report doesn’t include any guidelines on how to design the risk assessment beyond this limit.

The lack of guidelines and practices both regarding how to make the risk assessment within ALARP and how to treat catastrophic scenarios makes it even more difficult as it comes to overbuild and the issues described earlier. As a result of there being no specific guidelines or accepted practice, at the moment, there is a need for project-specific adaptations. There are several different solutions that have been applied within different projects. One quite common solution is that the DNV’s criteria are extended and that the same valuation principles as for fewer than 1,000 fatalities are used. However, this means that the background to the criteria is not followed (see above). In one large overbuild project where there were several building blocks planned, it was chosen to apply relatively extensive physical measures, among other things concerning the dimensional explosive load. This approach was accepted by the authorities and the detailed development plan gained legal force. After this, the authorities became unsure whether the measures taken were sufficient and therefore chose to introduce restrictions concerning transportations with explosive loads on the road that had been overbuilt. The result of that work was thus both extensive technical requirements and restrictions on the transport route, which also constitute a national interest for communication and was thus limited. In another project where buildings are planned close to, but not on top of, the overbuild, the design accident load for the decking has been chosen on a very loose basis which can lead to unmotivated high building costs or insufficient measures. Other examples exist where no consideration has been given to this type of accidents due to their low probabilities, which could result in risks that would be deemed unacceptable if highlighted.

In general, it can be said that there is a great deal of uncertainty concerning accidents that can lead to catastrophic consequences. The uncertainty is caused by many factors, e.g. limited statistical basis due to that this kind of accidents occurs very rarely, insufficient information about how large quantities of the relevant substances that are transported on one and the same vehicle, and uncertainty about the reliability of calculations and measures. It is also difficult to model the effect on the buildings above the decking which introduces additional uncertainties.

In a large project where extensive construction on top of the decking is planned, the lack of guidelines has led to project-specific guidelines. The guidelines include a method for risk assessment above the substructure and one for the area below, i.e. the platform room. The guideline for risk assessment for areas below the substructure has been developed by the Swedish Transport Administration. The guideline is formulated as: “The safety in the platform room under the overbuild must be at a similar level as in other modern platform rooms”.

In the guideline for risk acceptance above the decking, developed by the City of Stockholm (shown in figure 1), demands are made for carrying out an advanced analysis of potential barriers by identifying and assessing barriers that can reduce the probability of, or the consequence of, catastrophic scenarios, i.e., events that could lead to more than 1,000 casualties. Barriers here refer to physical or non-physical measures for to prevent, control or mitigate studied accidents. Barriers can include such technical and physical risk mitigation measures that are usually regulated in detailed development plans. But barriers can also include overall organizational structures and processes that contribute to increased safety, which is more difficult to regulate in a separate development plan. Also included is to consider barriers that include maintenance and control, which takes place through supervision according to several different regulations.
The method for risk assessment is based upon the DNV criteria for fewer than 1,000 fatalities. Furthermore, the limit for unacceptable risk is extrapolated with an unchanged slope into the area with more than 1,000 fatalities (see figure 1). However, for more than 1,000 casualties, there is no corresponding area where the risk is directly considered acceptable. This means that if there is an indication that catastrophic scenarios may occur, specialized analysis of scenarios and barriers must always be carried out in order to determine whether the level of risk can be tolerated or not.

Figure 1. Example of risk assessment criteria for societal risk development by the City of Stockholm, explaining how to assess risk for more than 1,000 casualties.

The method for risk assessment for impact above and close to the overbuild is based on a risk informed approach with focus on:

- The risk level
- The number of barriers
- The availability of barriers over time
- Cost-efficiency
- Uncertainties

As there is an inherent potential for disaster, a specialized analysis needs to focus on it to increase knowledge and reduce uncertainties. Other features of the risk level that may affect the need for
barriers have to be identified. The risk level controls the scope and depth of specialized analysis. Both technical/physical and organizational barriers are considered to achieve safety, throughout the system.

Different types of barriers are taken into account and evaluated, both within the infrastructure facility, within other parts of the planning area, readiness of actors on site and society's emergency preparedness. The barriers must be possible to ensure/regulate over time. Since there is no definition of acceptance level for catastrophic risks, the assessment method does not provide the answer to which barriers are required to achieve an acceptable risk. Instead, the decision-maker is expected to take a position on this upon the basis that different combinations of barriers and their risk-reducing effect are reported and what responsibility that will follow for the stakeholders.

The assessment method further states that the choice of barrier combination needs to be the result of, among other things, reducing the risk level, safety level and whether the uncertainties associated with it can be accepted or not. In summary, the assessment method requires a more comprehensive decision basis than is normally produced in the spatial planning process. Despite this, the decision-maker is faced with a challenging situation with limited guidance on what is a reasonable solution or not. The assessment method means that decision-making goes from being risk-based to being risk-informed, which means that additional factors, in addition to the quantitative risk level, form the basis for decision-making.

Several of the factors that, according to the assessment method, need to be included and evaluated is based on qualitative assessments. One of the assessment factors that is most likely to actually be based on quantitative criteria is the cost-efficiency, i.e. is a barrier reasonably practicable based on the cost of the barrier relative to its benefit (risk reduction).

**Potential barriers**

There are a number of barriers that all can affect safety to different extents. Some barriers induce a reduction in frequency of an accident, while others lead to a reduction of consequences. In general, measures that reduce the frequency of an accident are difficult to implement in the municipal planning process since the municipality does not have control over the relevant infrastructure or the design and load volumes of the transport vehicles. The focus will therefore often be to reduce the consequences, as is the case in projects where substructures over transport routes is mainly driven by a development purpose.

A consequence-reducing measure that has a major impact on the risk level is the extent of the exploitation that is planned. A reduced development in the immediate vicinity to an overbuild will be an efficient measure to reduce the consequences of an accident. By reducing the degree of exploitation and choosing land use that has a low population density, catastrophic consequences can be avoided. In theory, a low exploitation rate is therefore an effective measure. However, an overbuild generally means a large construction cost, which is often financed to some extent by the exploitation. This can therefore not be too limited. The dilemma then becomes that a high degree of exploitation is necessary to be able to carry out an overbuild (which has many positive effects, for example concerning noise and particles) at the same time, the high degree of exploitation can entail the risk of catastrophic consequences in the event of an accident. Another barrier that also has a consequence-reducing effect is the substructure and its inherent resistance to accidents that can cause catastrophic consequences. Dimensioning substructures for a high load can be both expensive and challenging construction-wise. It is therefore important to investigate which type of accident forms the basis for the design of the structure and the scope of measure.

For the area under the decking, it is primarily accidents involving dangerous goods and fire in vehicles that have a major impact on the risk level and which therefore need to be mitigated. For areas on top of and close to an overbuild, it is mainly accidents that lead to ruptures in the loadbearing structures that can lead to catastrophic consequences. Accidents that affect the structure's stability and durability are primarily very extensive fires and explosions of the type detonation. Around the openings of a tunnel other scenarios can cause extensive consequences, for example leakage of toxic gas. The impact can be equated with an accident that occurs in the open air, which rarely leads to
catastrophic consequences. Spatial planning along roads and railroads on the surface is affected by requirements for protective measures which entails a low population density close to the infrastructure, but these are not necessarily sufficient or even relevant for overbuilds.

When it comes to the impact from fires, there is a lot of knowledge and available technology how to reduce the size of damage. Accidents that lead to fire can therefore often be managed to such an extent that catastrophic consequences can be avoided. This implicates that perhaps the most important practically feasible barrier is to dimension the substructure for explosions. However, which dimensional load is suitable is not obvious and must be investigated. Dimensioning of dynamic explosion load for the overbuild’s load-bearing system is regulated in TRINFRA-00233 [6] where it is stated that if transports of dangerous goods in ADR/RID class 1, 2 and 5 according to Ordinance (SFS 2006:311) on the transport of dangerous goods is allowed in the tunnel, the dimensional explosive load must be determined through a special analysis. However, no guidance is given on how such a special analysis shall be conducted or what content that is expected at the moment. A knowledge gap exists.

When it comes to dimensional explosive loads, there is a lack of distinct and accepted methods and practices for which load might be suitable for an overbuild. A challenge in most overbuild projects is therefore to define how large an explosive load the substructure should be dimensioned for. Measures that alleviate the consequences of an explosion are often very costly and have a large climate footprint and are therefore not obvious to take. The potential benefit (i.e. the risk-reducing effect) of the measure therefore needs to be put in relation to the cost and other negative effects.

There are currently no accepted values for various input parameters that are required to make a complete analysis regarding the benefit of measures’ effect on the level of risk for third parties. Basically, this is due to the fact that there are no defined risk ratings per casualty or injury to third parties. In order to make an overall assessment of the benefits of the measures, a method and principle for risk assessment has been chosen in projects from the accident assessment of traffic accidents according to the Swedish Transport Administration’s “Analysis method and socio-economic calculation values for the transport sector”, ASEK 7.0 [9].

**Purpose and objectives of the developed method**

The overall purpose of the completed work is to evaluate the benefit of different dimensional explosive loads for the load-bearing substructures and the risk reducing effect relative to the cost of the measure. The work is performed by examining a method for cost/benefit analysis to see if it is suitable to use when evaluating risk-reducing measures in the spatial planning process. The focus has initially been to study the method for measures that reduce the impact on the loadbearing substructures in the event of an explosion causing detonation. The initial scenario has been an accident involving the transportation of dangerous goods. The work has been carried out within a specific project where the results are included in the risk analysis that forms the basis for the municipality’s detailed development plan.

The objective is to be able to supplement the decision-making basis for risk assessment and selection of measures with a substantiated investigation of the effect of various barriers on the risk level and associated cost/benefit analysis.

**Delimitations**

The work is based on a project that includes an railroad overbuild situated in a densely populated area. The focus is on accidents with transportation of dangerous goods that lead to explosions and possible adaptations of the intended construction to reduce the impact from these accidents. Different dimensional explosive loads are studied. The used method has so far only been applied to explosion-reducing measures in the substructures. The method has not yet been applied on impact from other types of accidents or measures.
METHOD

General
The basis for the methodology is cost-benefit analysis (CBA). The benefit-part of the CBA is based on a quantitative risk analysis (QRA) studying the impact on the societal risk. The initial step is to calculate the residual societal risk for a proposed development on top of an overbuild for different cases, where the load bearing system for each case is designed for a specific dimensional explosive load.

The quantitative risk analysis is based on a relatively classic structure and methodology with definition of the studied system, inventory and identification of risk sources and possible accidents, quantitative assessment of the scope of the risks (frequencies and consequences) and evaluation of the risk level based on established acceptance criteria.

Basis
As an initial input to the risk analysis a basic design for the overbuild is chosen. The design complies with applicable regulations, but no special consideration has been taken of accidents with dangerous goods. The basic design is defined as a baseline and a minimum requirement for the substructures dimensional load. The effect on the construction has been assessed and the number of fatalities estimated based on the extent of the damage.

With the purpose to increase the robustness and reducing the consequences of potential explosion scenarios, alternative designs of the overbuild are then studied where the dimensional explosive load is gradually increased. At this stage, a dialogue with experts should be initiated to identify possibilities and limitations regarding the technically feasible dimensional explosive load. For example, to include theoretical measures that turn out to be unfeasible only risks complicating the continued process introducing excessive hopes about what potential technical possibilities there are to deal with the risks.

Risk identification
The risk analysis studies accident that may have an impact on third parties on top of and close to the overbuild. The substructure will work as a shield against several accident that could, in the event of an accident in the open, affect the surroundings, e.g. accident with flammable liquids, gas leaks, etc. Due to this shielding effect, the risk analysis, and further analysis of measures/barriers, will mainly focus on explosion scenarios.

Dangerous goods are categorized into nine different classes depending on their specific characteristics. Of all the classes, it is the transport of a few individual classes that, in the event of an accident, can lead to explosion with extensive impact on the surroundings. The classes concerned are 1.1 – mass explosive substances and 2.1 – Combustible gases. In addition, there are certain substances belonging to class 5 – Oxidizing substances and organic peroxides which if, for example, involved in a fire or exposed to high pressure or mechanical impact can disintegrate extremely violently and involve explosive firer with equivalent forces as mass explosive substances.

Essential inputs
If possible, the risk analysis should be based on local statistics on dangerous goods to be able to calculate as realistic a risk level as possible. However, consideration generally needs to be given to the fact that dimensioning based only on this input data may lead to future restrictions regarding transportation on the road or railway in question. For example, if statistics show very small transport quantities of explosive substances while there are no restrictions preventing larger transport quantities from being transported, dimensioning based on very small quantities can call for restrictions of transport with larger quantities of explosive substances.

Another aspect that needs to be considered specifically for overbuilds is that it may be relevant to study a more nuanced distribution between different explosion scenarios. The reason is that potential
scenarios have a more significant contribution to the risk level in the event of an accident under an overbuild since the impact can be catastrophic. This means that a more distinct distribution between different explosion scenarios has a greater impact on the risk level compared to a risk analysis of infrastructure on the surface where more accidents (also probably with higher frequency) contribute to the risk level. The importance of nuanced distribution between different explosion scenarios is particularly important to provide a basis for further investigations regarding the need for risk-reducing measures. Otherwise it can be difficult to distinguish the risk-reducing effect of different measures, for example, with a distribution only including extreme values, e.g. very small explosions (which barely affect the F/N curve either with or without measures) and very large explosions (where realistic protective measures may have very limited effect on the consequences, i.e. the accident may have very large consequences both with or without measures).

**Essential output**
The output of the quantitative risk analysis results is different curves (risk levels), one for each of the studied cases, which are plotted in an F/N diagram, see example below.

![Figure 2. Example of a F/N diagram that shows the societal risk level for third parties regarding risks that may involve consequences on top of an overbuild depending on the dimensional explosive load.](image)

Based on the F/N diagram, it is possible to get an overall image of how each measure (case) affect the societal risk in relation to the baseline and to each other. The example above shows that the difference between studied cases mainly applies to consequences with more than 1,000 casualties. To make it easier to illustrate the differences between the studied measures, we zoom in on the F/N diagram, see figure 3.
The zoom in on the F/N diagram shows that the studied measures have a quite similar affect on to the societal risk. A gradually increasing dimensional explosion load will lead to a gradually decreasing number of casualties, but there are no giant steps on the curve. The difference between the baseline and the studied measures are mainly within consequences between 1,000 and 10,000 casualties. However, for the most extreme scenarios (with regard to damage areas and population density, etc.), the studied measures have a limited damage reduction.

This strongly indicates that there is a technical limit to what is possible to dimension the constructions for, and this limitation probably goes far below the very largest explosion scenarios.

Regarding the lack of guidelines and practices for risk assessment for more than 1,000 fatalities that is described earlier in this article, section "Risk assessment on catastrophic scenarios", figure 2 shows no limit for acceptable risk for more than 1,000 fatalities. Based on this, the assessment is that all studied cases fall within the boundaries of ALARP for consequences that lead to more than 1,000 casualties. A societal risk level within ALARP means that the risks must be carefully considered and reasonable measures must be taken to reduce the risks.

Comparing the societal risk for different levels of the deck’s dimensional explosive load, it is found that the impact is limited to the most extreme scenarios of societal risk. That is, how big the maximum consequences can be for the scenarios with the lowest frequency. An increasing level of dimensional explosive loads will have a gradual reducing effect on the maximum consequences, but the consequences can still be of catastrophic potential. Due to the lack of criteria for maximum acceptable consequences, we find the need to add a different approach to the decision basis which need to be transparent and publicly accepted for overbuild projects.

Simply studying and comparing the F/N curves for studied cases to identify which case presents the lowest risk does not constitute a sufficient basis for the decision on dimensional explosive loads because it does not provide a distinct answer as to whether the measure actually is reasonable or not. Additional parameters needs to be taken into account in evaluating the measure's risk-reducing effect.
Cost-benefit analysis
In order to evaluate the plausibility of studied levels of the dimensional explosive load, a cost/benefit analysis is carried out which compares the cost of the measure with the expected benefit.

The following steps are followed in the analysis:

- Definition and delimitation of the measure
- Identification and quantification of relevant effects
- Valuation of relevant effects in Swedish kronor
- Discounting of future benefits and costs to a present value
- Calculation of net present value ratio
- Sensitivity analysis

The first two steps are handled in the quantitative risk analysis. However, moving on to the cost/benefit analysis the societal risk for each case is converted into Potential Loss of Life (PLL), which is the expected number of fatalities within a specific population per year. PLL is the total of summarizing frequency (per year) x consequences (casualties) of each scenario, i.e.

\[ PLL = \sum (F_i \times N_i) \]

The effect of increasing the dimensional explosive load is shown as a comparison in relation to the defined baseline.

Since there are currently no accepted values for various input parameters that are required to make a cost/benefit analysis for third parties, in particular no defined risk ratings per casualty or serious injury, we need to look elsewhere. In order to assess the benefits of the barrier, risk ratings for third parties will be based on risk ratings for road traffic accidents according to the Swedish Transport Administration’s ”Analysis method and socio-economic calculation values for the transport sector”, ASEK 7.0 [9].

ASEK 7.0 reports risk ratings for road traffic accidents in millions of Swedish kronor per person injured or killed in traffic accidents. For the injured, different risk assessments are given for the levels seriously injured, very seriously injured and not seriously injured, respectively. The risk ratings according to ASEK for each category consists of a risk assessment and an assessment of material costs. The risk assessment consists of a human value that reflects society’s loss of utility in the event of the loss of a human life or the sacrifice due to physical and psychological suffering for those injured in a traffic accident. Material costs for a traffic accident consist of costs for medical care, net loss of production due to personal injury and/or loss of life, administration and damage to vehicles and other property.

Table 1. Risk ratings for road traffic accidents, per person injured or killed in traffic. Price level in 2040 (in 2017 monetary value). Material costs are stated including general VAT surcharge. In SEK and €.

<table>
<thead>
<tr>
<th></th>
<th>SEK Million 2040</th>
<th>€ Million 2040</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Material costs</td>
<td>Risk ratings</td>
</tr>
<tr>
<td>Casualties</td>
<td>6.23</td>
<td>62.07</td>
</tr>
<tr>
<td>Seriously injured</td>
<td>0.97</td>
<td>18.24</td>
</tr>
<tr>
<td>Very seriously injured</td>
<td>4.53</td>
<td>18.7</td>
</tr>
<tr>
<td>Not seriously injured</td>
<td>0.04</td>
<td>6.44</td>
</tr>
</tbody>
</table>
The result of a third-party cost/benefit analysis based on risk ratings for road traffic needs to be used with caution. There is ongoing research regarding individuals' risk assessment of public transport which suggests that there may be a higher willingness to pay to reduce risks when traveling in this way. In other words, there may be factors that mean that risk ratings for road traffic should only be used as an approximation in analyzes of measures for other types of traffic, e.g. rail traffic. Likewise, risk ratings for road traffic should only be used as approximations in third-person analyses. There are additional parameters that need to be considered in the assessment of the benefits of the measures, including impact on material damage and impact on national interest and urban functions, etc.

In order not to underestimate the risk ratings linked to the fact that ASEK refers to the transport sector instead of third parties, a sensitivity factor is applied to the risk ratings. This sensitivity factor also takes into account the fact that measures valued according to ASEK are generally about managing accident risks with relatively small consequences (few fatalities), while current measures aim to limit very large consequences, i.e. the sensitivity factor also partially takes into account the fundamental valuation principle of disaster avoidance. Based on this we add a quite high sensitivity factor on the risk ratings, approximately 10 times the risk ratings in ASEK.

Furthermore, the methodology according to ASEK states that the present value of the proposed measure must be calculated based on a discounting of future amounts due to today by reducing the future amounts by a certain interest rate. The recommended economic lifetime for new tunnels is stated in ASEK at 60 years. The real socio-economic discount rate must be set at 3.5%, which gives a zero sum factor (in Swedish nusummefaktor, NSF) over the lifetime of the overbuild of:

\[ NSF = \frac{1}{0.035} \left( 1 + 0.035 \right)^{-60} = 24.9 \]

Also, with regard to this parameter, we apply a sensitivity factor taking into account that an overbuild with buildings on top may have a longer recommended economic life or that the discount rate is not the same. Not to underestimate the benefits of studied measures based on a potentially long lifetime, we add a quite high sensitivity factor on the zero zum factor, 10 times the value according to ASEK.

### Additional estimation of consequences

The output of the risk analysis only include potential number of casualties since neither societal risk or individual risk consider potential number of injured. As mentioned above ASEK 7.0 reports risk ratings per person injured or killed. To be able to use ASEK 7.0 as input, an additional estimation has to be done of potential number of injured for each scenario, severely and slightly. We make an assumption that for every fatality, 5 people are seriously injured (very seriously injured according to ASEK 7.0), i.e. the number of seriously injured is 5 times as high as the number of people killed in an accident. The number of slightly injured (not seriously injured according to ASEK) is assumed to be 10 times as high as the number of fatalities. However, the sum of fatalities, severely injured and slightly injured is limited to the expected number of people within the studied area.

### Costs

The calculated benefit of each case (i.e. dimensional explosive load) in relation to the stated baseline needs to be compared to the estimated cost increase of each case. This cost estimation could be more or less detailed. There are a number of inputs that could be included in the cost estimation, such as potentially increased maintenance and limitations on exploitation. One input that has to be included is the expected additional cost for reinforcing the substructure to manage a higher dimensional explosive load in relation to the baseline. This requires input from the constructor.
**Comparing costs and benefits**

In ASEK 7.0 the assessment of measures based on a cost/benefit perspective is performed by subtracting the cost from the expected benefit. > 0 means that the measure is assessed to be reasonably practicable, and a negative ratio points to a not reasonably practicable measure.

The downside to this approach is that it provides a rough, and potentially loose, basis for deciding whether measures should be implemented or not. The report "Evaluation of Risk" funded by the Swedish Civil Contingencies Agency, [8] alerts the problem of dismissing measures on the grounds that they are marginally more costly than the benefit they can achieve. Adding a grossly disproportionate factor (GDF) to the assessment is applied in several areas and countries (see examples in, among others, [10] and [11]). In these cases, the assessment of whether studied measures are reasonably practicable or not is based on dividing the cost by the benefit to obtain the ratio between these two parameters. For a measure not to be judged to be reasonably practicable, this ratio needs to be > 1 x GDF.

Nor here there are guidelines, neither national nor international, on what is an acceptable level for GDF, i.e. the degree of "disproportionality". Normally, the GDF is determined by the actual risk level within ALARP. If the risk is low (i.e. close to the lower limit of ALARP) a low GDF can be considered, but with a high risk (close to the upper limit of ALARP), the GDF should increase. GDF greater than 10 is uncommon. E.g. the British nuclear power industry uses a GDF of 10 as the highest value where the cost of a measure can still be considered reasonable in relation to the measure's benefit [10]. There are few examples of other areas using higher levels of GDF at high levels of risk.

Considering the purpose of the specific measures, i.e. to reduce the risk level of catastrophic scenarios, a risk assessment area with sparse know-how, and practices or guidelines, we recommend that the GDF should be set high. For example, on assessing the most reasonably practicable dimensional explosive load for an overbuild with land use very close to, or on top of, the infrastructure, we set GDF = 100.

**CONCLUSION**

We are fully aware that risk ratings for road traffic accidents cannot be used directly calculating the benefits in a third-party analysis. The analysis should be regarded as a guideline for the benefit of the studied barrier explosion protection of structural elements. There are a couple of parameters that need to be addressed in the assessment of the benefit, including stricter risk acceptance criteria for third parties compared to road or railroad users, and also the basic risk evaluation principle that suggests that there may be a higher willingness to pay to reduce scenarios with catastrophic potential. We take these parameters in consideration by adding sensitivity factors while estimating the benefit of studied measures (both on risk ratings and zero sum factor of the barrier). On top of that, we recommend adding a grossly disproportionate factor (GDF) to the assessment of whether studied measures are reasonably practicable. Considering the purpose of the specific measures, i.e. to reduce the risk level of catastrophic scenarios, a risk assessment area with sparse know-how, and practices or guidelines, we recommend that the GDF should be set high.

Regardless of the identified uncertainties, we do believe that a cost/benefit analysis will make an important piece of the puzzle in the decision-making basis for the selection of dimensional explosive load and thereby accepting the resulting residual risk, as it gives a more complete image of the actual risk-reducing effect which leads to a less subjective risk evaluation.
REFERENCES

[2] WSP Sverige AB, "Regionernas kamp 2022".
Risk Assessment of Deckings of Dangerous Goods Routes
– A knowledge inventory

Henrik Tehler¹, Johan Lundin²
1 Division of Risk Management and Societal Safety, Lund University, Lund, Sweden
2 Brandskyddslaget AB, Sweden

ABSTRACT
This paper focus on challenges related to risk assessment and risk control when decking transport routes for dangerous goods with deckings. The objective is to carry out a knowledge inventory in international research literature on risk management and deckings, which also includes practice regarding different types of protection measures. This is done in combination with a current situation description of how this type of problem is handled in practice today. The review of literature is carried out with a so-called scoping study. It is expected to identify a number of possibilities for dealing with this type of risk management problem, as well as the evidence that may exist as support for different approaches. Interviews will be conducted with experts in the field who are active in Sweden. The interviews will partly be designed on the basis of the literature review and together these two methods will hopefully give a good picture of the current state of knowledge partly in the academic literature, but also in the practical context. In summary, we can state that there is some research concerning tunnels in general and the transport of dangerous goods, but when it comes to specific problems with deckings, there is a lack of studies. In some cases, the problem of deckings is mentioned, but there are no articles dealing with how this type of problem is solved in other countries, or about suggestions on how to manage risks in connection with deckings. From a risk governance perspective significant effort is necessary to facilitate sound and robust prerequisites to risk management of deckings to safeguard that we are not drifting into failure and introduce risks in our modern society that we potentially will regret tomorrow.

KEYWORDS: decking, underpass, overbuild, dangerous goods, restrictions, ADR, RID, risk analysis

INTRODUCTION
This paper will report on results from the research project "Risk assessment and risk control when decking transport routes for dangerous goods" which is carried out by the Division of Risk Management and Societal Safety, Lund University, and Brandskyddslaget AB on behalf of the Swedish Transport Administration during 2022.

Background
Projects to cover, deck or overbuild transportation routes are becoming increasingly common, sometimes creating an underpass under populated areas where transportation of dangerous good potentially can occur. However, there is considerable uncertainty with respect to how risk should be dealt with in this type of project. This is primarily related to risks associated with the transportation of dangerous goods.

One the one hand, there is an ambition to allow as much flexibility in terms of the usage of the piece of land above or in direct vicinity of the decking. On the other hand, there is also a desire to not impose too much restrictions in terms of what kind, and how much, dangerous goods can be transported on the route. These two overarching goals can end up in conflict with each other. For
example, if a building with high occupant load is built on top of the decking, restrictions in terms of transportation of dangerous goods might have to be imposed and/or restrictions in terms of the use/design of the building.

The fear of exploitation above deckings is that accidents involving the transport of explosives (ADR / RID class 1) and oxidizing substances and organic peroxides (ADR / RID class 5) can cause accident scenarios that result in damage to a large number of people, and buildings, above and adjacent to the canopy. In a dense metropolitan environment, there may be very many people who could potentially be exposed to negative consequences from this type of accident scenario. The damage can be considered unproportionally large.

Regarding this type of potentially catastrophic scenario, there are no overall safety targets or acceptance criteria regarding risk in Sweden that can be directly applied to deckings. There are no accepted principles for risk assessment of this type of risk, in addition to a general statement that it is desirable to try to avoid disasters. This means that it is unclear what constitutes the basis for assessment, e.g. when assessing whether it is safe enough to build above a cover of a transport route for dangerous goods. Such assessments are necessary to answer questions such as: "Is it appropriate to build on top of a decking?" or "Are more risk mitigation measures required for this to be appropriate land use and a good built environment?" or "Does the proposed land use above the decking entail any restrictions on what is allowed to be transported on the road and rail network?". There is therefore a need for increased knowledge about how this type of project should be handled from a risk perspective.

The present paper is a result of a research project aimed at contributing with knowledge about the problem of managing risk in this type of context and contribute to a more appropriate management in practice. The project was focused on the Swedish context, but it is likely that similar problems are encountered in other countries as well. To increase our knowledge on how these types of potential conflicts between exploitation (of the area above the decking) and transportation (of dangerous goods below the decking) are dealt with and suggest ways to improve practice, two methods were used. First, a review of international scientific papers focused on risk management and deckings were carried out to determine what is known about the management of risks with respects to transportation of dangerous goods and deckings. Secondly, an interview study was conducted focusing on Swedish professionals involved in decking projects with the aim of describing current practice and identify challenges and opportunities for development.

The paper is organised as follows. First the literature review is presented, and its results are briefly discussed. Then the interview study is presented, and the results are discussed considering the literature review. Finally, we offer some suggestions on what might be done to improve the management of risk with respect to transportation of dangerous goods in decking-projects in Sweden and elsewhere.

**METHODS**

**Literature study**

To carry out the review of knowledge in international scientific journals, a so-called Scoping study was used. There are several different ways that you can use to systematically search scientific literature for relevant knowledge. There are several reasons why we chose this method.

First, we do not expect the knowledge sought to necessarily be found within the framework of a specific research area, or in one or a limited number of scientific journals. The reason for this is that the problem of managing risk with regard to dangerous goods in connection with the decking of transport routes is multifaceted and thus there are several different perspectives that can be taken to
study it. For example, one could focus on the construction aspects of the problem and investigate the impact of blast load on various building elements that occur in decking constructions. Another example is that one could focus on the decision situation, for example how to make (or should make) balances between different goals, in connection with this type of project. There are thus several different types of studies that could potentially be of interest within the framework of this project and we have no reason to believe that these are limited to a research area or in a limited number of journals. Scoping studies are suitable in such contexts (see for example [1]) because they provide the opportunity to search widely in the scientific literature, but at the same time offer a methodology that makes it possible to filter and focus on the material that is of interest in the project. An alternative approach could have been a so-called systematic review [2]. However, such an approach presupposes a well-defined problem and research question(s). And what is common with this type of study is that you want to study the effects of interventions by combining results from several studies that are based on quantitative methodology. Roughly, one can say that a systematic review would have been appropriate if we knew where (which journals) we could expect to find it and if the methods used were similar (and quantitative).

Another alternative to applying a scoping study would have been to carry out the literature review in a less systematic way. After all, scoping studies require a rather large effort (see below) and it is not always certain that such an effort is justified. However, our assessment is that we could not satisfactorily achieve the first goal without conducting a comprehensive and systematic review of the literature. This is because the problem of managing risk associated with the transport of dangerous goods is multidisciplinary, meaning that it has been tackled in several different scientific disciplines. For example, one can imagine that the impact of explosions on a decking has been discussed in scientific journals with a focus on construction technology. Furthermore, the question of disaster risk, i.e. risk associated with potential events that can cause a great deal of damage, can be dealt with in journals that have just such a focus.

We have followed the general method description for scoping studies as described in [3] [4] [5]. There are minor variations in how such studies are conducted, but there is nothing affecting in this context. The methodological steps that are usually included in a scoping study are the following (based on [3]):

1. Formulate a research question
2. Develop relevant keywords and search strategies
3. Filter and select relevant studies
4. Describe the results
5. Summarize and report

We have followed these steps, but we have also added more analysis of what we find in our searches than is normally associated with a scoping study. And we have also added a citation analysis under point 3 which is not normally found in this type of study (see description below).

Formulate a research question
The literature study aims to provide answers to two questions (see the previous chapter) which deal with covers and dangerous goods. We could have used these as a starting point for the scoping study, but the risk is that the question is too narrow and that we then miss literature that is relevant to the study, but which does not specifically address the issue of coverage. Therefore, we have started from the broader question: “What knowledge about risk management with regard to the transport of dangerous substances in tunnels or under covers is described in the scientific literature?”

Develop relevant keywords and search strategies
In order to answer the research question, one must find a number of keywords that adequately reflect it. The keywords are then used to conduct searches in various databases that contain scientific articles. We have chosen to apply a strategy that involves searches in all scientific journals that are included in the Scopus database. It contains over 30,000 scientific journals and is one of the most comprehensive databases of scientific articles.
When designing a search strategy, a balance must be made between how much work can be put into the search itself and the risk of missing relevant articles. We have chosen to limit our searches to articles published in scientific journals after 2010 until March 2022. This means that neither publications in scientific conferences, nor those published in 2010 or earlier are included in our search. Our assessment is that this delimitation is reasonable given that we are interested in the current knowledge front. In addition, we include a citation analysis in our search strategy, which means that we can also capture older relevant publications (see below). Another limitation that we have chosen to implement in order to avoid an excessive amount of hits during the searches is to exclude scientific journals in areas that we do not consider relevant in this context. Based on the research question above, use the following keywords in the searches: "risk management", "risk assessment", "risk governance" and "risk analysis".

We first tried just using the term "risk", but that generated too many hits to be useful. Next, we tried different variations of keywords to see which generated a manageable number of articles in the results and also seemed to result in relevant ones. The four concepts above are used in slightly different contexts. Together they seem to capture a wide range of articles that are variously relevant here. For example, the keyword "risk analysis" gives hits on articles that often deal with methods for assessing risk, while "risk governance" gives hits that are more focused on managing risk in complex contexts with several actors involved. However, these risk keywords are too broad to provide meaningful results in this project. You need to make further delineations in order to find articles that are of interest from an overlap/dangerous goods perspective.

It is not easy to find suitable such keywords. For example, we have included words such as "capping" and "decking" (see below), but these in combination with the risk keywords do not yield as many hits. Therefore, we have also chosen to include keywords that are significantly broader, for example "urban". We have chosen these keywords by testing searches with them, in combination with the risk keywords, and analyzing the hits we have received. If we received many relevant hits, we have chosen to use the keyword. The final list of keywords that we combined with the risk keywords are: "infrastruct*" "transport*" "urban", "capping*" "decking*" "overbuilding*", "underpass*". Using "*" in a search means covering several different specific keywords. For example, "infrastruct*" means that both "infrastructure" and "infrastructures" are covered.

In addition to combining the keywords dealing with risk with those associated with the transport/construction itself, searches were also carried out with the keyword "tunnel" in combination with either "hazardous material" or "dangerous goods". In total, this gave rise to 18 different searches in Scopus. The searches, as well as the number of hits they resulted in, are illustrated in the figure below. The searches take place in the titles and abstracts of the scientific journals. In order to generate a hit in a search, at least one risk keyword and at least one of the other keywords must be found in either the title or abstract.

In total, the 18 searches thus resulted in 27254 hits, i.e. articles that meet the conditions in any of the searches. However, these hits contain some duplicates because the same article can meet the conditions in more than one search. After duplicates were sorted out, 21155 articles remained.
Figure 1. Description of the various searches and their results. The searches mean that the word at the top (e.g. "risk analysis" or "risk assessment") must be in the title, abstract or keywords for a scientific article to be included in the search results. In addition, one of the keywords found under these words must also be included in these search fields.

Filter and select relevant studies
Such a large number of articles cannot, for obvious reasons, be reviewed in detail. And it is also not desirable because most of these are probably not relevant to this study. Instead, the scoping study methodology means that you have to filter the results in different ways to reduce the number of articles to a manageable number. Filtering thus means removing articles that you judge not to be of interest.

Filtering Step 1: Filtering based on journals
The first filtering step that we applied in this study is based on identifying journals that are not judged to be relevant to the question. An example of such a journal is the "International Journal of Pediatric Otorhinolaryngology". In that case, it is clear that the articles included in the results from our search...
and published in that journal are not relevant. The focus of the journal is surgery concerning the neck and head for babies and children. The reason why we still found articles in that journal that meet our criteria may be that they write about risk assessments in healthcare and that the article may be about some type of new "infrastructure" to do this. There are several thousand irrelevant journals in our material. By reviewing all journal titles in our material and deciding whether it is relevant in the context, we were able to remove 3253 journals. In this review, we were supported by an algorithm that identified potentially irrelevant journals based on the number of articles identified in the journal. If only single articles are included in our results from a specific journal, it is a good indication that the focus of the journal is probably not relevant within this study. After the articles from these journals were filtered out, 5322 articles remained that were published in 140 different journals.

Filtering Step 2: Filtering based on titles
The next step in the filtering process involved a review of the articles' titles. The goal was to identify articles that are with a high degree of certainty not of interest in the study. Articles that are not specifically about covers and dangerous goods, but which we judge could still be of interest, are not filtered out. This could, for example, be about titles that indicate that an article is about tunnel safety. Examples of articles removed in this step are those where the titles indicate that they are about cyber security\(^1\), flood risks\(^2\), risk management in critical infrastructures such as electricity distribution systems\(^3\), etc.

Both authors reviewed all 5322 titles. In order for a specific article to be filtered out, it was required that both authors assessed the article as uninteresting for this study. If only one made such a judgment, the specific article was not removed. The result was that 5124 articles could be filtered out and thus only 198 articles remained after this filtering step. In 97.3% of the cases, the authors made the same assessment of whether a specific article is of interest to the study.

Filtering Step 3: Filtering based on abstract
The final filtering step to identify relevant studies involved reviewing the abstract for each of the 198 articles and determining whether a specific article could be removed from the study. In addition, in connection with this review, a classification of the articles that were not removed was carried out. The classification meant that the remaining articles were divided into two groups, group 1 and 2. The articles that ended up in group 1 were judged to be of greatest interest to the current study, and those that ended up in group 2 were judged to touch on aspects that could possibly be of interest. The result after this filtering step was that 13 articles ended up in group 1 and 41 ended up in group 2. Figure 2 illustrates the entire filtering process from start to finish.

The figure also illustrates the result of a citation analysis that was carried out based on the 13 articles that ended up in group 1. The analysis means that all articles that refer to any of the 13 in group 1 were identified via a search in Scopus. The result was 207 articles. The idea of this analysis is to capture any articles that may be relevant to the study, but which for some reason we did not find through the procedure described above. Since the 13 articles in group 1 are those judged to be most relevant to this study, it is reasonable that other articles that refer to them could also be of interest. The result of this analysis, however, meant no further additions to group 1, but instead 1 article was judged to be relevant enough to end up in group 2. This brings the total number of articles in that group to 42. In addition to these 42, we are also aware of 4 articles that were not included in the scoping study. This is because they were published earlier than 2010 or are published in journals that are not included in Scopus. The four articles are included as the last 4 in the final analysis presented in the next chapter (see Table 2).

---

1 One example is the title “Stochastic Counterfactual Risk Analysis for the Vulnerability Assessment of Cyber-Physical Attacks on Electricity Distribution Infrastructure Networks”.
2 One example is the title “A Probabilistic Model of the Economic Risk to Britain's Railway Network from Bridge Scour During Floods”.
3 One example is the title "Risk reduction methods for managing the development of regional electric power industry".
Many of the articles in groups 1 and 2 are published in journals that are well known in risk research (Safety Science, Risk Analysis and Reliability Engineering and Systems Safety). In addition to these, several articles have been published in journals with a focus on sustainability research (Sustainability and Sustainable and Resilient Infrastructure). In addition, there are some publications in journals focused on transport research (e.g. Transportation research and Transport policy). See Figure 3 for an overview of all journals and the number of articles published in them.

![Figure 3. The number of articles in groups 1 and 2 that are published in various scientific journals.](image)

Regarding articles included in group 1, almost half of the articles are found in Safety Science or Sustainable and Resilient Infrastructure, see Figure 4.

![Figure 2. Description of the filtering process.](image)
Figure 4. An account of how many articles in group 1 are published in various scientific journals.

Figure 5. Illustration of the number of published articles per year that are part of groups 1 and 2. Blue bars show the number of articles from both groups. Red bars show group 1 only.

Overall, the figures above indicate that the type of research that is of interest within the scope of this report appears to be spread across several different research fields. Roughly speaking, the fields can be called Risk/safety research, Transport research and Sustainability research. The most relevant research seems to be concentrated in the journals that are normally associated with traditional risk/safety research, but there are also some such contributions in journals that are more about sustainable development research. Furthermore, it appears that interest in this type of research has been relatively constant, at a low level, over the past ten years. By "low level" we mean the fact that we find fewer than ten articles per year that have to make them the type of problem of interest. The number of articles is even lower if you consider those that are of high interest. Such a limited amount of articles is considered "low" considering the very large amount of research articles published each year in any of the three areas above.

Interviews

To supplement the input on how risk is managed in connection with deckings and dangerous goods that we can get from the scientific literature, an interview study is also included that can provide better insight into how this type of problem is handled in practice in Sweden. The purpose of the interview study is thus to supplement the literature study in order to be able to give a more comprehensive answer to questions 1 and 2 (see chapter 2).
It is important to note the limitations of the interview study right from the start. It is not intended to
give a representative picture of what different people working with the current problem think or do.
Such a study must be much more comprehensive than the one included in this project. Instead, the
interviews are used to gain insight into how risk is managed today, as well as to gain knowledge about
problems and opportunities. In order to best achieve the purpose of the project, the people interviewed
have been selected to get as wide a spread as possible in terms of which different actors (Traffic
Agency, municipality, county board, etc.) the people represent. In addition, the focus has been on
contacting people who we judge to have very good knowledge of the current type of problem. A total
of 10 interviews have been conducted with 11 people. The turnout among the respondents was good.
Only a few declined. Table 1 shows which organizations those interviewed in the project work within.

Table 1. List of organizations that the interviewees work within.

<table>
<thead>
<tr>
<th>Interview</th>
<th>Stakeholder</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The Swedish Transport Administration</td>
</tr>
<tr>
<td>2</td>
<td>The Swedish Transport Administration</td>
</tr>
<tr>
<td>3</td>
<td>The Fire and Rescue Service in Stockholm</td>
</tr>
<tr>
<td>4</td>
<td>The Fire and Rescue Service in Stockholm</td>
</tr>
<tr>
<td>5</td>
<td>The City of Stockholm</td>
</tr>
<tr>
<td>6</td>
<td>Jernhusen*</td>
</tr>
<tr>
<td>7</td>
<td>The National Board of Housing, Building and Planning in Sweden</td>
</tr>
<tr>
<td>8</td>
<td>The Swedish Transport Agency</td>
</tr>
<tr>
<td>9</td>
<td>The Swedish Civil Contingencies Agency</td>
</tr>
<tr>
<td>10</td>
<td>The County Administrative Board of Halland (2 persons)</td>
</tr>
</tbody>
</table>

The interviews were carried out during the period 2 June to 21 October 2022 and they were carried
out partly on site (4 interviews) and remotely (6 interviews). Both authors were present at all
interviews. One was responsible for taking notes and one was responsible for managing the interview.
The interviews were conducted as semi-structured interviews, which means that there was an
interview guide as support for the interviews, but that deviations from this were accepted if it was
judged to be in the interests of the project. The interview guide was developed in the spring of 2022
and is structured in three parts. The opening part is about the person being interviewed being able to
tell about their own role in working with deckings, the middle part is about the current situation, i.e.
how risk is managed in decking projects today, and the concluding part focuses on how management
can be improved in the future. The interview guide shows which questions were asked can be found in
the project report soon to be published.

RESULTS AND ANALYSIS

Scoping study
In Table 2 there is information on the 13 articles which, based on analysis of titles and abstracts, were
judged to be very relevant to the project based on the scoping study and the additional 4 identified in
addition. In the text below, we use square brackets and the numbering on the far left of the table when
we refer to them. For example, [a] means a reference to the first article, [b] to the second, and so on.

An overwhelming majority of the reviewed articles have a geographical focus on Europe [a, b, c, e, f,
g, h, i, n, o, p, q], followed by North America [d, j, m]. Others have a more general global focus [k].
Most have a focus on road transport [a, e, g, h, i, l, q], others on rail [c, d, f]. Other articles do not deal
with any specific type of transport.

The articles that focus on Europe in most cases address and relate the research to EU Directive
2004/54/EC [6] [a, e, g, h, I, q], while others only concern the Dutch legislation [c, f]. Only one of the

---

4 Jernhusen is a publicly owned real estate company with properties related to the Swedish railroad system and railway infrastructure.
articles with a European focus lacks a clear connection to legislation in the area [b, n, o, p]. None of the articles with an overseas focus concern legislation to any great extent.

Table 2. The 13 + 4 articles belonging to group 1, i.e. those that, based on the title and abstract, have been judged to be highly relevant to the current project.

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Title</th>
<th>Journal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>Kazaras, K., Krypytopoulos, K., Rentziazis, A.</td>
<td>Introducing the STAMP method in road tunnel safety assessment</td>
<td>Safety Science</td>
</tr>
<tr>
<td>2013</td>
<td>Renn, G., Klinke, A.</td>
<td>A framework of adaptive risk governance for urban planning</td>
<td>Sustainability</td>
</tr>
<tr>
<td>2013</td>
<td>van der Vlies, V., van der Heijden, R.</td>
<td>Urban planning and rail transport risks: Coping with deadlocks in Dutch urban development projects</td>
<td>Safety Science</td>
</tr>
<tr>
<td>2014</td>
<td>Kazaras, K., Krypytopoulos, K.</td>
<td>Challenges for current quantitative risk assessment (QRA) models to describe explicitly the road tunnel safety level</td>
<td>Journal of Risk Research</td>
</tr>
<tr>
<td>2016</td>
<td>Houdijk, R.M.</td>
<td>Rail transport of hazardous substances from the perspective of ‘All Hazard’ Risk Management</td>
<td>Chemical Engineering Transactions</td>
</tr>
<tr>
<td>2017</td>
<td>Benekos, I., Diamantis, D.</td>
<td>On risk assessment and risk acceptance of dangerous goods transportation through road tunnels in Greece</td>
<td>Safety Science</td>
</tr>
<tr>
<td>2018</td>
<td>Salem, S., Campidelli, M., El-Dakhakhni, W.W., Tait, M.J.</td>
<td>Resilience-based design of urban centres: application to blast risk assessment</td>
<td>Sustainable and Resilient Infrastructure</td>
</tr>
<tr>
<td>2019</td>
<td>Lundin, J., Antonsson, L.</td>
<td>Road tunnel restrictions – Guidance and methods for categorizing road tunnels according to dangerous goods regulations (ADR)</td>
<td>Safety Science</td>
</tr>
<tr>
<td>2020</td>
<td>Stewart, M.G., Mueller, J.</td>
<td>Terrorism risks, chasing ghosts and infrastructure resilience</td>
<td>Sustainable and Resilient Infrastructure</td>
</tr>
<tr>
<td>2005</td>
<td>Suddle, S. och Ale, B.</td>
<td>The third spatial dimension risk approach for individual risk and group risk in multiple use of space</td>
<td>Journal of Hazardous Material</td>
</tr>
<tr>
<td>2009</td>
<td>Sudder, S.</td>
<td>The risk management of third parties during construction in multifunctional urban locations</td>
<td>Risk Analysis</td>
</tr>
<tr>
<td>2009</td>
<td>Suddle, S.</td>
<td>The weighted risk analysis</td>
<td>Safety Science</td>
</tr>
<tr>
<td>2018</td>
<td>Lundin, J.</td>
<td>Risk Evaluation and Risk Control in Road Overbuilding of Transport Routes for Dangerous Goods</td>
<td>Journal of Civil Engineering and Architecture</td>
</tr>
</tbody>
</table>

Risk analysis methods
In our material there are some articles that explicitly deal with deckings and risk analysis [n, o, p]. Suddle and Ale introduce a risk analysis method that they call third-dimensional risk analysis and show how it can be applied to roofing in the Netherlands [n]. This method is then used by Suddle when he shows how it can be used to analyze risk with regard to falling objects during the construction period (it is then assumed that the traffic is allowed on the traffic route during the overlay) [o], and also how it can be developed into to become a type of cost/benefit analysis [p].

Several articles deal with methods for carrying out risk analyses/risk assessments. The so-called DG-QRAM method (Dangerous Goods – Quantitative Risk Assessment Model) often appears in the reviewed articles. It can, for example, be about showing its application in a specific case [i], where that method is one of several being tested [h], or where DG-QRAM is used as a reference to develop simplified risk assessment models [g]. DG-QRAM appears to be a commonly used method for risk analysis with respect to tunnels. However, it makes no difference whether the tunnel in question is overbuilt or not. Another method that is also based on quantitative risk analysis (QRA) is presented in [f]. That method has been developed within the EU-funded projects MiSRaR and PRISMA. There, the Dutch method for analyzing SEVESO facilities and the transport of dangerous goods to and from them has been compared with the method used in the Netherlands to carry out so-called “all hazards

This method was developed by the organizations PIARC and OECD and is used today in 26 countries (see DG QRAM Webinar – 23/06/21). There is software that can be used to carry out risk assessment using the method.
risk assessments”. These analyzes have their background in the Sendai framework which, among other things, means that countries carry out analyzes of disaster risks at national level. In Sweden, these are carried out by the Swedish Civil Contingencies Agency (MSB) and are part of what is called the National Risk and Capability Assessment. The method proposed in [f] involves a combination of the two methodologies with application to urban planning.

Another example of a risk analysis method focuses on rail transport [d]. However, that method is limited to assessing the likelihood of different types of derailment scenarios. It does not contain any support for impact assessment (given that a derailment has occurred), nor does it have support for presenting and assessing risk. In another article, the Systems-Theoretic Accident Model and Processes (STAMP) method is applied with regard to tunnels and risks [a]. STAMP is a relatively new type of method developed to deal with some of the weaknesses associated with traditional quantitative risk analysis methods. There are also examples of work where several different quantitative variants of risk analysis methods for tunnels are compared. Reference [e] is an example where the Austrian method TuRisMo, the Dutch TUNPRIM RWS-QRA, DG-QRAM, and QRAFT are compared. However, the article does not contain much detail regarding the various methods and overlaps are not given space in the analysis. However, it presents an analysis of weaknesses that apply to all the methods discussed in the article. Some of these may also be relevant in relation to coverages for the management of risk in respect of dangerous goods. Especially those that deal with weaknesses in handling uncertainty and the systems' complexity and development over time.

Problems/Difficulties/Solutions
The articles reviewed contain several accounts of problems and difficulties with regard to risk management in the current context. Some of the articles have a strong focus on explosions and in these [j, m] they discuss, for example, the difficulties of weighing the costs of protecting various buildings against explosions against the benefits that protection provides should an explosion occur. Particular emphasis is also placed on the fact that current legislation (in North America) is based on individual components when analyzing the impact of buildings on explosions rather than considering several components as a cohesive system. It is proposed [j] a development that involves the use of PRA (Probabilistic Risk Assessment) to analyze explosion risk from a system perspective, i.e. where you consider the building construction as a whole and not just focus on individual components. In addition, a more resilience-inspired approach is advocated, where the focus is on the impact of an explosion on the societal function maintained by the building in question. Loss of functionality and recovery time are important to consider from this point of view. This is a big difference to how safety in tunnels is usually analysed, at least according to the analysis methods described above, where the focus seems to be on life safety and not the functionality of the tunnel/overbuilding. Also [m] touches on an interesting difficulty with analyzes of primarily explosion risk as a result of antagonistic attacks. It is noted that in this type of analysis, the person analyzing the risk often tends to focus on worst-case scenarios and thus overestimate the risk. The article contains a review of previous terrorist attacks with powerful bombs. They focus on infrastructure and are therefore only interested in larger charges that can cause extensive damage to buildings, bridges, tunnels, etc. After their analysis of the problem, they conclude that terrorists (in a Western context) rarely succeed in causing extensive damage to various infrastructures and that many of the robustness-enhancing measures that have been taken in the US in particular are not cost-effective, given that a terrorist attack is very unlikely and if one does occur, it is very unlikely that it will succeed in causing extensive damage.

In [b], problems and difficulties with regard to risk management that can arise in connection with urban planning are described. The article is not about deckings or other tunnel types. Despite that, the material may be of interest here because it deals with general risk management situations in connection with urban planning and describes some of the difficulties that can arise where there are many different actors involved in the management and where the situation is characterized by great

---

7 See, for example, the report “Kraftsamling – för en stärkt civil beredskap” av MSB, 2021.
uncertainties, complexity and ambiguity. One also presents a type of solution for how risk management problems should be handled. It is based on a risk governance model developed by the IRGC (International Risk Governance Council) and the article describes how it could be applied with regard to community planning. However, the model is relatively abstract and does not provide much concrete guidance. In addition, the authors point out that the model is still untested in practice.

In [f] several problems are highlighted with the quantitative risk analysis methodology used in the Netherlands, both for the analysis of dangerous goods risks in tunnels and at SEVESO facilities. It concerns, for example, that the results from such an analysis can vary greatly based on which assumptions are made. This in itself is not so strange because all risk analyses mean that you have to make assumptions. But in the Netherlands, the method you have to use is strictly regulated by law and the analyses themselves carry a lot of weight when it comes to decisions regarding risk issues. Therefore, it is particularly serious that despite a well-specified method for the same system, e.g. the same tunnel, can have very different results depending on which assumptions you make. It should also be noted that all these assumptions can be seen as reasonable and acceptable under the current legislation. They also touch on the problem that they often only focus on the protection of life and health in this type of analysis and not on the functionality of society. Another article that highlights problems common methods for analysing risk in tunnels (eg DG-QRAM, TuRisMo, etc.) are associated with is [e] and to some extent [a]. [e] focuses on several different aspects that are inadequately handled in the current methods of risk analysis, for example human behaviour, system complexity, the dynamic nature of risk, etc. One aspect that the authors are particularly critical of is how uncertainties are analysed and described in the analysis models. They suggest, for example, that existing quantitative risk analysis methods used in the field of tunnel safety be supplemented with clear descriptions of the so-called knowledge base, which for example includes accounts of assessments and assumptions made in analyzes (see, for example, [6]).

Article [c] differs somewhat from the other articles in terms of problems and solutions addressed. That article focuses on the institutional problems that arise in relation to the management of risk in relation to the transport of dangerous goods in connection with the planning and construction of railways (in the Netherlands). It identifies six categories of problems and suggests how the effects of these problems could be mitigated through a change in the decision-making processes surrounding the construction of new railways in the Netherlands. Also [i] addresses problems that are not so much about how to analyse risk in tunnels, but about how to decide which category (A to E) a tunnel should be classified as. The categories govern which restrictions with regard to the transport of dangerous goods must be applied in the tunnel. It also mentions that dangerous goods that cannot be transported through a tunnel must travel on an alternative route, which means that you expose others (not those staying in the tunnel) to risk. Analysing risk with regard to such an alternative route is very important to have something to compare with a possible tunnel transport. This problem is also discussed in [i].

Interviews
We do not reproduce individual interviews in the results section, but only summarize them by presenting several themes that have been touched upon. If there are aspects that have only come to light in individual interviews, this is evident from the text. When we describe the themes, we have chosen to also relate them to the literature study and to other knowledge in the area of risk management.

The big problem is disaster scenarios
If you combine what we have seen in the literature study with what emerged during the interviews, it is clear that the difficulties in managing risk in connection with the design of deckings with a focus on the transport of dangerous goods are above all about disaster scenarios with cargo that, under unfortunate circumstances, can lead to detonation (e.g. ADR/RID class 1 and 5). These are scenarios that could potentially lead to a very large (thousands) number of dead/injured people. There are of course also challenges with risk management regarding other types of scenarios, for example a serious fire in a tunnel under a decking, but this type of scenario is usually handled in the methods used today in Sweden and elsewhere. This is also the case with the methods that we came into contact with
within the framework of the literature study, for example the so-called DGQRAM method. What can be noted is that disaster scenarios, for example an explosion in a transport with more explosive goods than what the tunnel construction was designed to withstand, are not explicitly included in these methods. This is problematic.

How this type of disaster risk should be valued is not clear in the studied literature, and from the interviews we get the impression that in practice there is no accepted way of handling this type of risk either. Admittedly, proposals for handling such risks in projects have had to be drawn up (e.g. for the decking of the central station in Stockholm), but then a lot of work has been put into coming up with suitable working methods to manage the risk in that particular project. However, whether these methods can/should also be used in other places and in other projects is unclear, which leads us to the next theme.

**Lack of guidance**

As pointed out above, there are several different risk analysis methods for analyzing and evaluating risk in connection with dangerous goods in tunnels. However, when it comes to the most serious scenarios that can occur, there is a lack of accepted methods to evaluate these, which creates difficulties for various actors and stakeholders. Regardless of whether it is a municipality that must approve a detailed plan, or whether it is a county administrative board that must make a decision to review or re-examine such a plan, or a designer that develops proposals for risk-reducing measures, the lack of guidance leads to problems. Above all, because it creates great uncertainty among the actors involved.

It is important to be clear that there are different types of uncertainty in these contexts. Firstly, there is uncertainty regarding the overlay itself, i.e. whether there will be an explosion, for example, or not there, and if so, what the consequences will be. This uncertainty is normally handled in different types of risk analyses. However, the lack of guidance also creates another type of uncertainty that is not directly related to the facility itself. It is rather about uncertainty regarding what the actions of the actors, for example a certain decision, will entail. In the end, this uncertainty contributes to something that can be described as "project risk" for the various actors, i.e. the possibility of suffering negative consequences due to activities within the decking project and not due to, for example, a dangerous goods accident.

In this context, project risk can mean that an actor, for example the Swedish Transport Administration, a municipality or a developer, risks being affected by delays and increases in costs in a decking project. And, the lack of guidance means that the uncertainty about whether such consequences may arise is greater than it would have been if there had been better guidance on how (catastrophic) risk in relation to the transport of dangerous goods would be managed. But project risk in this context does not only have to be about potential financial costs in the specific project, it can also be about the possibility that an actor makes a decision that is subsequently criticized and perhaps even turns out to be incorrect. Because guidance is perceived to be lacking, or at least deficient, there is always some possibility that a decision that has been made may turn out to be wrong in retrospect. Even if one disregards possible financial consequences, there still remains a risk for the stakeholders, even for individuals, for example administrators, to make decisions that later appear to be incorrect, or otherwise very bad.

This type of project risk is of course always present, but in most cases it is less extensive because there are well-developed methods, procedures and reference examples (practice) for how to handle different types of safety problems, for example life safety in tunnels. What makes deckings special from this perspective is that the uncertainty for the actors involved becomes greater.

Finally, there is another aspect which is important in this context and which is related to the lack of guidance. We call it precedent risk. As there is relatively little guidance regarding how disaster risk with regard to the transport of dangerous goods should be handled, each completed project means that the handling applied there becomes a precedent that can then be used in subsequent projects. This is
usually something positive because it is a type of learning, i.e. experiences from previous projects are used in subsequent ones. But, in this case, it can also be perceived negatively because potentially negative consequences with respect to the project are not limited to the current project, but can also extend into future projects. If, for example, a decking has been built with a certain design that has been judged to have an acceptable level of safety, it will take a lot for the same design to be considered unacceptable in future constructions. This applies even if the conditions surrounding the decking are different than in the previous projects.

The existence of project risks of the type described here and also precedent risk is not unique to decking projects. Such have been described in studies of several previous infrastructure projects. For example, [7] shows in a study of six major tunnel projects in Sweden (e.g. Hallandsås tunnel and City tunnel) the existence of similar risks. But, as pointed out above, in projects with deckings the uncertainties can be greater and the risk assessment more complex.

The management of risk takes place above all through design solutions. Many risks related to the transport of dangerous goods under a decking are similar to those encountered in a normal tunnel. In these cases, the safety solutions used are basically the same as those used in tunnels, e.g. fans for fire gases, alarms, escape routes, etc. But when it comes to the risk of large explosions and the possibility of such an impact on buildings above a decking, there is a difference. In a normal tunnel this is not normally a problem, but in a decking project it is a type of risk that must be managed more actively. The most common way to handle it is via different construction solutions. It may seem obvious that this is so, but an alternative to dealing with this type of risk could be restrictions on what can be transported under a decking. However, enforcing restrictions does not seem to be very common on major roads already pointed out as dangerous goods routes.

That this type of risk is managed via construction solutions means that some type of dimensioning load is established, often expressed in the form of the amount of explosive material (tons of TNT) that is assumed to detonate under the cover. With the help of this load, one can then carry out calculations of how the construction would be affected in the event of an explosion under the decking. If the damage caused by such dimensioning loads is judged to be acceptable, the risk is judged to be acceptable.

A problem when using dimensioning scenarios when designing a decking is that you have to decide how large the dimensioning load should be. If no restrictions are imposed on the amount of explosive material that may be transported under the cover, it is conceivable that 80 tons of explosive material is transported there if the transport takes place by rail and 16 tons if it is transported by road. Dimensioning a construction to withstand such powerful explosions without damage to any buildings above is not possible in practice. A difficult question then becomes which load level to start from when carrying out your dimensioning. This choice indirectly means that you decide what is acceptable residual risk in the current case. More severe dimensioning load means lower residual risk, but at the same time higher construction costs. There are no fixed guidelines that describe which dimensioning blast loads to use and thus in practice this becomes something that you have to decide on in connection with individual projects. Guidance on how a decision-maker should proceed to make such a decision is missing according to above.

Large uncertainties create problems
A circumstance that makes the choice of dimensioning explosion scenario difficult is the large uncertainties that exist regarding possible future explosions under a decking. It is very difficult to make estimates of how often such events can conceivably occur and it is also very difficult to assess the extent of damage that will possibly occur, given such an explosion. This type of uncertainty affects the management of risk in many different ways. It contributes, for example, to the difficulty of choosing the dimensioning explosion load (see above). The more likely the catastrophic explosion scenarios are judged to be, the stronger the dimensioning explosion load is justified.
The uncertainty regarding possible future explosions cannot be completely eliminated when a decking is built. It can certainly be reduced significantly, for example by restricting what can be transported. But even so, it is not possible to know with certainty whether the coverage will be affected by a catastrophic scenario in the future. In the context of risk management, two types of uncertainty are usually distinguished: stochastic uncertainty and knowledge uncertainty. Knowledge uncertainty (epistemic) can be reduced by gaining more knowledge about the current risk, but stochastic uncertainty cannot be reduced in that way. The stochastic uncertainty corresponds in this case to the uncertainty of whether one or more explosions will occur in the future and what the consequences will be in that case. In this case, the uncertainty of knowledge corresponds to how likely it is that one or more events will occur, and how likely it is that the consequences in that case will have a certain extent. Regardless of how much knowledge we obtain, we will never be able to know with certainty whether an explosion will occur in the future (stochastic uncertainty). However, through systematic knowledge development, for example by improving the models used to assess the consequences of an explosion, knowledge uncertainty can be reduced.

Knowledge uncertainties can thus be said to exist both in terms of how likely it is that one (or more) explosions will occur in the future, and in terms of how likely it is that the consequences will be of a certain order of magnitude given that a certain explosion scenario has occurred. Knowledge uncertainty of the last type is handled with the help of the designers who are knowledgeable about the impact of explosions on building structures. The knowledge uncertainty of the first type, i.e. how likely it is that a certain type of explosion scenario occurs requires knowledge of how much dangerous goods (which have the potential to cause explosions) are transported under the deck, how often it happens, how often explosions of this type have occurred, etc. Also, explosions in connection with the transport of dangerous goods that occurred in places other than under deckings, including in tunnels, are of interest in being able to reduce knowledge uncertainties. It does not appear that this type of information is widely available, which makes it difficult to assess risk.

Even such a thing as knowledge concerning how much dangerous goods is transported on a certain route in Sweden seems to be difficult to obtain. At least when it comes to details regarding the substances that have the potential to cause large explosions. This is something that was also observed in one of the studies summarized in the literature review [c], but in that case the problem concerned the Netherlands. The fact that it is difficult to know details about dangerous goods transport today, makes it also more difficult to assess what and in what way transport can be planned to take place in the future.

Many actors - Difficult to take an overall perspective

Another important aspect that emerged during the interviews and which was also noted in the Netherlands is the difficulties that arise when a risk management problem involves several actors who have different interests. Having different interests is nothing strange, but what can make things complicated in the context of risk management is when risk management requires trade-offs between different goals and these goals affect the actors in different ways. For example, it is natural that a developer would like to build as much as possible above a decking, that the Swedish Transport Administration wants to have as few restrictions on transport as possible, and that the decking must be built at as low a cost as possible. In practice, trade-offs between such goals are required, and since different actors can value one and the same goal differently, the risk of deadlocks increases. That such balances must take place when the guidance on how to handle them is missing or deficient (see above), and when the uncertainties are very large (see above) can make it difficult to assess different design alternatives and security solutions from an overall perspective. This can lead to blockages in the process which means that it is difficult to move forward. Such have been described previously in Sweden [7] and also in the Netherlands. Finally, not only do the difficulties of adopting a holistic perspective lead to potential deadlocks, they can also lead to a situation of different security solutions, and even different levels of security, in different places in the country.

CONCLUSIONS
In summary, we can state that there is some research concerning tunnels in general and the transport of dangerous goods. Regarding the specific focus on deckings, there are only a few studies that are relatively old, i.e. published before 2010 (the exception is [q]). There are some ideas on how quantitative risk analysis methodology (QRA) can be used to analyze risk with regard to the transport of dangerous goods in connection with deckings and underpasses. The focus is on the Netherlands, where traditional risk measures such as individual risk and UN curves are used to assess risk.

In the other articles, when it comes to specific problems with deckings, underpasses and overbuildings, there is a lack of studies. In some cases, the challenges of deckings are mentioned, but there are no articles dealing with how this type of problem is solved in other countries, or about suggestions on how to manage risks in connection with deckings. There may be several different reasons why the knowledge base in the international research literature is so thin with regard to covers and dangerous goods. The results indicate a lack of academic interest. For example, it could be because cover projects are considered like any other tunnel project and that no particular importance is attached to the fact that there may be buildings over the cover/tunnel. This is probably a perfectly reasonable conclusion regarding the vast majority of types of dangerous goods. However, in cases where the dangerous goods in the tunnel could cause a large-scale explosion/detonation, the situation could be very different when comparing a normal tunnel with a deck or underpass. In the literature we reviewed, however, we do not find much that deals with this potential problem, except for [n, o, p, q]. And it also doesn't seem that those risk analysis methods (with respect to dangerous goods) in tunnels consider this type of scenario (explosion scenarios with flammable liquids/gases and also BLEVE are considered).

The concept of deckings carries many benefits. At the same time, it could be an initiative challenging the Sendai agreement, since an accident can potentially affect very many people at the same time. The knowledge base whether this is a good idea or not is weak in the scientific literature. The knowledge base is also weak regarding how to assess such risks. From a resilience-base perspective this indicates that such risks are troublesome to consider acceptable. To apply a risk-informed perspective challenges arise on how to determine preferences for very large accidents and uncertainties quite difficult to reduce. Several practical implications have been found in the risk management situations related to deckings that need to be dissolved to make it possible to operationalise effective risk reducing measures. From a risk governance perspective significant effort is necessary to facilitate sound and robust prerequisites to risk management of deckings to safe-guard that we are not drifting into failure and introduce risks in our modern society that we will regret tomorrow. Pushing boundaries is necessary for innovation. It is not contradicting to sustainable development. It is rather a question of how we do it and if we aspire to make risk informed decision or if the decision making is limited to other aspects. Given the circumstances one can also question if it is sensible from national authorities to delegate decision making of this type to single construction projects before more support is offered.

ACKNOWLEDGEMENTS

This work was funded by the Swedish Transport Administration. Their support is gratefully acknowledged.

REFERENCES


RiskTUN: An ICT-based Concept for a Risk-aware Decision Support System for Tunnel Safety

Naeem Khademi1, Henrik Bjelland1, Erik G. Nilsson2 & Konstantinos Boletsis2
1University of Stavanger, Stavanger, Norway
2SINTEF Digital, Oslo, Norway

ABSTRACT

Safety in road tunnels are of utmost importance for the public notion of safety within the road system. In recent years, there has been significant progress in multiple areas of artificial intelligence, sensor fusion and communication technologies. Together with increase in computing power, this has enabled processing capabilities and aggregation of large amount of data from heterogeneous sources. This allows for more intelligent decision-making in real-time in presence of risk in a dynamic environment provided by a decision support system. Previous work in this direction do not actively combine risk-awareness, real-timeliness, and artificial-intelligence in a dynamic operational environment of a tunnel in operation for decision-making through considering the capabilities that recent technological advancements enable. To address this gap between decision-support systems and state-of-the-art technologies, this paper proposes RiskTUN, a general framework for developing risk-aware decision support systems for the safety of tunnels in operation. RiskTUN architecture allows for integration of various sources of data in a heterogeneous environment where various stakeholders (e.g., road users, emergency responders, traffic centers, etc) can be both contributors or the users of the decision support system. There are major opportunities associated with taking better advantage of available data, but challenges are also identified and discussed. System implementations made based on RiskTUN framework are expected to better adapt to the user needs within the area of tunnel safety as technologies evolve.

KEYWORD: decision support, ict, emergency response, risk, tunnel safety

INTRODUCTION

Accidents in road tunnels can and do occur. A fast and effective response by traffic operators and emergency responders can mean the difference between life and death. Recent history has shown that tunnels constitute dangerous environments in case of emergency [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. More recent tunnel accidents in Norway has revealed challenges associated with operators’ and emergency responders’ lack of dynamic information about vehicles and road users’ positioning, safety equipment status and smoke management strategies [2].

The tragedies in mid-Europe and recent accidents have shown the need for an effective emergency response and the serious consequences of incorrect or delayed decision making [1] [3]. Accident prevention is a key factor in tunnel safety but by itself does not address the full extent of the problem since emergencies can still take place. Having an accident-preventative strategy along with a proper emergency management plan – one that maximizes the speed and effectiveness of a response – is vital to minimize the risk of injury and death [1]. Traditionally the decisions by the tunnel operator are based on fixed protocols that may not be suitable for all possible situations during the continuous development of an emergency [1]. At the same time, tunnel operators may have different incoming data at their disposal from each tunnel, since usually every tunnel is an individual entity with its own dedicated infrastructure [4]. When emergencies occur, time becomes a critical factor. The tunnel
operator, in these extreme and stressful cases, must deal with time-critical information and large amount of incoming data, whose processing for making an informed decision can create cognitive load (i.e., intense use of working memory resources) and delays and can potentially lead to erroneous decision making with grave consequences [5]. Moreover, successful emergency response often depends on the efficient collaboration of several actors – e.g., healthcare personnel, firefighters, police and road users – under stressful and time-critical conditions. In such situations, information about the situation, verification, and suitable presentation is highly important. For this reason, the information provided to the actors should be as comprehensible, complete, and prioritized as much as possible [1]. Research has supported that using decision support systems for emergency management in such complex situations can be highly beneficial [1] [6] [7]. Decision support systems are mainly based on automated processes in order to analyze the input coming from tunnel sensors and data, and assist the tunnel operator in making an informed decision in cases of emergency [1] [7] [8]. Figure 1 demonstrates a generic scheme of a decision support system for tunnel safety inspired by [1].

![Figure 1](image_url)  
**Figure 1** Accident scenario – general functionality of decision support system for tunnel safety inspired by [1].

Significant progress has been made in recent years in several fields – e.g., automation, sensor, communication, and data processing technologies – referred to as Information and Communication Technologies (ICT) hereafter. Hence, these new technologies allow for the aggregate of input data to be automatically gathered from various sources through communication links in order to inform the decision model in a more sophisticated decision support system than those employed previously. This process can potentially make use of Artificial Intelligence- (AI)-based methods for data processing and analytics as well as within the decision support systems’ reasoning mechanism.

Moreover, the importance of incident prevention using decision support has been recognized [1] [8]. Efficient incident prevention requires accurate risk analysis [9] [10]. This necessitates a good understanding of the safety situation in the tunnel – i.e. the system’s capability of preventing losses on the short and longer term. However, most current road tunnel risk analysis models only assess physical aspects of the tunnel system or consider hazards related to the transportation of dangerous goods through a tunnel [11]. They are therefore unsuitable for adoption by a decision support system for tunnel safety since they do not capture the dynamic changes in the tunnel and its environment and users – i.e., through dynamic changes in the traffic pattern, tunnel conditions or the evolution of an impending incident – which in turn affects the safety or the risk situation in the tunnel.

**Problem statement**

We therefore define the notion of risk aware decision support system as a system that takes into consideration the dynamic situation of risk using a broad and transparent risk model developed collectively by several stakeholders in its decision model. Using an exploratory research approach, we propose RiskTUN, a theoretical concept that combines the emergency management and incident prevention through introduction of dynamic risk analysis in the decision support system. The goal of RiskTUN is to provide a conceptualized framework acting as a high-level description and a guide for
the design and implementation of risk aware decision support systems that can be of further use by various stakeholders of the tunnel safety field as well as the researchers in the field.

Developing a decision support system is inherently a design task and progress in design projects often occurs by iterations and incremental development. Formulating the design problem is often part of the design task, which is also the case in this paper. Our method is therefore to reflect on our pilot development, and to clarify design problems that needs attention in the next phase. Safety analysis and holding a futuristic perspective, serves as an important basis for the decision support system. We cannot validate, in the traditional sense of the concept, analyses (or models) of the future. This calls for a fundamental analysis of the risk concept, as it is applied in RiskTUN, and how its characteristics and application affect the development process. A thorough discussion is beyond the scope of this paper, in which we focus more on the user needs, technology and architecture, but will be provided in a separate work. However, we will provide a summary of user needs in this paper.

User Benefits
In identifying the user benefits we use Norway as an example use-case due to the fact that the country has numerous tunnels within a complex geographical landscape and tunnel safety is of high importance for various tunnel safety stakeholders within the country. Table 1 presents the potential benefit(s) of RiskTUN framework for each stakeholder in Norway.

Table 1 The tunnel safety stakeholders in Norway; user needs and potential benefits from RiskTUN decision support system framework.

<table>
<thead>
<tr>
<th>Stakeholders</th>
<th>Potential benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norwegian Ministry of Transport (NMT)</td>
<td>Decision support to management of traffic safety and tunnel safety regulations. Decision support for administration and communication with the European commission.</td>
</tr>
<tr>
<td>Norwegian Public Road Directorate (NPRD)</td>
<td>Decision support to management of traffic safety and tunnel safety regulations.</td>
</tr>
<tr>
<td>Tunnel owners/managers (NPRA, Regional municipalities and Nye Veier)</td>
<td>Decision support on risk-exposed tunnels or elements, to support prioritization of rehabilitation funding. Information about the operational status of tunnels and equipment, to support efficient management and maintenance.</td>
</tr>
<tr>
<td>Norwegian Public Road Administration (NPRA), traffic control centers</td>
<td>Decision support for actions to prevent tunnel accidents. Decision support for consequence-reducing actions during tunnel accidents. Workload reduction from automatic alarm management.</td>
</tr>
<tr>
<td>Norwegian fire and rescue services</td>
<td>Decision support to prioritize risk prevention activities. Decision support to on-scene emergency management commanders. Decision support to rescue personnel involved in tunnel accidents.</td>
</tr>
<tr>
<td>Road users</td>
<td>The road users are intended as the main profiteers of the riskTUN solutions. From a long-term perspective it includes improvements in safety design, traffic management and education. In a short-term perspective, riskTUN will provide road users with decision support to better facilitate for self-rescue in tunnel accidents. Road users will receive targeted (position specific) information, suggested actions, and wayfinding guidance.</td>
</tr>
<tr>
<td>Road management and maintenance contractors</td>
<td>Decision support on maintenance intervals for specific equipment in tunnels.</td>
</tr>
<tr>
<td>Research institutions</td>
<td>Better understanding of accidents and underlying causes.</td>
</tr>
<tr>
<td>Engineering consultants</td>
<td>Data for risk assessments in design of new tunnels.</td>
</tr>
</tbody>
</table>
Our paper’s motivation

Our motivation for this paper stems from the emerging need for such decision support system in Norway—a mountainous country with more than 1200 road tunnels spanning across the entire country, 641 of which are being monitored by the Norwegian central traffic center. Keeping the flow of transportation and mobility within Norwegian tunnels safe and efficient is of great long-term strategic importance for Norway and plays an important role in the country’s policy on public road infrastructure. In Norway, the operation of the tunnels are presided by five traffic centers across the country known as Vegtrafikkcentralen, shorty referred to as VTS hereafter. In addition, the maintenance of tunnels by various contractors also needs to be coordinated with the VTS. Therefore, the risk aware decision support system can potentially be deployed at the VTS which can provide emergency responders and road users with necessary information for decision-making.

It is worth noting that our paper’s primary focus is mainly on tunnels in operational and maintenance and emergency situations that can arise during these phases. While risk assessment and analysis are also highly important during the design and construction phases and can benefit from informed decisions during operation and maintenance—e.g., in construction of future tunnels—we explicitly choose to maintain our focus on the operation and maintenance phases due to the dynamic aspects of risk for tunnels in operation and maintenance which needs to be investigated on its own merits.

Our paper’s contributions

The main contributions of our paper are as follows:

a) We identify the system description and user needs from various stakeholders in tunnel safety.

b) We contribute to EC directive 2004/54/EC which requires best practice risk management approaches for tunnels. While most other decision support models are investigating larger time spans, RiskTUN is focused on real-time and dynamic risk management aspect. The approach taken by RiskTUN is connected to addressing the user needs—e.g., from traffic manager perspective.

c) We investigate various risk factors and associated key performance indicators in road tunnels.

d) Most importantly we provide a conceptual framework on risk aware and dynamic decision support system for tunnel safety.

Paper structure

The remainder of this paper is structured as follows: Section 2 provides a background on already proposed decision support systems for roads and traffic management in general and for tunnels in particular and makes a case for a dynamic risk aware decision support system for tunnels in operation and maintenance. Section 3 provides insight into understanding the risk in road tunnels as a prerequisite to designing a risk aware system. Section 4 presents RiskTUN as risk aware decision support system for road tunnel safety. In doing so, it identifies the actors and user needs, functionalities, risk factors in tunnels and proposes a generic system architecture. Section 5 lays out a detailed discussion on several important aspects related to RiskTUN—i.e., on how to understand the risk in road tunnels, applicability of artificial intelligence in RiskTUN, and design suggestions. Finally, Section 6 concludes the paper and presents the future work.

BACKGROUND

In this section we provide background on the use of decision support systems in the context of road tunnels. First, we investigate the use of decision support for road (and tunnels) in general. Second, we look into related work on real-time decision support for the public roads. Third, we focus on the prior use of decision support for traffic management. Fourth, we discuss the previous initiatives on decision support particularly aimed at road tunnels. Finally, given the limitations of each category, we make a case for our dynamic risk-aware RiskTUN framework for road tunnels in operation.

Decision support systems for road and tunnels

Decision support systems have been considered for use on the maintenance and operation of the road network. For instance, Fancello et al. propose a multi-criteria decision support system model based on
concordance analysis to provide the road administrator with the information on the road segment with the worst safety conditions identified based on variable weighting criteria [13]. Dell’Acqua et al. proposes a decision support system to identify and rank hazardous sites on road networks supporting road administrators in defining infrastructure projects to reduce these sites on the road networks [14]. On the other hand, the SafetyCube DSS project (2015-2018) [15] has developed a decision support system tool aimed at policy makers and stakeholders that identifies numerous road accident risk factors and related safety counter measures extensively [16]. An important aspect of road safety is identifying the Key Performance Indicators (KPIs). This has been addressed by Meißner et al. for use-cases where polices are involved [17].

**Real-time decision support on the roads**

Mentioned works in previous sub-section focus on general policy and decision making by the road safety authorities and lack real-time response to the events and incidents as they occur on the road, something that is necessary for road monitoring during the operation and maintenance – e.g., for central traffic monitoring center. Zografos et al. propose a real-time decision support system for road Incident Response Logistics as part of an Incident Management System aiming at reducing the incident duration, among other things by producing the shortest route to the incident [18].

**Decision support for traffic management**

Wismans et al. [19] and Casas et al. [20] offer decision support system for traffic management by providing the short-and medium-term predictions of traffic state based on surveillance systems data and simulation inputs respectively. Moreover, current practices of decision support system for traffic management are laid out by Miller et al. [21]. Other works such as [22] focus on the use of decision support system for active traffic management – e.g., by employing the notion of travel time reliability using a model predictive control method hence allowing for identification of a proper response plan for the reduction of travel time and the improvement of its reliability.

**Decision support for tunnels**

Use of decision support system in tunnels has been considered in different contexts. For instance, decision support system can be used in guiding the tunnel construction. An ongoing project at the University of Alberta explores the possibility of an automated and integrated decision support system for tunnel construction leveraging real time data to direct tunneling operations in reaction to deviations or irregularities in construction [23]. Another similar ongoing project at the University of Rutgers takes into consideration risk assessment and management in large scale tunneling projects through identification of risky spots along the tunnel as well as quantitative risk assessment [24].

On the other hand, decision support system has also been considered for the operation of road tunnels as explored by Alvear et al. [1] – e.g., by using a predictive model that provides the tunnel operator with the decision recommendations based on the severity of an incident and associated rescue and evacuation times. Capote et al. [8] present EvacTunnel, a real-time stochastic evacuation model for road tunnels. While the decision support model in EvacTunnel is aimed at providing shorter response time, it is exclusively focused on tunnel evacuation during emergency response and does not consider the real-time decision support for prevention nor the involvement of various stakeholders in a dynamic environment. Another example is an earlier European project SIRTAKI that focused on the use of ICT for a generic decision support system in road and rail tunnels [25]. Although many architectural insights from SIRTAKI is still valid the ICT technologies has significantly been revolutionized since the project’s conclusion in 2004. Therefore, the need to take into consideration the state of the art and emerging sensor, communication and automation technologies persist though some high-level architectural insights from SIRTAKI can still be relevant today. This is something that RiskTUN aims to investigate.

**RISKTUN DECISION SUPPORT FRAMEWORK**

The main contribution of the work presented in this paper is RiskTUN, a concept for a risk-aware decision support system for tunnel safety. In this section we present the RiskTUN concept, including
stakeholders, their needs, as well as the anticipated functionality supporting these needs. We also outline the most important risk factors that RiskTUN should handle, and a high-level systems architecture.

**Identified actors and their needs**

The main stakeholders involved in tunnel operations and emergency response are: a) tunnel operators, b) emergency responders (fire rescue service, ambulances, etc.), and c) road users (e.g., passengers and drivers). RiskTUN supports tunnel operators both during day-to-day operation and during emergencies, while emergency responders and road users are mainly supported during emergencies. During day-to-day operation, RiskTUN provides a real-time risk picture for a given tunnel. This picture supports the need for accident prevention, and highlights possible risks based on collection and processing on data collected from sensors, systems and services.

During an emergency, RiskTUN supports different need for the three types of stakeholders. A tunnel operator provides information for emergency responders and road users. This information will primarily be collected from RiskTUN, but may also come directly from people in or close to the tunnel. In addition to providing information, a tunnel operator will also do various measures like turning on/off or change the direction of fans, close parts of or the entire tunnel, and give audio instructions through car radios and/or speakers in the tunnel. Such measures are executed through existing systems in the tunnel, like the SCADA systems. Emergency responders primarily need as accurate and up-to-date information as possible to respond to an emergency in a best possible manner. This information may come orally from the tunnel operator, and/or through a tailored, mobile version of RiskTUN focusing on the needs of emergency responders. Important information for emergency responders includes the exact type of incident, the location of the incident, the types of vehicles involved, access routes, and temperature in different parts of the tunnel. Road users primarily need information aiding their ability for doing self-rescue. This may come orally from the tunnel operator, from signs and lights in the tunnel, and/or through a tailored, mobile version of RiskTUN focusing on the needs of road users. The most important information are evacuation routes and safety information, like whether they should evacuate the tunnel by driving out (in some direction), stay in the car, or try to walk (in some direction) to a place of safety. RiskTUN is intended for use and facilitation of the stakeholders’ need just outlined. Below, we present the main functionality supporting these needs.

**Functionality**

The functionality of RiskTUN decision support system is visualized in Figure 2. The RiskTUN decision support system is basing its operation on three elements: i) input data, ii) operation platform, and iii) notifications and navigational assistance. The design of these elements is inspired by decision support system for road tunnels currently described in research literature [1] [2] [3] [8] [9] [11] [26], cross-referenced with real-life practices and needs, coming from discussion with representatives from stakeholder organizations.
RiskTUN collects input from the available tunnel technologies, i.e., cameras, Automatic Incident Detection (AID) systems, thermal sensors, fire detection systems, phone booths, etc., along with tunnel’s characteristics (e.g. length, elevation, direction and angle of turns, etc.). The central element in RiskTUN’s input stream is vehicle positioning and communication. There is the need for precise and cost-effective positioning technology of vehicles in tunnel conditions, where global positioning systems (GPSs) do not work [27].

Bluetooth Low Energy (BLE) technology is presently considered as the primary form of wireless technology in mobile devices and has been suggested as one of the most cost-effective and efficient method for indoor positioning when GPS is not available [28]. Other technologies can be used and, potentially, be more efficient. For example, positioning could be done with cameras (normal and infrared) and communication could be done through GSM/xG radio systems. The work of Khademi and Sommer [29] is also a promising alternative, focusing on 5G cellular networks and the new opportunities that arise from their deployment within the tunnels. In a longer timeframe, vehicle-to-infrastructure solutions that are coming and already exist in some modern cars may also be used. In RiskTUN we focus on established technologies that could provide a satisfactory ratio of cost/efficiency, without having to rely on any previously installed tunnel equipment.

When the input data are collected, a risk grade is assigned to every vehicle entering the tunnel for accident-preventative purposes. In case prevention is not possible and an accident does take place, the same data are used to handle the emergency quickly and to assign risk grades for further derived accidents – e.g., to avoid multiple-vehicle collision. The system, based on the tunnel’s protocols, suggests respective actions to the user, i.e., the tunnel operator, so that it alleviates the cognitive load coming from drafting action plans in cases of emergency. The suggestions come with the related explanations (explainability) – i.e., data and information that justify the suggestion, thus avoiding creating a “black box” system, which the user have to trust blindly. The algorithms and AI applied at this level are of deterministic nature and the tunnel operator is the one making the decisions, deciding to approve or decline the system’s suggestions. The User Interface (UI) of the platform is an important element since it must support the cognitive-load relief coming with the explainability of the system. To that end, we have gone beyond traditional decision support system functionality and designed an adaptive UI that produces alerts and shapes itself based on the related emergency. The operation platform facilitates the tunnel operator’s access to information and it also coordinates – based on the approved actions by the operator – the output that comes in the form of notifications and assistance for the emergency responders and the drivers.

The output of the system/operation platform will be disseminated according to each emergency and the actions taken/confirmed by the tunnel operator. The target here is to design a decision support system that not only supports the decision-making process of the tunnel operator but of the emergency
responder and the road user, as well. Therefore, the system must be able to notify drivers and assist emergency responders in a critical situation. The system will support current protocols which dictate that in case of an accident, vehicles in the tunnel are treated in zones and differently depending on their distance from the accident site – i.e., vehicles closer to the site need immediate attention, etc. Tunnel notification equipment, such as LED displays and illuminated exits can be used for these purposes. Design suggestions on the navigational assistance that may be provided to the stakeholder through UIs and applications designs are presented in the sub-section on Design suggestions.

**Risk factors in road tunnels**

In RiskTUN, input data from in-tunnel conditions will be collected and a risk grade will be assigned to every vehicle entering the tunnel, for accident-preventative purposes. To do so, there is the need to identify the risk factors that synthesize the risk picture of a tunnel. The identification and synthesis presented below is based on recent related work on risk factors for Norwegian tunnels [36], as well as international work on the subject. We group risk factors into primary and secondary ones. Primary risk factors are the basic ones which apply in every case, producing a risk grade for every vehicle entering a tunnel. Secondary risk factors do not apply in every case, i.e., are circumstantial. These factors can be the result of primary factors or take place individually. When occurring, both primary and secondary risk factors may lead to different types of incidents. In Table 2 and Table 3 we present the primary and secondary risk factors currently identified for RiskTUN, and indicate which risk factors that may cause which types of incidents. In the tables there is one column for each risk factor, and one row for the incidents these risk factors may cause. “Black holes” refer to risks due to sudden change in visual environment – i.e., the driver adapting to the dim light condition (“black hole”), and speed variations among drivers [32] [33] [37] [38]. The other risk factors should be self-explanatory.

### Table 2  The primary risk factors and the incidents they can cause.

<table>
<thead>
<tr>
<th>Risk factors → Incidents</th>
<th>“Black hole”</th>
<th>Driving attitude [30]</th>
<th>Highway geometric design [31] [32] [33]</th>
<th>Traffic volume [32] [33][30][9]</th>
<th>Vehicle type [33] [34] [12] [26]</th>
<th>Surface conditions [32]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crash (with or without fire)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Overheating/ Fire without crash</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Ventilation problem [35]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Road spillages</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respiratory issues</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3  The secondary risk factors and the incidents they can cause.

<table>
<thead>
<tr>
<th>Risk factors → Incidents</th>
<th>Road Spillages</th>
<th>Crash</th>
<th>Fire</th>
<th>Ventilation</th>
<th>Pedestrian/ Animal/ Object on the road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crash (with or without fire)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Overheating/ Fire without crash</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Ventilation problem</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road spillages</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respiratory issues</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In Table 4 we detail the incidents’ characteristics and what kind of outcomes might the aforementioned incidents have. Eventually, there may be a connection between two incidents – e.g., a crash causing a fire. However each incident can also take place on its own.

Table 4  Summary of incidents that may happen inside tunnels along with their potential outcomes.

<table>
<thead>
<tr>
<th>Incident</th>
<th>Potential outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crash</td>
<td>Fire</td>
</tr>
<tr>
<td></td>
<td>No fire</td>
</tr>
<tr>
<td>Spillage</td>
<td>No spillage</td>
</tr>
<tr>
<td>Serious (injuries, fatalities)</td>
<td>Light (rear-end)</td>
</tr>
<tr>
<td>Can cause another crash</td>
<td>Can stop traffic</td>
</tr>
<tr>
<td></td>
<td>No effect</td>
</tr>
<tr>
<td>Spillage</td>
<td>Serious (can cause crashes)</td>
</tr>
<tr>
<td></td>
<td>Light (no effect)</td>
</tr>
<tr>
<td>Fire</td>
<td>Regular</td>
</tr>
<tr>
<td></td>
<td>Toxic</td>
</tr>
<tr>
<td>Ventilation malfunction</td>
<td>Serious (can cause respiratory issues)</td>
</tr>
<tr>
<td></td>
<td>Light (no significant effect)</td>
</tr>
<tr>
<td>People/Animal/Object on the road</td>
<td>Can cause crash</td>
</tr>
<tr>
<td></td>
<td>Can stop traffic</td>
</tr>
<tr>
<td></td>
<td>No effect</td>
</tr>
</tbody>
</table>

Table 5  Possible Key Performance Indicators for the identified risk influencing factors

<table>
<thead>
<tr>
<th>Risk influencing factor (RIF)</th>
<th>Main indicators</th>
<th>Related sensors</th>
<th>Measurement frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Black hole&quot;</td>
<td>Position in the tunnel (in meters)</td>
<td>Cameras, Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)</td>
<td>Constant (every second)</td>
</tr>
<tr>
<td></td>
<td>Direction</td>
<td>Cameras, Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)</td>
<td>Constant (every second)</td>
</tr>
<tr>
<td>Driving attitude</td>
<td>Speed (km/h)/vehicle</td>
<td>Cameras, Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)</td>
<td>Constant (every second)</td>
</tr>
<tr>
<td></td>
<td>Number of lane changes/vehicle</td>
<td>Cameras, Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)</td>
<td>Constant (every second)</td>
</tr>
<tr>
<td>Highway geometric design</td>
<td>Curvature of turns (degrees)</td>
<td>Tunnel’s construction design data, Manual measurements</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Elevation (degrees)</td>
<td>Tunnel’s construction design data</td>
<td>Annually</td>
</tr>
<tr>
<td>Traffic volume</td>
<td>VKM (vehicle X km)</td>
<td>Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)</td>
<td>Constant (every second)</td>
</tr>
<tr>
<td>Vehicle type</td>
<td>Vehicle category (private car, HGV, motorcycle)</td>
<td>AID, details from the RiskTUN app or AutoPASS</td>
<td>Upon entrance</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------------------------------------</td>
<td>---------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Surface conditions</td>
<td>Temperature (degrees Celsius)</td>
<td>Thermal cameras</td>
<td>Constant (every second)</td>
</tr>
<tr>
<td><strong>Secondary Risk Factors</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road spillages</td>
<td>Temperature (degrees Celsius)</td>
<td>Thermal cameras</td>
<td>Constant (every second)</td>
</tr>
<tr>
<td>Crash</td>
<td>Vehicles being extremely close to each other or to a tunnel element (e.g., wall)</td>
<td>AID, Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)</td>
<td>Constant (every second)</td>
</tr>
<tr>
<td>Fire</td>
<td>Temperature (degrees Celsius)</td>
<td>Thermal cameras</td>
<td>Constant (every second)</td>
</tr>
<tr>
<td>Ventilation</td>
<td>Binary (working/not working)</td>
<td>Ventilation system</td>
<td>Hourly</td>
</tr>
<tr>
<td>Pedestrian/Animal/Object on the road</td>
<td>Foreign object in tunnel</td>
<td>AID, Thermal cameras</td>
<td>Constant (every second)</td>
</tr>
</tbody>
</table>

Based on the tables above and RiskTUN concept and functionality, we define the Key Performance Indicators (KPIs) for calculating the risk factors in an objective way. KPIs consist of the main indicators, the related sensors that can capture the main indicators in a, as much as possible, quantitative way, and measurement frequency. The defined KPIs are summarized in Table 5.

**System architecture**

Figure 3 presents a logical view of the system architecture for RiskTUN. This architecture shows the main component in a decision support system, supporting different types of reasoning mechanisms and both actual sensors being deployed and simulation of sensor values. The core of the architecture is a reasoning mechanism. This may be a traditional probabilistic mechanism or a module based on AI/ML. In both cases the reasoning mechanism need a risk model. When using AI/ML, the risk model will be built from training data, typically log data, including from past events. When using a probabilistic model, the training data plays a less important role, but is still needed to verify that the reasoning mechanism evaluates historical data correctly.

At runtime, the reasoning mechanism works on real time data from sensors and services. This includes sensors and other mechanisms for positioning – i.e., determining the position of vehicles, persons, incidents, etc. AI/ML may be used as part of the processing of sensor data and/or when fusing data from different sensors. The input interface makes it possible to use input simulators in combination with or instead of real time data. This interface will enable such changes to be transparent to the input collector and reasoning mechanism. The role of the input collector is to collocate value from different sources, including to synchronize data with time stamps. The input collector may also do some types of sensor fusion to provide derived and richer information. Any suggestions from the reasoning mechanism are communicated to the users through the user interaction, denoted driver UI, VTS UI and ER UI in Figure 3. Users in the tunnel (e.g., drivers and emergency responders) may be equipped with sensors, including positioning. Information provided by such sensors are also relevant for the reasoning mechanism and is transported through the input interface and input collector.
In this section we elaborate on understanding the risk in road tunnels, provide insight on the applicability of artificial intelligence in RiskTUN, and offer design suggestions for the RiskTUN’s UI.

Understanding the risk in road tunnels
Risk analyses of road tunnels became a major issue following the implementation of Directive 2004/54/EC on Minimum Safety Requirements for Tunnels in the Trans-European Road Network, which aims to ensuring a minimum level of safety for road users in tunnels with lengths above 500m on the Trans-European Road Network (TER-N). Risk analysis is introduced as a tool to support both design decisions and tunnel operation. This duality is also made clear in the preparatory work for the directive. For instance, in the European Commission’s white paper on European transport policy for 2010, it is specified that the “European Union can help to improve safety both at a technical level and in the way in which tunnels are operated” [39]. In Norway, risk analyses are conducted to support design decisions in all tunnel design projects.

Best practice risk analysis methods for design purposes and assessment of the risk associated with dangerous goods transport through tunnels has been subject to extensive research since mid-2000s. However, implementation and research into risk analysis for tunnel operation, including emergency response, is not equally common, although some examples exist in the literature [1] [8] [40] [41] [42]. No such tool for real-time risk analysis to support tunnel operation and emergency response exist in Norway. By developing the RiskTUN concept, we aim to support decisions to be made in real time by tunnel operators, road users and emergency responders, to both prevent and reduce consequences of accidents. In 2007, the European Parliament commissioned a study on Assessment of the Safety of Tunnels [43], which highlights challenges associated with risk analysis of road tunnels. The study also includes recommendations on how to apply risk analyses in the context of tunnels. Although, the publication is coming of age, it is interesting to note its recommendations and discuss today’s status on these issues, in the context of RiskTUN. Some of the recommendations to improve road tunnel safety, which are relevant to the RiskTUN project, are discussed below.

Coordinated European action to collect and distribute information and knowledge: Appropriate and readily available data is essential for any analysis. Beard & Cope [43] calls for a coordinated European action to improve data availability and quality, which includes, inter alia, a uniform system for reporting of incidents, continuous improvements of the knowledge base for dynamic systems (new vehicles, new transport services, climate change, population development, distribution of goods
road/rail etc) and best practice definitions. Presently, it is hard to see that such coordinated action has occurred, which means that the availability and quality of data relevant for detailed risk assessments are scarce. The original concept for RiskTUN, which is described in this paper, implements fundamentally a deterministic risk analysis model, which is inherently vulnerable to incomplete understanding of risk phenomena and dynamicity. Existing tunnels produce extreme loads of potential data, which is presently unstructured and not coupled to models representing risk phenomena, i.e. tunnel fires. A next step for RiskTUN should be to consider whether machine learning methods could be applied to transform the flow of data into appropriate real-time decision support.

Open source: the recommendation from Beard & Cope [43] is especially concerned with open and readily available source codes computer models and code. The key is to provide transparency into modeling and modeling assumptions, as well as not commercialize the safety of tunnels. Since 2007, there has been an immense development in data processing capacity of computers, which has paved the way for machine learning methods in many societal areas. A shift from deterministic and probabilistic risk models to introduction of deep learning networks, calls for new ways to handle transparency and explainability of decision support systems. In a previous study [44], we conducted an analysis of a new “best practice risk assessment software” for tunnel design projects, and pointed to several challenges, including black-box behavior, limiting assumptions associated with the concept of risk, and issues associated with flexibility and dynamicity connected to the commercial interests of the developer. RiskTUN stands at risk of meeting the same challenges and due considerations should be made in the further development process to provide transparency, explainability and flexibility for the user in the context of a constantly changing world.

Appropriate regulatory framework: the major point of Beard & Cope [43] back in 2007, is that a tunnel design and management regime based on model-based risk analyses, is quite a paradigm change. Traditional safety management in the tunnel industry is built on experience-based prescriptive solutions and procedures. Although existing Norwegian, and European through the EC Directive, regulations open for risk-based decision making, the old paradigm has a strong foothold. For the RiskTUN development project, this means that successful implementation is far from only a technical issue. Adaption of regulations, with special emphasis on European regulations on the use of AI for safety critical decisions, might be necessary. More important might be the cultural change within the tunnel industry necessary to trust recommendations provided by a decision support system based on real-time risk analysis.

Independence of analyst and system: according to Beard & Cope [43], risk assessments should be conducted by a person who is independent person of the system under scrutiny and checked by another independent person. A similar formulation is implemented in the EU directive on tunnel safety (2004/54/EC). In the case of RiskTUN, or any other real-time data-based risk analysis tool, on can ask who is performing the analysis? A deterministic or probabilistic model is pre-determined by the developers, which certainly fulfills the independence criterion. An AI-based decision support system is similarly built by the developers, although one can discuss whether the decision support system is doing the analysis itself. Still, there is independence between the analyst and the system under consideration. However, a major benefit of risk analysis is the possibility of including local, project-specific, and context-specific knowledge into the assessment. Another recommendation from Beard & Cope [43] which highlight this is that measures should be taken to establish a healthy mixture of prescriptive requirements, qualitative risk assessments and quantitative risk assessment in decision-making on safety. In many cases, the best provider of qualitative, local and context-specific knowledge will be persons associated with the system under scrutiny – e.g., the tunnel operator at the control center. Consequently, we question the general recommendation of independence. On the contrary, we are explicitly calling on the user to support the decision support system with its own personal risk analysis. A tunnel operator who blindly initiates actions based on the independent decision support system would be a dangerous operator.

Criteria for acceptability of risk should be explicitly decided; ever since the early morning of risk analyses, risk experts have cried their need for explicitly stated risk acceptance criteria. The idea is
that without such criteria, risk analyses are futile and insipid. However, risk analyses are conducted in every Norwegian tunnel design project and are still considered useful [45], without any nationally stated risk acceptance criteria. Hence, we question the validity of the general recommendation. However, RiskTUN would ideally become a tool that constantly supervises the risk level of hundreds of tunnels. It seems rather clear that it is of vital importance to strike the appropriate balance between sensitivity and specificity to not overload the tunnel operators with red flags or risk reducing recommendations.

Consider specific hazards associated with road tunnels: according to Beard & Cope [43], steps should be taken to consider specific hazards associated with tunnels and underground spaces. This includes considering whether measures adopted for non-malevolent acts are adequate for malevolent acts, reduce deaths and injuries from common traffic, i.e. non-fire accidents, address the challenge of heavy goods vehicles in tunnels and prevent hydrogen-powered vehicles from passing through tunnels. The latter serves as a reminder of the loss potential associated with hydrogen and other new energy carriers introduced in tunnels now and in the future. Still, the recommendation of a prohibition of hydrogen in road tunnels seems rather unrealistic in 2023, considering climate change and the move towards sustainable transport systems. Similarly, malevolent acts have gained increased attention since 2007 and a more digitized and interconnected transport network increases vulnerability to both physical and digital malevolent acts. RiskTUN is currently considering safety of road users. Future development steps should carefully consider whether it cover issues such as malevolent acts and the dynamicity connected to technology, energy carriers and climate change.

Applicability of artificial intelligence in RiskTUN
The use of AI is envisioned in RiskTUN framework and is an important part of it. AI can potentially be applied in various components of RiskTUN architecture. For instance, AI can be applied to sensors and services – i.e., at the edges of the architecture (see Figure 3). An example of this is the use of AI in automatic incident detection sensors. In addition, AI can also be used for the reasoning mechanism by leveraging the training data. Providing a set of training data representative of different scenarios and dynamic conditions in a road tunnel has been a major challenge. However, when aggregate of data over many tunnels across an entire country and over long time-span and from various sources (e.g., road-side sensors, vehicles, etc) are leveraged, a more representative set of training data can be derived. In addition, it is expected that in the future, as connected (and automated) vehicles become more prevalent on the road system, more publicly available vehicular data become available. The privacy regulations and scope of data types, sharing and access policies and methods are out of scope of this paper and require a separate work.

RiskTUN can be somewhat considered as a safety-critical system, as it provides recommendations for safety-critical situations in road tunnels – e.g., to the VTS operator or emergency responders. European Commission’s proposal (COM(2021) 206 final) [46] lays down harmonized rules on AI and among other things discusses specific mandatory rules for high-risk AI systems. The AI mechanisms implemented in RiskTUN, particularly in the system core (i.e., reasoning mechanism) should therefore allow for explainability of the recommended decisions, and human operator oversight.

Design suggestions
As RiskTUN is a framework and not an operational system, the actual UI design of the functionality for the stakeholders is not specified. Still we provide some early sketches of possible UIs for mobile applications for road users and emergency responders. For the RiskTUN functionality to be useful for tunnel operators it needs to be integrated into the operational systems used by the tunnel operators today. As different tunnel operators use different operational systems, we do not provide design suggestions for tunnel operators. In Figure 4, we present example UIs (low-fi prototyping sketches) for a possible driver application (left) and a possible mobile application for emergency responders.
Figure 4  UI prototypes of the RiskTUN mobile application for road users (left, including an example notification), and for emergency responders (right, providing navigational assistance)

This UIs follow the paradigms of prevalent navigational applications (e.g., Google Navigation, Waze) and offers a top-down view of the tunnel. One implementation option for these applications is to provide them as plug-ins to navigation systems used by road users today, either on mobile phones or to in-car navigation systems. For emergency responders, an additional channel of communication between the operator and the emergency responders can be established through a mobile application that displays messages from the operation center and the position and additional information on vehicles inside the tunnel. It can also display the vehicle zones based on which different protocols are applied and the vehicles are treated accordingly. In the right part of Figure 4, the colors of the cars represent the zones; with red signifying the vehicles that were involved in the accident, the orange icons being the vehicles and tunnel equipment in the vicinity, and the green ones are the ones away from the accident site and in a safer place. At the same time, the operator can also see the position of emergency responders and have a better overview of the situation. From our discussion with emergency responders, it is a common practice for rescue team members to carry mobile devices.

Potential contributions to EC directives
As previously mentioned, the EC directive on minimum safety in road tunnels 2004/54/EC, was a major trigger for widespread application of tunnel risk analyses and risk model development within tunnel safety, and consequently fundamental for the RiskTUN work as well. However, a successful development and implementation of RiskTUN, or similar tool, has the potential of developing new knowledge about tunnel safety, by identifying leading indicators that lead to accidents, coupling of data to accident phenomena and identifying weak linkages (high risk tunnel systems) in the road system. RiskTUN has thus the potential of supporting development EC regulations and best practice risk analysis methods for road tunnels.

CONCLUSIVE REMARKS AND FUTURE WORK
In this paper we presented RiskTUN, a risk-aware decision support system for tunnel safety during operation and maintenance phases. RiskTUN’s idea is motivated by the emergence of new ICT technologies, and the aggregate of data that can be leveraged in an intelligent way for better decision making. New opportunities arise when various tunnel safety stakeholders are involved in the process. For doing so, we have identified the potential benefits and user needs of each stakeholder. Further we
have identifies the risk influencing factors in road tunnels through a literature study and insight gained from various stakeholders and laid out potential KPIs associated with these factors in order to form a risk picture. RiskTUN’s system architecture allows for the use of AI/ML both in reasoning mechanism as well as within sensors and services. Our work in this paper is primarily focused on motivating the RiskTUN idea and laying out the system architecture. A more detailed exploration of the risk ontology, understanding risk in the context of road tunnels and the issue of uncertainty and its relation to risk assessment is out of main scope of this paper and will be presented in a separate work. While our proposed RiskTUN idea is a generic decision support system framework, real-life implementation work inspired by it will be undertaken by us in the future through collaborative initiatives with various tunnel safety stakeholders in Norway.

REFERENCES


Innovative approach to Improve the Safety of Tunnels and Tunnel Control Centres

Harald Kammerer¹, Bernhard Klampfer¹, Anne Lehan², Hendrik Wahl²
¹ ILF Consulting Engineers, Linz, Austria
² Federal Highway Research Institute, Bergisch Gladbach, Germany

ABSTRACT

Developments in the field of digitalization of the road and its infrastructure are strongly aimed at connected and automated driving. The collection of vehicle mobility data and its use for traffic monitoring and control can make a significant contribution to preventive event detection and the early initiation of protective measures for tunnel control centres. In particular, information from C-ITS communication can be used to improve the reliability of event notifications as well as the response time in case of an emergency. By using real-time risk assessment of safety in tunnels, it is possible to intervene in a controlling manner before the event occurs and thus mitigate or even completely avert negative effects. The potentials arising from the additional information from mobility data are faced with major challenges, e.g. how to check the integrity of these large volumes of data, and how to select, merge, analyse and evaluate them systematically. Here, the application of Artificial Intelligence is considered as a very promising method. With that in mind, the research project KITT – “Artificial Intelligence to Improve the Safety of Tunnels and Tunnel Control Centres” is investigating for the first time the possibility of carrying out a risk assessment of the overall safety situation in tunnels in real time by using weak AI on the basis of sensor-based data from the conventional tunnel operation and traffic engineering equipment. On the other hand, it is being investigated which additional vehicle data from C-ITS could be available in the future. It is expected that their targeted use will contribute to a significant increase in tunnel safety and to maintain the availability of tunnels.

KEYWORDS: tunnel safety, real-time risk assessment, artificial intelligence, C-ITS, incident detection, sensor fusion, emergency response

INTRODUCTION

Tunnel control centers play a crucial role in ensuring the availability of the road network. In normal operation, they monitor and control the traffic in tunnels; thus ensure safe and efficient traffic flow. In the event of an incident or emergency, tunnel operators initiate measures to protect road users and the structure as well as support the emergency and rescue services in a coordinating manner. Dealing with incidents in tunnels requires special attention because, unlike on the open road, road users are in a structure that restricts smoke-propagation as well as rescue options. Therefore, events in tunnels have a serious impact on user safety compared to the open route and cause damage to the structure and tunnel equipment. The refurbishment usually leads to long traffic restrictions and often causes considerable additional travel times due to the use of low-performance alternative routes. Therefore, strategies and technical solutions to avoid and mitigate the effects of these events are important for maintaining the availability and safety of tunnels and tunnel control centers.

As a consequence of the big tunnel fires in the Montblanc, Tauern and Gotthard tunnel around 2000 extensive regulations and guidelines have been implemented on European and national level. However, as a result of the introduced minimum safety requirements relevant for road tunnels [1] and
the increasing traffic volume, the implementation as well as the complexity of tunnel monitoring and tunnel control systems are steadily increasing. In order to counter this complexity, there has been a trend in recent years for operators to centralize tunnel monitoring and control. Due to the increase in information and communication technologies (ICT), the number of digital points of attack is growing and with it the challenge of ensuring operational safety and the resulting safety of road users.

Nevertheless, digitization harbors great potential for significantly improving tunnel safety and availability. Developments in the field of digitization of the road and its infrastructure are strongly aimed at connected and automated driving. The field of Mobility 4.0 opens up a new possibilities: the use of the traffic collective as a fully digitized mobility, information and communication platform. This technology, known as Cooperative Intelligent Transport Systems (C-ITS) is to be regarded as an extension of driving assistance systems. In future, it will make additional information available to infrastructure operators and road users to assess the current traffic or safety situation in the tunnel [2].

On the other side, the potentials arising from the additional information from C-ITS are faced with major challenges, e.g. how to check the integrity of these large volumes of data, and how to select, merge, analyse and evaluate them systematically. Moreover, the additional information should not lead to a further increase in the workload of the operating personnel in tunnel control centres. If, in the medium term, additional data from C-ITS should be used to improve tunnel safety, concepts must be developed to use them in an appropriate manner. The use of (weak) Artificial Intelligence (AI) offers a promising approach. Potentially it can be used to support operators in assessing the overall situation and making decisions in the event of an incident, as well as in predicting exceptionally dangerous situations. With that in mind, the research project KITT (“Artificial Intelligence to Improve the Safety of Tunnels and Tunnel Control Centres”) is investigating for the first time the possibility of utilizing AI to:

- reduce reaction times in event detection and management,
- mitigate events or prevent them entirely by proactive implementation of real-time safety measures,
- provide emergency services and tunnel users with targeted information,
- secure the interfaces of C2I and the communication in the entire network by means of anomaly detection

The main objective is to further increase tunnel safety and to maintain the availability of tunnels. This paper will present the first findings of the KITT project and discuss future innovative ideas.

**UTILIZATION OF NEW C-ITS DATA**

C-ITS allows to exchange information continuosly between vehicles and the road infrastructure. Depending on the direction in which the data is exchanged, several types of communication exist:

- **Car to Infrastructure (C2I)**: Information is sent from the vehicle to the traffic infrastructure and control centers respectively.
- **Car to Car (C2C)**: Vehicles communicate directly with each other.
- **Infrastructure to Car (I2C)**: Information is sent from the infrastructure to the vehicles.

As information for tunnel users is available not just at single points along the road (e.g. variable message signs), but continuously over the whole road network, information can be provided directly and individually.

Various hardware components are required to enable a wireless communication between individual vehicles and traffic infrastructure. Triggering a message in a vehicle, various kinds of safety equipment, often standard in modern cars, are necessary. This might be rain and light sensors, ESP (Electronic Stability Program) or ABS (Anti-lock Brake System), to name just a few of them. The actual communication then happens via the OBU (On Board Unit). This unit enables the vehicle to communicate with its surrounding environment.

The central elements of C-ITS on the infrastructure are the Road Side Units (RSU), receiving information from the vehicles and transmitting information to the vehicles. Thus, the RSU serves as...
information transfer point between control centers, traffic infrastructure and vehicles. The networked communication usually takes place via WLAN, in order to establish short-term connections between vehicles and the infrastructure.

In order to enable an efficient data flow and data processing standardization of message formats and interfaces is crucial. The European Telecommunications Standards Institute (ETSI) issues technical standards in the field of ICT. It defines in detail the format of C-ITS-messages. There is a rough classification of message types which provide information continuously or just event-based. In this context, the Cooperative Awareness Messages (CAM) and Decentralised Environmental Notification Messages (DENM) formats used to transmit information are considered particularly relevant in the context of tunnel safety. CAMs contain static and dynamic information on the vehicle status, such as position, direction, speed, vehicle type (car, truck, etc.), propulsion system (battery, gas, etc.), vehicle occupancy, etc. and are transmitted continuously, approx. every second. DENMs are notifications of road users or infrastructure systems sent only in case of safety-critical events with specific event information. Corresponding messages can be e.g. accident type, emergency braking, traffic jam, road works or tunnel closure. Almost all events can be indicated according to the requirements defined in the corresponding standards, except of fire. However, a direct coupling with ambient temperatures of the vehicle can be optionally sent in a DENM, for instance in case of a vehicle breakdown. The available message types are listed in the corresponding ETSI standards for CAM [5] and DENM [6].

At this point, a distinction between mandatory and optional information has to be made. Mandatory information are basic sets which must be made available in accordance with the ETSI standard. They allow a prompt implementation in tunnel operation, as all C-ITS equipped vehicles transmit this data. Nevertheless, the rapidly advancing technologies in the field of digitization with regard to connected and automated driving call for considering not yet mandatory information at an early stage. Furthermore detailed definitions already exist in the standards, so that applications already can be built on it.

The collection of vehicle mobility data and its use for traffic monitoring and control can make a significant contribution to preventive event detection and the early initiation of protective measures by tunnel control centres. In contrast to conventional detection systems, which just react to effects of incidents, C-ITS technology allows detecting its causes directly [3]. Furthermore, the additional information source can be merged with other conventional sensor data, i.e. to check plausibility and reduce false alarms respectively. Moreover, the dissemination of additional information to other involved actors, such as emergency services, but also road users, was assessed as having great potential.

THE ROLE OF ARTIFICIAL INTELLIGENCE

Processes from the field of Artificial Intelligence (AI) have been the subject of research for many years. Artificial intelligence is understood to be the constructed replica of intelligence that is orientated on the intelligent abilities of humans. In this replication of intelligence, two types of AI have to be distinguished: weak and strong AI.

The weak Artificial Intelligence has no creativity and no explicit ability to learn independently. Its learning skills are mostly reduced to training recognition patterns or comparing and searching through large amounts of data. It can be used to deal with clear defined tasks with a set of predefined methodologies in order to solve more complex but recurring and well-specified problems. The special advantages of weak AI lies in the automation and controlling of processes, but also in speech recognition and processing. Popular examples are text and image recognition, speech recognition, translation of texts, navigation systems, etc. Digital assistance systems such as Alexa, Siri and Google Assistant also belong to this category. The most significant successes have been celebrated with methods based on Machine Learning, which is an approach to achieve Artificial Intelligence by learning from experience in order to find patterns in a range of data.
The second type is the strong Artificial Intelligence. However, the realization of a strong AI in practice is not yet within reach. A strong AI can independently recognize and define tasks and autonomously develop and build up knowledge of the corresponding application domain. It examines and analyzes problems in order to find an adequate solution – which can also be new or creative.

In KITT the weak AI will be developed to support in the following tasks: First, the AI should improve the detection of (potential) critical traffic situations (e.g. slowly driving or stopping vehicles, dangerous driving, congestion, etc.) at an early stage. The improved knowledge about these events can be used to warn the tunnel operators or to adapt the results of the real-time risk assessment by varying the probability of events. Moreover, in this step the AI is used to cope with the big amount of data transmitted by vehicles via C-ITS technology. In particular the continuously transmitted CAMs generate a flood of information that cannot be processed meaningfully and in a reasonable time without machine-supported procedures.

In addition, a major advantage is seen in sensor fusion, i.e. to meaningfully merge the information from innovative C-ITS with conventional information from tunnel sensors and check its plausibility. On the one hand, a benefit is expected due to the increased information density. On the other hand, it is assumed that false alarms can be reduced by plausibility checks from different systems. Overall, this is seen as increasing the efficiency of traffic monitoring and control.

However, obstacles and risks lie predominantly in the handling of the AI with new data from C-ITS, such as the lack of verification or possible misinterpretation of the data by the AI, the lack of legal framework conditions for the use of AI and the requirement of extensive data bases for training the AI.

Furthermore, AI methods should be used to detect security-relevant events (tunnel security and security of the IT systems), i.e. anomalies, at an early stage in time series of sensor and log data. Finally, a concept for on-the-job learning will be developed. The experience of the operators is used to continuously improve the performance of the AI modules. The modules can learn from the reactions of the operators. However, the improvement of AI components through further learning during operation is a major challenge, especially in safety-relevant application scenarios. It must be ensured that further learning does not lead to a deterioration in the overall system and thus to critical situations. In addition, it is being investigated whether this improvement can take place automatically and continuously during operation or whether it has to be a separate, manual process.

REAL-TIME RISK ASSESSMENT

The main objective of KITT is the improvement of safety of road users. In general, this is achieved through an adequate protection against collisions and fires as well as the optimised handling of self-rescue and emergency response measures. In KITT, however, innovative tools like C-ITS and AI should be used to extend common risk assessment methods and investigate the possibility of carrying out a risk assessment of the overall safety situation in road tunnels in real-time and implement fast mitigation or protection measures.

Generally, the concept for assessing risk in tunnels may consists of three major elements:

- a fault tree analysis to assess potential causes of initial events and estimate the respective probabilities.
- an event tree analysis to assess different chains of events leading from a (statistically known) initial event to potential consequence scenarios and estimate the respective frequencies.
- a consequence analysis to assess the consequences of each tunnel collision and tunnel fire scenario.

Currently, quantitative risk assessment studies are based on static tunnel parameters (e.g. tunnel length, gradient, cross section dimensions, etc.) as well as on average values of dynamic parameters (e.g. for traffic volume, truck share, driving speed, congestion hours, vehicle occupancy, etc.), leading
to annual average risk values. Currently, these risk values are used for example to design the required tunnel equipment, like the ventilation system, or to define consistent operational measures, like the maximum speed limit.

In a real-time risk analysis dynamic data (real-time data) will be used in addition to standard values, leading to a better understanding of the current safety situation in the tunnel. This real-time data originates on the one hand from C-ITS data transmitted from vehicles, on the other hand from existing tunnel sensor systems (see Table 1). This allows for a real-time assessment of safety in road tunnels and an intervention in a controlling manner before the event occurs and thus mitigate or even completely avert negative effects.

Table 1   Overview of different input parameters for the real-time risk analysis and their sources

<table>
<thead>
<tr>
<th>Static tunnel parameter</th>
<th>Tunnel sensor systems</th>
<th>C-ITS</th>
<th>Processed by AI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural tunnel data</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic data</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Vehicle data</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Environmental data</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Event information</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Tunnel equipment status</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incident probabilities</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
</tbody>
</table>

For the real-time risk analysis existing quantitative risk assessment tools are used and expanded to include additional safety-related information and functionalities (see Figure 1). Both, in Austria [7] and Germany [8][9] sufficient flexible methodologies for risk assessment are available for this purpose.

Figure 1   Major elements of a risk analysis extended by real-time information
In KITT, a user demand analysis was conducted, from which representative Use Cases were derived. In the Use Cases relevant for the real-time risk analysis the following three potential risk situations were identified:

- stopping vehicles in the tunnel (due to vehicle breakdown, technical defect, etc.)
- traffic congestion in the tunnel (due to traffic overload)
- traffic accidents in the tunnel (potentially resulting in a fire)

The above mentioned risk situations will be assessed in the real-time risk analysis. In the following chapters the process is explained in detail including the potential where C-ITS data can be implemented and where AI can be of support.

**Fault tree analysis to estimate the probability of initial events**

When assessing safety in road tunnels using quantitative risk analysis tools, the safety assessment is based on triggering initial events: vehicle breakdowns, collisions, fires. The probabilities of initial events are usually determined using basic statistical data. In the real-time risk analysis the basic probabilities are continuously determined based on the current traffic situation and vehicle data. A similar approach has been realized in the research project ESIMAS [10]. In the course of this, numerous fault trees were developed illustrating which initial events can be deduced from risk situations. In KITT, the ESIMAS-concept will be expanded by data derived from C-ITS communication. Such data can be treated as an additional sensor system included in the fault trees. In addition, the AI can enable the early detection of risk situations and thus provide real-time probabilities for the initial events required in the risk analysis. This allows to detect additional causes of events and to recognize initial events or risk situations better and faster.

**Event tree analysis to estimate the frequency of incident scenarios**

In the event tree analysis, the frequency of a series of predefined damage scenarios is estimated. Starting from an initial event (for which the frequency is known) various possible chains of events leading to different damage scenarios are developed in several steps (branches of the event tree). Possible branching points are, on the one hand, failure probabilities of tunnel safety equipment and, on the other hand, traffic parameters (e.g. traffic situation), share of vehicle types (e.g. cars, trucks, buses), existing vehicle propulsion systems, share of dangerous goods transport, etc. By quantifying the event tree (absolute probability of initial event and relative probabilities of different branches), the frequency of each individual consequence scenario can be estimated.

**Consequence analysis to estimate the consequences of collisions and fires**

In the consequence analysis the effects of the individual damage scenarios are estimated. The basis for the consequence analysis for tunnel collisions is provided by statistical data of tunnel incidents. In many countries statistical values for general tunnel types or individual tunnels are existing. Real-time traffic data can be used to dynamically adapt the standard values based on current traffic data, like vehicle velocities or driving behaviour.

The consequence analysis for tunnel fires is determined by using complex simulation models for fire development, smoke propagation and evacuation behavior. Thereby, the impairment of tunnel users during evacuation is determined. In KITT, the CFD code Fire Dynamics Simulator (FDS) from the National Institute of Standards and Technology (NIST) was used. The fire model implemented in FDS allows for a realistic reproduction of specific energy and smoke releases and determine the effects of a fire by calculating the smoke distribution, the visibility, the CO-concentrations, the temperature and the longitudinal flow velocities in the tunnel over time. Real-time data, like existing vehicle types, the share of Dangerous Goods transport vehicles, the existing propulsion systems or the incident location can be used to influence the smoke-propagation results. Due to the complexity and the computational cost of these three-dimensional simulations it is necessary to precalculate a representative set of damage scenarios, which are used during the real-time process.

The results of the smoke-propagation simulations are combined with an evacuation simulation. Thereby, the accumulated effect of the noxious substances and the visibility are determined for each
time step, resulting in survival rates for each tunnel user. With that, parameters like the number and position of tunnel users, the evacuation time, the walking speeds or the escape route lengths can be assessed. Real-time data like vehicle position, traffic volume, bus share or vehicle occupancy can be used to estimate the number and position of people in the tunnel and influence the results of the evacuation simulation.

**Risk evaluation and visualisation**

The risk in the tunnel will be the product of the estimated consequence and frequency of each individual damage scenario. In the risk assessment the collective risk of all tunnel users is estimated, represented by the statistical number of fatalities in the tunnel per year. The real-time risk is evaluated by using a relative approach: The real-time risk value of the tunnel is compared to the risk value of an idealised reference tunnel exactly fulfilling the relevant guidelines and standards. If the risk of the assessed tunnel is below or equal to the risk of the reference tunnel, the tunnel is considered to be sufficiently safe. If the risk of the assessed tunnel exceeds the risk of the reference tunnel, additional risk-mitigation measures are required.

The real-time risk and appropriate risk-mitigation measures are visualised to the tunnel operator on a specific platform. A similar graphical user interface has been realized in the research project ESIMAS [10] (see Figure 2) and will be further developed in KITT.

![Figure 2](image)

**Figure 2** Visualisation of risk situations and real-time risk in the tunnel (left) and appropriate risk-mitigation measures (right)

**IMPROVING USER INFORMATION**

Collecting and processing data only provide added value, if the results and findings are made accessible to stakeholders, who make use of it. Here comes another variaty of C-ITS into play: C2I-communication, as described above, allows for a direct data transfer from the infrastructure (e.g. tunnel control center) to the affected tunnel user – during normal operation as well as in case of an emergency.

In comparison to conventional systems, information is made available instantaneously and continuously over the whole road network. Furthermore, additional and individual information for specific vehicles can be provided. Thus, due to better information the probability of incidents can be reduced during normal operation and the self-rescue can be improved in case of an emergency.

As information requirements are different for road users still in front of the tunnel or already in the tunnel, C-ITS technology allows to provide this information individually depending on the current situation and the position of the vehicle.
Beyond that, not only the tunnel users itself might take advantage of the additional and improved information, but also and with large extent rescue services, especially the fire brigade. They will benefit from the innovative C-ITS-communication and the resulting additional and more precise information. First of all the localization of the event can be defined very accurate. On the basis of DENM further information helpful for planning rescue operation may be the type of the event, the type and number of involved vehicles, the number of people in the tunnel, the type of propulsion system, etc. With respect to rescue services C-ITS provides further opportunities like prioritization of emergency vehicles at traffic lights to ensure a fast access to the event location.

SYSTEM ARCHITECTURE

Due to a multitude of data origin and data processing within the KITT-system a comprehensive but clearly arranged system architecture to define the flow of data is inevitable. In this respect the developed architecture is built modularly with the result that all relevant data can be systematically analyzed by the implemented modules. In the end the output of all processes can be presented to the operator in the tunnel control center by means of an user interface. Security-by-design principles are applied to address security at a very early stage. Flexible interface selection allows for the implementation of KITT in already existing tunnel systems.

To enable the interaction of data with different origin and various simultaneous processes an effective information broker comes into operation. It provides a basis for the data flow and acts as middleware to enable the connection of external systems as well as the exchange of information between the KITT modules. External information is provided by the RSU and by conventional tunnel monitoring systems. As large amounts of data can be generated, especially in C-ITS communication, high-performance exchange is required. Therefore RabbitMQ, a open-source software, is used as information broker. It has two mechanisms for distributing information: Queues and Streams. A queue is a sequential data structure with two primary operations: An element can be placed in a queue (added) at the end and taken out (consumed) at the head of the queue, applying the concept "first in, first out".

One of the main goals of the KITT system is the early detection of potential hazardous situations in road tunnels. For this purpose, AI techniques are to be used to identify anomalies indicating such situations on the basis of incoming C-ITS communication. It should be noted that only CAM messages will be analyzed for possible traffic events, as incoming DENM messages already describe a specific event.

In addition to C-ITS, data from conventional tunnel monitoring systems will also be taken into account. These two distinct types of information will be processed in the first step by means of two independent traffic AI modules. Detecting a dangerous situation, the tunnel operator will be informed by the graphical user interface (GUI) via plausibility checks of the probabilities of both AI modules ("Traffic AI" and "Tunnel AI").

In addition to safety events, AI is used to detect anomalies regarding security issues too. The Risk assessment module performs a risk analysis and evaluation in realtime, based on the probabilities of an initial event generated by the Safety Event Detection Module. The measures for risk reduction depend on the current traffic situation to mitigate the actual increase in risk. The measures are based on the results of the risk assessment of the evaluation module.

The user interface is used for the graphical processing of the evaluations carried out by the evaluation module and the selected measures for the tunnel operator. Central components of the user interface are an overview of the overall safety situation and a listing of specific recommendations for action.
LEGAL AND ETHICAL ASPECTS

The current legal situation with regard to the above-mentioned range of topics is already very extensive. The equipment and operation of road tunnels are covered in Austria [11] and Germany [12] by special safety regulations, which also implement European requirements. The Austrian Road Tunnel Safety Act [13] also contains specifications for tunnel surveillance using video surveillance, and therein already specifications for data minimization. In the area of cyber and information security the extensive European requirements (NIS Directive) have also been implemented nationally. In the area of data protection law and privacy, the legal framework is largely specified by the European legal framework (especially GDPR) and is also specified and implemented in the national DSG (Austria) and BDSG (Germany).

However, due to the technical development in the field of automation and networking in traffic an evaluation and possibly an adaptation of the current legal situation may be required. C-ITS provides for an extensive data exchange between vehicles, but also between vehicles and infrastructure. The collection and aggregation of a large amount of individual data, but also the additional communication channel that is opened up as a result, which can result in new security gaps, require not only technical innovation but also a legal framework that is dynamic on the one hand, in order to be able to take technical progress into account, and on the other hand, sufficiently specific to comply with fundamental rights and the rule of law and to ensure legal certainty.

A major objective of KITT is a review of all relevant legal as well as ethical aspects arising from new developments within this project. For that, two Universities from both, Austria and Germany, each specialized in privacy, liability law and legal informatics conduct extensive analyses in this area.

Figure 3  Arrangement of the KITT-elements in a tunnel system architecture
CONCLUSION AND OUTLOOK

At the time of the preparation of this paper, the requirements for the use and integration of C-ITS and the application of AI processes were determined on the basis of the state of the art, regulatory requirements and user demands. These are currently brought together in utilisation concepts. A particular focus is currently on providing a training data basis for the AI. Due to the low vehicle penetration rate with C2X-capable vehicles, this is done using synthetically generated training data and corresponding traffic simulation software [14].

Even at the current stage of the project, it is clear that this project is to be designed with great perspective, but the relevance requires this early step due to the rapidly advancing digitization in the area of connected and automated driving. The requirements from the point of view of tunnel safety must be formulated at an early stage, as they may well deviate from those of the open road. This addresses infrastructure operators for the development of the necessary technical infrastructure and integration into existing monitoring and event management concepts as well as the development of competences of system users and vehicle manufacturers who include safety aspects and the requirements derived from them in their design when providing information to the infrastructure. This opens up potentials that can contribute to improving road safety. For tunnel monitoring, concepts for targeted data fusion and plausibility checks can be expected to provide opportunities for better incident prevention. For the interpretation of the large amounts of data, methods such as AI are needed that make them manageable. At the same time, it can be assumed that improvements in the case of incident management and explicitly for self-rescue can be achieved through the possibility of individualised responses.

ACKNOWLEDGEMENT

The project was funded by the German Federal Ministry of Education and Research (BMBF) within the framework of the call "Artificial Intelligence in Civil Security Research" and by the Austrian Federal Ministry of Agriculture, Regions and Tourism (BMLRT) within the framework of the funding programme for security research KIRAS and was handled by the VDI Technology Centre and the Austrian Research Promotion Agency (FFG). The project started on 01 April 2021 and is expected to end on 31 December 2023.

REFERENCES

6. ETSI TS 102 637-3: “Intelligent Transport Systems (ITS); Vehicular communications; Basic set of applications; Part 3: Specification of decentralized environmental notification basic service”, v1.3.1, 2019
7. Österreichische Forschungsgesellschaft Straße-Schiene-Verkehr, “RVS 09.03.11 Tunnel-Risiko-Modell (TuRisMo)”, 2015.
11. Österreichische Forschungsgesellschaft Straße-Schiene-Verkehr, RVS 09 Tunnel Guidelines.
An AIoT-based smart digital twin for real-time tunnel fire safety monitoring

Xiaoning Zhang¹, Xiqiang Wu² & Xinyan Huang¹
¹The Hong Kong Polytechnic University, Hong Kong, China
²Southeast University, Nanjing, China

ABSTRACT

Road tunnels have played significant roles in the model transportation system with the development of the economy and urbanization. Fire accidents occurring in the tunnel are fatal and destructive, which may pose great threats to the trapped person and firefighters. This work proposes an AIoT-based smart digital twin to predict the real-time fire risk such as the fire size based on deep learning algorithms. The numerical model is first validated by the full-scale tunnel fire test, and then a numerical database of 30 tunnel-fire scenarios is established under different conditions. The Transformer architecture is adopted to construct the AI model, and the AI model attains an accuracy of 98% in predicting the fire information. Then the digital twin system was developed by the game engine and trained AI model. Finally, the system is demonstrated on a full-scale tunnel to predict the real-time fire size. The results show that the fire size can be accurately predicted.

KEYWORD: Tunnel fires, Digital Twin, Artificial intelligence of things, Fire modelling

INTRODUCTION

As an important part of the modern transportation system, tunnels bring great conveniences but also increase the chance of fire accidents. Due to the enclosed tunnel environment, evacuation is difficult during emergency incidents, and the safety issue is essential, which should pay careful attention. For example, the Mont Blanc tunnel fire that occurred in 1999 caused 39 deaths and 14 injuries [1]. The high density and toxic smoke and rapid development of fire make it difficult to perform firefighting and rescue activities. Detecting and monitoring real-time fire information is significant for evacuation and firefighting activities.

Recently, many studies have been done to detect and monitor tunnel fires. For example, the widely used fiber optic linear heat detection system, which is based on Raman scattering, could provide information about temperature profile and fire location [2]. Although conventional fire detection systems can determine the fire location in the early stage, no more information (e.g., size, severity, development, and critical events) can be obtained from simply fire detection. Therefore, intelligent real-time fire prediction methods should be included in the fire detection system.

Artificial Intelligence (AI) methods have been widely applied in fire detection and forecast in different scenarios. For example, Wu et al. proposed the AI model to recognize the fire source information in tunnels [3]. However, applying digital twin and Artificial intelligence of things (AIoT) in monitoring the real fire in the tunnel has not been investigated. The aim of this study is to propose an AIoT-based smart digital twin to monitor tunnel fire in real-time. The tunnel digital model is constructed based on a real-scale tunnel, with a dimension of 140m × 8 m × 6 m. A deep learning
model will be built for real-time fire identification, and the capability of the system will be demonstrated.

FRAMEWORK OF DIGITAL TWIN

A digital twin (DT) is defined as the virtual representation of the physical entity [4]. The basic DT model usually consists of three main parts: (a) physical entities in real world, (b) virtual model in digital world, and (c) the data and information between real and virtual model. In present study, the typical three-dimension DT model is adopted. The architecture of the proposed tunnel fire digital twin, each component and their relationships are shown in Figure 1. The system includes real tunnel, digital tunnel, data connection and fire information between real and digital tunnel, corresponding to the three components of the digital twin. Compare with the previous intelligent tunnel fire system [5], the DT tunnel system proposed in present study adopted full scale tunnel to demonstrate the capacity and can be used for daily management and fire safety emergency response by directional data.

Figure 1 The overall architecture of the proposed tunnel fire Digital Twin system

The physical tunnel consists of the tunnel itself and other entities. Three types of entities are defined in the system, namely fixed entities, movable entities, and probabilistic entities, which correspond to
the tunnel systems, passing vehicles or passengers, and fire risks, respectively. During the fire, the fire severity can be quantified by the fire location, fire dimension, fire heat release rate, temperature distribution, fuel type, development trend, etc.

The fire could be detected and identified by fixed entities such as fire detectors, sensor networks, and surveillance cameras. Then the entities used to control or distinguish the fire could also be triggered to mitigate the fire risk, such as the firefighting system and ventilation system. The dynamic warning and evacuation signs can help trapped people evacuate to safe places.

The proposed digital twin system is developed using game engine Unity 3D and can evolve with the changing tunnel environment, with the feed of data collected from installed sensors or devices to form a dynamic data-driven system. The whole lifecycle of the proposed digital twin system includes data collection, data transmission, data storage, data processing, and data visualization. The proposed system can be used for daily fire risk monitoring, facility management, fire prediction and evacuation guidance. In present work, the fire safety monitoring is demonstrated.

EXPERIMENTAL VALIDATION OF NUMERICAL SIMULATION

The AI prediction model plays a key role in the proposed digital twin system. A comprehensive database is important to train a well-performed deep learning AI model. However, the fire test data from previous studies are difficult to obtain or not suitable for model training, most only give some statistical data at a steady state [1]. Simulation data validated by experiments is a better alternative to solve the problem of insufficient training data. In this work, the Fire Dynamics Simulator (FDS) [6] developed by NIST is adopted to generate enough simulation data. FDS has been widely used for the simulation of tunnel fires by previous studies in terms of smoke movement (Hu et al. 2007; Chow et al. 2015), ceiling temperature distribution [7,8], and ventilation [9].

Figure 2  Full-scale tunnel fire tests (a) full-scale tunnel laboratory in SCFRI, (b) full-scale pool fire tests inside the tunnel; and (c) tunnel geometry and distribution of thermocouples.
The tunnel fire model is established using FDS 6.7. The tunnel geometry is 140 m in length, 8 m in width, and 6 m in height, which is referenced to the real-scale experimental tunnel at Sichuan Fire Research Institute (SCFRI) in China, as shown in Figures 2 (a) and (b). The inlet and outlet of the tunnel are set as open, as shown in Figure 2(c). The inner surfaces of the tunnel were assumed as perfectly smooth, and all walls were defined with default inert surfaces with a fixed ambient temperature of 20 °C. The mesh size of 0.1 m is adopted to conduct the simulation.

Inside the real tunnel, two smoke curtains are constructed to collect smoke and protect the tunnel structure during the fire tests, which are located at 5 m and 50 m. As shown in Figure 2(c), the smoke curtain is also included in the numerical fire model. Between the two smoke curtains, the tunnel walls and ceiling are protected using fireproof materials., and then fire tests can be conducted. During the real tests, 11 thermocouple trees were adopted to collect the temperature data along the tunnel centerline. The thermocouple tree is symmetrically distributed along the fire source (i.e., the sixth is the closest to the fire). In the present study, only the ceiling temperature data is used.

As a comparison, 11 thermocouples were defined on the tunnel ceiling in the numerical model [10]. They were evenly distributed with an interval of 1 m along the tunnel centerline to imitate the temperature sensors (e.g., heat detector or fiber-optic fire detection system) in a real tunnel, as shown in Figures 2(b) and (c). Then serval full-scale fire tests were conducted to validate the numerical simulation and test the established tunnel fire safety digital twin in the following part, as shown in Figure 2.

Then, serval full-scale fire tests were conducted in the tunnel to validate the numerical models [10]. As shown in Figure 2(b), a square fuel pan filled with heptane was burned, and the mass loss during the tests was measured secondly by an electronic balance under the fuel pan. The tunnel is well-ventilated, and the ambient temperature is around 20 °C, which remains consistent with the conditions of the simulation. The value of HRR is then calculated by \((\dot{m} \times \Delta H)\), where \(\dot{m}\) is the mass loss rate of the fuel at steady state (kg/s), and \(\Delta H\) is the heat of combustion for heptane equal to 44.5 MJ/kg. Two fuel pans with an area of 0.36 m\(^2\) and 1 m\(^2\) are used in the tests, and their calculated HRRs are 624 kW and 2,130 kW, respectively. The same configurations, including the location and dimensions of the fuel pan and the value of HRR, were then adopted in the numerical models.

The distributions of the measured and simulated sensor temperature at the steady-state are compared in Figure 3(a). The simulated and experimental sensor temperatures at the same location (the fire source is located at 80 m) are compared in Figure 3(b). Although a slight difference exists at some sensor locations due to the buoyancy-induced puffing, the general matching of the respective profiles demonstrates the rationality of the established fire models.

![Figure 3](image_url)  
*Figure 3* The comparison of simulated and experimental ceiling temperature data of (d) stationary fires and (e) growing heptane pool fire at 80 m.
DEEP LEARNING FIRE PREDICTION MODEL

To monitor the real-time tunnel fire risk, such as the fire location and fire size, Artificial Intelligence (AI) methods, especially deep-learning, can give more accurate results than traditional detection methods. The validated CFD models are used to simulate various fire scenarios. In the present work, a Transformer model based on self-attention mechanism is adopted to predict the real-time fire information with the temperature sensors as the model input. The training dataset of the proposed model is generated from numerical simulation data. Fire Dynamics Simulator (FDS) is adopted to conduct the fire simulation of different scenarios [11]. The tunnel geometry and simulation conditions are the same as the setting in section 3. The fire database is constructed from 30 fire scenarios considering three fire locations (15 m, 20 m, 25 m) and ten HRRs (0.1 MW, 0.2 MW, 0.5 MW, 0.8 MW, 1 MW, 1.5 MW, 2 MW, 5 MW, 10 MW, and 20 MW). More smaller fire cases are considered when construct the fire scenarios in order to get better prediction results when fire is relatively small. All the cases were simulated for 120 s, which was long enough to reach the steady stage.

Then the simulation data was extracted to construct the training database. The generation process of the dataset for model training and the Transformer model architecture are shown in Figure 4. The purpose of the AI model is to predict the fire size using real-time ceiling temperature data. Therefore, the 11 ceiling temperature data is used as the model input and the fire size is the output. The time-sequence temperature data for different fire scenarios are organized to 3,600 (30 × 120) samples.

![FDS Simulation Results](image)

**Figure 4** Generation of the training database and Transformer model architecture.

In present system, raw sensor data will input to the system and fire information such as fire size will be output. The input-to-output transformation process highly relies on the AI model, as the relationship between input and output are complicated and cannot be obtained by empirical model or statistical methods. In present study, we propose a deep learning architecture based on Transformer to identify the real-time fire information using the temperature sensor data as model input.

Transformer is new type of deep learning model based on self-attention mechanism (Vaswani et al., 2017), which is designed to process the sequential data. The Transformer model process whole input sequence data at one time, and the significance or attention of each part of input data will be generated through the training. In present work, the aim of the proposed model is to predict the fire information using given sensor data, however, the fire information is mostly captured by the sensors near the fire.
Especially in long road tunnel, the sensors far away from the fire source may not get any information, the sensors near the fire should have heavier weights than other sensors. Therefore, Transformer model is suitable for fire identification using distributed sensors.

The model architecture of proposed Transformer model is shown in Figure 5. Temperature sensor data at different locations are input to the Transformer model, and fire information includes fire size and location can be predicted by the model. The normalization and inverse normalization processes are carried out before the input and after the output, respectively, to optimize the training process. Four encoder blocks and 4 decoder blocks are added to the model. Inside each encoder-decoder architecture, multi-head attention layer and fully connected layer are added.

After training, the model performance was evaluated using different metrics. Figure 6 shows (a) the loss and (b) R2 of the proposed model on the training dataset and validation dataset evolving with training epochs. The loss value decreases with the number of training epochs on the training dataset, as expected. The model loss quickly reaches a relatively low value, and finally keeps at around 0.005 on both training and validation datasets, indicating that the epoch number of 200 is sufficient to converge the model. While R2 shows an opposite trend with a sharp increase at the beginning and an eventual converge of 98 % on both training validation datasets. The high R\textsuperscript{2} score indicates an accurate prediction of the desired output. The comparable loss and accuracy on training and validation datasets indicate the effectiveness of the setting of the dropout layers in alleviating the overfitting.

REAL-TIME FIRE SAFETY MONITORING

Based on the proposed digital twin framework and fire prediction AI model, a real-time tunnel fire digital twin system was developed to monitor the tunnel fire risk during the fire. The proposed digital twin is built based on a real tunnel in Sichuan Fire Research Institute (SCFRI), the tunnel is 140 m in length, 8 m in width and 6 m in height, as shown in Figure 6. The digital tunnel model and vehicle model are designed in SketchUp with a scale of 1:1. The fire and smoke effects are created in Unity 3D (v2020.3.25) using Particle System, which is currently one of the most advanced technologies to render the fire and smoke in real-time.

The system performance was then evaluated using real-time experimental data. Two large scale tunnel fire tests were conducted to demonstrate the proposed system in SCFRI (Sichuan, China). The fire source is located at the ground 20 meters from the tunnel entrance. At the tunnel ceiling, 11 thermocouples are mounted to record the temperature, as shown in Figure 2(c). The real-time temperature data are collected and fed into the AI model for further processing.
Then the performance of the AI-driven system was demonstrated by comparing the predicted HRR (generated by AI model) and real HRR values (measured by mass loss rate). The mass loss during of the liquid fuel were recorded by an electronic balance under the fuel pan. The HRR values \( \dot{Q} \) over time are estimated using the following \( \dot{m} \times \Delta H \), where \( \dot{m} \) is the mass loss rate (MLR) of the fuel at different combustion stage (kg/s) and \( \Delta H \) is the heat of combustion for heptane equal to 44.5 MJ/kg. The time varying HRR values of the two tunnel fire tests are displayed in the Figure 7 (a) and (b), which are marked as blue dash line. The predicted HRRs are marked as red lines, as shown in Figure 7. The predicted HRRs for both cases are comparable to the measure HRRs, the trends and peaks of fire development were accurately predicted.

**Figure 6** Development of tunnel fire monitoring digital twin: (a) front view and (b) top view of real tunnel, (c) top view, (d) front view and (e) inside view of digital tunnel

**Figure 7** Comparison between the forecasted HRR by AI model and measured HRR by MLR: (a) case 1, (b) case 2.
CONCLUSION

In the present study, an AIoT-based smart digital twin for tunnel fire safety monitoring is proposed and demonstrated on full-scale tunnel. The digital twin comprises three main components and can monitor the real-time fire risk for supporting firefighting activities. The digital twin is driven by its AI engine which is constructed by Transformer layers and trained by numerical database. The numerical simulation is validated by full-scale tunnel fire tests and then numerous data is generated from simulation. The proposed AI model attains an accuracy of 98% in predicting the fire information on the database. The trained AI model is then deployed on the data centre to drive the digital twin system developed by game engine. Finally, the system is demonstrated on a full-scale tunnel to predict the real-time fire size. The results show that the fire size can be accurately predicted.

REFERENCES

Locating people in tunnels using Wi-Fi technology

Håkan Frantzich¹, Karl Fridolf² Staffan Liljestrand³, Alex Henningsson³ & Johan Lundin⁴
¹Lund University, Lund, Sweden
²The Swedish Transport Administration, Malmö, Sweden
³Bumbee Labs, Stockholm, Sweden
⁴Brandskyddslaget, Stockholm, Sweden

ABSTRACT

The overall aim of the current project is to investigate the possibility of using people's mobile phones to locate people in a tunnel environment, both during normal operation and during an emergency. As part of the project, a technology for locating people based on Wi-Fi communication between access points in a tunnel and the user's mobile phone is investigated. To examine the precision of the localization system, 39 different trials have been carried out under different conditions during an experiment in a road tunnel in Stockholm, Sweden. In the tests, the Wi-Fi-based predicted location has been compared with the actual location of the people in the tunnel. The conditions investigated include the number of people in a group, the number of available access points in the tunnel, whether the mobile phone distinguishes between an active or passive connection, whether it differs between a person moving or standing still and whether the mobile phone is held in the hand or is stored in the person's pocket. The results indicate that the mean value for the distance between actual and predicted position is in the order of 20 m or less. The variation in distance for a single individual is relatively large and the standard deviation for the mean distance is in the same order of magnitude as the mean value. Despite this, there is a good potential to locate individuals in a tunnel as the distance between emergency exits is often much longer than the uncertainties in the predicted locations of people. These results are promising and indicates the potential of cost-efficient improvement of tunnel safety both for existing and new tunnels. With a refined positioning system, there is potential for further improved ability to locate individuals in a tunnel fire environment with this technology.

KEYWORDS: tunnel safety, evacuation, rescue services, Wi-Fi, indoor localization, indoor mapping, sensor

BACKGROUND

Safety in underground facilities for road and rail traffic, i.e. road and rail tunnels, is largely associated with the technical characteristics of these structures with regard to safety in the event of fire. This applies in particular to the technical characteristics that affect, on the one hand, what possibility people have to self-evacuate or otherwise get to safety, and on the other hand, what possibility the rescue services have to carry out an efficient rescue operation. Mainly, this is because fires in road and rail tunnels can be expected to both develop faster and be larger than in ordinary buildings above ground [1–3]. In the event of a fire in a road or rail tunnel, it is also likely that smoke will quickly spread in large parts of the tunnel system. A consequence of this is that people in road and rail tunnels can be forced to evacuate under very difficult conditions, for example long distances in dense smoke with only a few meters of visibility [4–7]. The unfamiliar road and rail tunnel environment and the long distance to the nearest emergency exit also aggravate the situation. As such, the need for evacuation assistance is often higher compared to normal above-ground buildings.

The need for help during an evacuation of a road or rail tunnel is to some extent met by the recommended tactical approach for rescue efforts in this type of construction [8]. The problem, however, is that also the efforts of the rescue services are associated with great difficulties [9–11].
Apart from the low experience in carrying out interventions in road and rail tunnels, the intervention is usually performed from a limited number of access points. The rescue services will thus lack a complete overview of the accident scene especially in the initial stages of the operation. In this regard, a lack of information about what is burning, where the fire is, whether there are people still in the tunnel, and if so where, has been pointed out as difficulties for a rescue effort [8, 12]. Difficulties that can be crucial when determining for example the appropriate direction for ventilation flow for rescue purposes with tunnel ventilation or mobile fans.

In many cases, the difficulties can be partially managed with the help of various technical systems that can inform about the event that has occurred, for example fire alarm systems, automatic water sprinklers and CCTV systems. However, the majority of these systems are designed in such a way that they mainly contribute with information about the fire, but not the evacuation. Furthermore, systems designed to facilitate evacuation are most useful in the initial stages of a fire and can thereafter provide information only in those parts of a road or rail tunnel that are not affected by fire smoke.

With this background, one of the most prioritized tasks appears to be determining whether people are still inside road or rail tunnels, in which parts of the facility they are located and in which direction they are moving. This information is crucial to determine what strategy and what resources are needed to try to rescue them. A system for locating evacuating people can therefore be a technical installation that can largely contribute to increasing both people’s ability to reach a place of safety and the ability of the rescue service to carry out an effective operation.

One such method to locate people could be to exploit the fact that many people already today own a smart phone that has the ability to automatically communicate with a wireless local area network (WLAN). The question is therefore whether this can be a technology that can be used for locating people or whether the technology itself is too imprecise. Seen from a research perspective, there is also an interest in investigating whether the technology can be used to collect data about how people move to be able to predict movement for modelling purposes. There are examples of research that used certain technologies, such as RFID technology, IR technology and Bluetooth technology tested with varying degree of success [13–15]. Still, the technique must be considered in an early stage of development and validations studies are needed.

Objective
The paper, therefore, aims to investigate the conditions for locating people in a road tunnel using the Wi-Fi function of the person's smart phones during normal conditions, i.e., without any presence of heat or smoke.

The primary goal is to investigate, based on a realistic experiment, the accuracy of a positioning system based on Wi-Fi technology to assess whether the technology can be used for locating people during normal situations and in the case of an emergency.

The goal is also to investigate whether, and if so under what circumstances, the same positioning system can be used as a data collection technique in future research contexts to both facilitate and streamline as well as increase the accuracy of empirical studies of people's movement.

TECHNIQUES FOR LOCATING PEOPLE

Today there are several more or less developed technologies (and related location algorithms) for locating people and their movement outdoors as well as indoors under normal conditions [16]. The GPS technology is the most commonly used in outdoor environments but can only be used to a limited extent when locating people indoors and then it needs to be supplemented with other technologies [17]. However, in road and rail tunnels as well as other types of deep underground facilities, such as mines, with only a limited number of entrances/ exits, the GPS technology is not a practical option for locating people, even when supplemented with other technologies.
Bluetooth, RFID and Wi-Fi are, in this context, various examples of technical solutions that can be used indoors for locating people under normal conditions. Which one is most suitable to use in a particular application depends, among other things, on the need for level of detail, precision, range, response time and reliability. The RFID technology has, for example, been applied for a longer time in the mining industry to monitor the location of miners in the many times long and deep networks of tunnels that occur in this type of operations [18]. However, it can primarily (and has historically) been used to identify people within zones rather than their actual position. In other applications, Wi-Fi based technologies have been used to, for example, within a commercial context in detail describe how many visitors make it to a certain part of a shopping center, how long they stay there, and which are the most common walkways [19]. Previous research has shown that the technology can predict the location of a mobile device with a precision of a few meters [20]. This indicate there is a potential for using the technology also for a tunnel environment. More details on this, an overview of other localization technologies as well as techniques for positioning are presented in [21]. As concluded, there seem to be a potential for wireless technologies to track people. However, little research seems to have focused on practical testing, particularly within an emergency application.

METHOD

In this paper, the results from an experiment in which participants (subjects) moved in a tunnel according to predetermined routes is presented. During the experiment, the test subjects wore devices that corresponded to a mobile smart phone, and were located using a Wi-Fi technology. The position was determined through an analysis of the collected material after completed trials. During the experiment, the actual positions of the test subjects in the tunnel were documented using video recording to be able to compare this position with the one obtained from the localisation with the Wi-Fi technology. After the data had been post processed, it was used in analyses with regard to aspects such as precision and accuracy related to the positioning technique. This was done for a variety of set ups, related to the number of people in a certain trial, type of connection condition (e.g. passive and active connection), number of available access points, etc.

EXPERIMENTAL CONDITIONS

The road tunnel

The experiment was carried out in the Sickla tunnel, which is part of the Södra Länken (Southern Link) road tunnel system in Stockholm and at the same time part of national road 75. The tunnel has two unidirectional lanes, and it slopes downwards in the direction of travel (south). The test area is located approximately in the middle of the tunnel, where the tunnel has a straight design. Figure 1 shows a view of the tunnel seen from the north side in the south direction.

![Figure 1. Picture showing the tunnel seen from the north side of the tunnel in the direction to the south. The first red-white marking indicates the experimental area’s limitation to the north.](image-url)
At the test site, the tunnel is approximately 10.4 m wide with two lanes of 3.7 m each (measured in the center of the lane markings) and a road shoulder on each side. Along the right side, the shoulder is approximately 2 m wide, while on the left side it is approximately one meter wide. On each side of the tunnel, there are edge elements placed along the tunnel, which provide a smooth surface along the tunnel up to approx. 1.4 m above road level. The experimental area is approximately 110 m long, which is the area between the outermost access points plus 10 m further in each direction. This is illustrated in figure 2, which schematically shows the relevant part of the Sickla Tunnel with the marked trial area and various installations.

![Figure 2. Simplified view of the test area in the Sickla tunnel. Yellow and green bands along the test area indicate the approximate coverage areas of the cameras.](image)

**Wi-Fi devices**

To avoid a possible conflict with the General Data Protection Regulation (GDPR), which among other things regulates how collected data may be handled, the subjects’ own mobile phones were replaced with battery-powered Wi-Fi devices (figure 3), which technically corresponds to the function that mobile smart phones have in terms of communication with surrounding receivers for a Wi-Fi signal. Every Wi-Fi device communicates at least as often as a mobile phone does if it is actively connected (active listening) to a wireless Wi-Fi network. In the current case, a communication between the Wi-Fi devices and the access points took place every second. This is more frequent compared to how a mobile phone usually communicates. However, in this way a controlled connection was obtained and in the following analysis an average value of the data set over each 5 second interval is used for determining each position. The passive listening is represented in the analysis by the fact that only a smaller, randomly chosen sample was included for the positioning. In all trials, each research subject carried two Wi-Fi devices, one held in one hand and the other placed in one of the research subject's pockets.
Access points
To locate the subjects, 20 access points were set up along the experimental area, see figure 2. The access point is the device that can communicate with the Wi-Fi devices that the subjects carried with them during the experiments. The access points were of the Teltonika RUT955 type, which is also a 4G router with built-in GPS, and thus makes it a suitable access point for mobile measurements. Each access point was placed on the ground along the long sides of the experimental area at 10-meter intervals.

Video cameras, markers and obstacles
In order to document the real position of the subjects during the tests, six video cameras on tripods were used and placed on the edge elements along the right side of the tunnel with a c/c approximately corresponding to 20 m. The location of each camera is shown in figure 2 where they are illustrated as small arrows in the lower part. Each camera recorded approximately 20 m of the length of the tunnel and basically the entire width of the tunnel.

To facilitate the analysis, there were distance markings along the tunnel and markings across the tunnel at 5-meter intervals. In this way, each research subject could be located on the videos. The tunnel was also equipped with directional markers (road cones) that the research subjects used to keep a straight walking direction.

A vehicle was placed in the tunnel during some of the trials to investigate the effect of shadowing the radio signal. The vehicle was of the minibus type and, when it was used, was located approximately 80 m from the starting point.

Participants
A total of 16 people participated in the trials. These were recruited from fire engineering consultancy firms in the Stockholm region as well as from Brandforsk, LTH Fire Safety Engineering, Region Stockholm and the Swedish Transport Administration. The recruitment was carried out via personal contacts with the respective organization and the criterion for being allowed to participate was that each person had a self-assessed physical ability to move freely within the trial area. Due to the recruitment procedure, all research subjects were known to the researchers.

The recruitment was carried out in such a way that the person received complete information about what the experiment was about. This was done in order to allow for the test subject to assess whether he or she wanted to sign up and participate. An internal ethics assessment was carried out prior to the trials to ensure that the research subjects would not be exposed to any unnecessary risks or intrusions into their personal integrity. As part of risk minimization, all research subjects were provided with a safety vest and a protective helmet. Each subject had to sign a consent form prior to his/her participation, and was compensated with 500 SEK (approx. € 50) afterwards. All research subjects
were insured in a so-called special personal injury protection insurance from the Legal, Financial and Administrative Services Agency (Kammarkollegiet) in Sweden.

**Trial scenarios and implementation**

The experiment included four different main scenarios. Each scenario included a number of different trials. Within one scenario, there is mainly a variation in the number of research subjects who move in the tunnel and several trials are repetitive. This means that a scenario is characterized by:

- walkways for the research subject or group of research subjects,
- if the subject, for a while, stands still at a certain position in the tunnel, and
- if there is an obstacle in the form of a vehicle in the tunnel.

In each trial, data was collected from both Wi-Fi devices of the research subjects (representing a smart phone). A total of 39 trials were conducted. The number of research subjects who carried out a single experiment varied from a single individual to the entire group of 16 people.

**Walking routes**

There was a total of five different walkways or routes along which the research subjects could move, see Figure 4. Route A and B (used in scenarios 1 and 3) were near the middle of the two lanes of the tunnel. Route E (used in scenario 4) followed the lane line marking on the right side. Route C and D (used in scenario 2) only partially followed the tunnel's natural route. The participants were asked to walk as straight as possible along the designated paths, which were highlighted with road cones.

![Figure 4. Walkways for the different scenarios.](image)

**Stop in the tunnel**

Scenario 3 is characterized by the research subject first walking a distance, approximately 50–60 m and then stopped in the tunnel. The person stood still for one minute and then walked the final part of the route. In these cases, the movement took place along routes A and B.

**Obstacles**

In scenario 4, there was a vehicle deployed in the tunnel, see Figure 4, and in that scenario the research subjects walked along section E in the tunnel.

**Procedure**

The experiment was carried out on the night between 27 and 28 October 2021. All the people involved gathered for a joint briefing at 22:00 on 27 October. Research subjects signed the consent form, and was then given the two Wi-Fi devices that would represent mobile phones as well as number pads to be put on the clothes. Thereafter, everyone was transported to the trial site and the trials were prepared.
At the start of the experiment, the video cameras were synchronized with an audio signal at exactly 23:45:00. Based on that signal, the video films were later prepared so that they could be viewed synchronized with the same start time and with the Wi-Fi-based locations. Before each trial, the research subjects who participated in each experiment were informed about the conditions that applied. Research subjects who did not participate in an ongoing trial were approximately 10 m outside the experimental area.

RESULTS

The main results from the trials are the difference in location between the two measurement methods, Wi-Fi and video-based locations respectively. The data collected has been processed in different ways to represent the possible methods of Wi-Fi communication to investigate the effect of the number of access points available in the tunnel. In all cases, the Wi-Fi position is based on an analysis of the three strongest signals from the mobile device at any given time (trilateration). Prior to the analysis, a number of different ways of processing the collected material were investigated and the method with the three strongest signals was shown to provide reasonably good precision on a test data. It should be mentioned that the experiment included a variety of alternative conditions manifested in the trials. In this paper only a few of the experimental conditions are presented due to space restrictions.

The analysis of the positioning takes place as a comparison between a Wi-Fi-based position and the corresponding real position as documented by the video cameras. The amount of data is extremely large, and therefore only part of the material from the trials will be reported in this paper. The remaining data material will be published in later papers, but a good idea of the capabilities of the technology can still be obtained through the results now presented.

Most of the results presented are based on analysis with data where every other access point is available for communication (called base case), figure 5. A comparison is also made against the cases where all access points are available for positioning. Furthermore, the results are mainly based on experiments where a single research subject or a small group participates in the experiment. The diagrams in the paper reporting the results show the same view as the illustration below but with the research subjects' locations inserted.

Figure 5. Available access points for the base case of the results.

Location in the base case with single individuals and with a hand held mobile phone device
In trials 1–3 and 7–9, the research subject moves along the middle of the lanes in the tunnel, i.e. along walkways A and B respectively, see figure 4. In all experiments reported in this section, the research
subject holds his mobile phone device in his hand. Figure 6 and figure 7 report the position of the six research subjects who participated in the six trials. The diagrams indicate whether it is real position, marked with R for the research subject's number (e.g. R170) or W for the Wi-Fi position. In trials 1–3, all subjects walked about 4.1 m from the side of the tunnel.

In trials 7–9, the research subjects walk back to the starting point of the experiment along route B, which in this case is 7.1 m from the side of the tunnel. The tunnel's lanes are in the diagrams between 2.0 m and 9.4 m. The total width of the tunnel is 10.4 m.

![Figure 6. Trial 1–3 in the base case with a hand-held device. W indicates Wi-Fi position and R indicates real position.](image)

![Figure 7. Trials 7–9 in the base case with a hand-held device. W indicates Wi-Fi position and R indicates real position.](image)

It can be observed that there is a relatively clear deviation between the actual (R) position in the tunnel and the one predicted by the Wi-Fi system (W) and the deviation between individual comparisons is difficult to follow (a single R vs. W location). Figure 8 shows the results for trial 1 where the subject's actual locations have been linked to the corresponding Wi-Fi-based locations.
In principle, it never occurs that the real and the Wi-Fi-based position correspond precisely, but there is a certain pattern in the deviation between the two locations during the course of the experiment. At the beginning and at the end of the experimental area, the Wi-Fi positions tend to lean towards the middle of the tunnel. This tendency is also visible in other trials and for other conditions. The first access point for trials 1–3 is located 10 m from the starting point, which means that the Wi-Fi equivalents of the first real positions are based on access points 10, 30 or even 50 m from the starting point, as three signals are used for locating the device.

Considering the tendency in the direction of the deviation illustrated in Figure 8, the mean distance and the associated standard deviation are calculated for the positions that are between the access points used, i.e., between 10 m and 100 m. Mean value and standard deviation (for a sample) were determined for the results of all investigated research subjects and for the entire experimental group in question. Trial group refers to trials that are designed in the same way, e.g. T1–3. Table 1 below reports calculated distances for trials T1–3 and T7–9.

**Table 1. Calculated mean distances between real and Wi-Fi-based position for the base case and handheld mobile device.**

<table>
<thead>
<tr>
<th>Trial No./Subject No.</th>
<th>Locations between 10m and 100 m</th>
<th>Mean value, m</th>
<th>Std. deviation, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1/170</td>
<td>16,6</td>
<td>9,0</td>
<td></td>
</tr>
<tr>
<td>T2/173</td>
<td>25,5</td>
<td>18,2</td>
<td></td>
</tr>
<tr>
<td>T3/165</td>
<td>16,2</td>
<td>14,6</td>
<td></td>
</tr>
<tr>
<td>T1–3</td>
<td><strong>19,4</strong></td>
<td><strong>14,8</strong></td>
<td></td>
</tr>
<tr>
<td>T7/177</td>
<td>19,9</td>
<td>18,5</td>
<td></td>
</tr>
<tr>
<td>T8/163</td>
<td>18,6</td>
<td>10,7</td>
<td></td>
</tr>
<tr>
<td>T9/178</td>
<td>12,2</td>
<td>7,7</td>
<td></td>
</tr>
<tr>
<td>T7–9</td>
<td><strong>16,8</strong></td>
<td><strong>13,2</strong></td>
<td></td>
</tr>
</tbody>
</table>

In a comparison when all positions are used for calculating the average value and when only those between 10 m and 100 m are used, it is found that there is a fringe effect at the edge of the test area that affects the precision of the Wi-Fi technology. However, in most cases the difference is not that great and for the case above with the average value for all positions 20.3 m for tests 1–3 and 19.3 m for tests 7–9, with should be compared with 19,4 m and 16,8 m.
Location in the base case with single individuals and a mobile phone device in the pocket
To investigate the effect of how the mobile phone is stored during locating the device, each research subject carried two devices, one of which was kept in the pocket. The analysis for this has been carried out for trials T1–F3 and T7–F9. Distance between real position and Wi-Fi-based position is reported in table 2. The variation is also reported in the form of the standard deviation. In the column to the right the corresponding results from experiments with handheld devices are presented for a comparison.

Table 2. Calculated mean distances between real and Wi-Fi-based position for the base case and mobile phone device carried in the pocket.

<table>
<thead>
<tr>
<th>Trial No./Subject No.</th>
<th>Locations between 10m and 100 m. Device located in the pocket</th>
<th>Locations between 10m and 100 m. Handheld device.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean value, m</td>
<td>Std. deviation, m</td>
</tr>
<tr>
<td>T1/170</td>
<td>15,8</td>
<td>13,6</td>
</tr>
<tr>
<td>T2/173</td>
<td>20,0</td>
<td>20,4</td>
</tr>
<tr>
<td>T3/165</td>
<td>14,8</td>
<td>8,9</td>
</tr>
<tr>
<td>T1–3</td>
<td>16,8</td>
<td>14,6</td>
</tr>
<tr>
<td>T7/177</td>
<td>16,6</td>
<td>11,1</td>
</tr>
<tr>
<td>T8/163</td>
<td>16,2</td>
<td>11,2</td>
</tr>
<tr>
<td>T9/178</td>
<td>12,4</td>
<td>7,7</td>
</tr>
<tr>
<td>T7–9</td>
<td>15,0</td>
<td>10,0</td>
</tr>
</tbody>
</table>

It seems that the handheld device results in a larger deviation between real location and Wi-Fi-based location. The two devices did also not predict the same location as indicated in figure 9 (for trial 2). In this figure the lines connect locations predicted by the two devises (having the same time stamp) as the subject went along the experimental route. This large deviation is also found for the other investigated trials.

Figure 9. Wi-Fi-based positions for trial 2 in the base case but with a differently held mobile phone device, in the hand or in the pocket, for all time steps in the trial.

Location in the base case with a small group and hand held mobile phone device
The number of people moving in a group can affect the accuracy of Wi-Fi location. In the problem identification before the trials, this variable was noted as one to be included. Several different group constellations were examined during the trials, but only one trial is presented in this paper.
In trial 4, it is investigated when five people in a group move along route A. The positions of the five research subjects are reported in Figure 10. In this case, the people move more laterally while walking along the experimental route compared to the previous cases when basically all walks an identical path.

![Figure 10. Trial 4 in the base case with hand-held device. W indicates Wi-Fi position and R indicates real position, also marked with line.](image)

As can be seen from the figure, the spread is relatively large also in this case. Table 3 reports the mean value and standard deviation of the difference between real position and Wi-Fi-based position for the five people in the trial.

**Table 3. Calculated mean distances between real and Wi-Fi-based position for the base case and handheld mobile device.**

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Locations between 10m and 100 m.</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean value, m</td>
<td>Std. deviation, m</td>
<td></td>
</tr>
<tr>
<td>163</td>
<td>9,6</td>
<td>7,7</td>
<td></td>
</tr>
<tr>
<td>175</td>
<td>14,0</td>
<td>10,6</td>
<td></td>
</tr>
<tr>
<td>177</td>
<td>15,4</td>
<td>10,4</td>
<td></td>
</tr>
<tr>
<td>178</td>
<td>14,3</td>
<td>12,8</td>
<td></td>
</tr>
<tr>
<td>162</td>
<td>16,0</td>
<td>17,0</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>13,9</td>
<td>12,1</td>
<td></td>
</tr>
</tbody>
</table>

**Location in the base case with single individuals, with handheld mobile phone device and stopping in the tunnel**

In trials 27–28 and 30–31, the movement was carried out with an inserted pause. Table 4 reports the accuracy of the positioning for the time the research subject was standing still. Figure 11 illustrates the variation in the calculated position in relation to where the research subjects de facto stood during the break. Three of the research subjects stood at 50 m and the fourth at 60 m.
Table 4. Comparison of mean and standard deviation of difference in distance between Wi-Fi-based position and true position for trials 27–28 and 30–31, standing still research subject.

<table>
<thead>
<tr>
<th>Trial No.</th>
<th>All locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean value, m</td>
</tr>
<tr>
<td>T27</td>
<td>14.5</td>
</tr>
<tr>
<td>T28</td>
<td>11.6</td>
</tr>
<tr>
<td>T30</td>
<td>17.4</td>
</tr>
<tr>
<td>T31</td>
<td>4.7</td>
</tr>
<tr>
<td>All</td>
<td>12.1</td>
</tr>
</tbody>
</table>

Figure 11. Trials 27–28 and 30–31 in the base case with hand-held device. The more heavily marked points indicate the place where the four research subjects stood still. Note that the lower heavily marked point is actually the location of two research subjects (two points in almost the same location).

It can be stated that there is still a significant variation between the real position and the location calculated by the Wi-Fi technology. The variation for an individual research subject is, however, quite large, where the person in trial 31 (subject 162) has a clearly better precision compared to the others who have both a higher average distance and a greater variation in calculated distances.

DISCUSSION

Using wireless technologies is today frequently used to track people for the purpose of surveying areas of interest, duration of stay at certain locations in buildings, etc. It has, however, not been widely explored for the purpose of tracking people in emergency situations and enabling an incident commander to use this information for tactical reasons. Before the experiment, the Wi-Fi technology was deemed as a promising technique to do so. Partly because people in general carry Wi-Fi enabled devices (mobile smart phones), and partly because the owner (at least ideally) does not have to do anything to allow the tracking given that Wi-Fi is enabled. Still, it must be emphasized that the technology is still in an early phase given the stated purpose and type of environment, and much is still needed to determine the characteristics for an optimal performance of the system.

The sample data collected during the experiment, which is presented in this paper, suggest that the Wi-Fi technology alone cannot be used to precisely assess or predict the position of an individual (or a group) in a tunnel. Possibly and expectedly, precision and accuracy may be improved with either even more capable access points or complementing technologies (such as Wi-Fi coupled with Bluetooth).
In the current experiment the selected access points provided a basic type of output data for analysis. It can be expected that with more high-end type of access points a better precision may be achieved. Localization is in the current analysis performed using a trilateration process meaning that the predicted point is determined using differences in distances between devices and access points. A triangulation procedure can in combination most likely enhance the precision, as triangulation uses angular information to predict a position. However, the currently used access points did not have this feature. Using better access points is of course preferred but has to be evaluated with respect to the increased cost if looking from a practical perspective.

Consequently, relying on the current technology in a research based application, i.e., to collect data on people movement to be used for modelling/predictive purposes, does not seem possible. In other words, the Wi-Fi technology alone is not accurate enough to be used for data collection with the purpose to establish, for example, relationships between movement speed and population densities, flow rates through components such as cross sectional emergency exits in tunnels, etc.

The above do, however, not mean that the technology cannot be used to provide value during the operation of a road or rail tunnel, as the need for accuracy is much lower. It must be emphasized that in these facilities, distances to safe locations are typically in the order of a couple to many hundreds of meters. Whereas the results of the experiment demonstrate a difference between the real and by the Wi-Fi technology assessed position around 20 m, this is still well within the expected distance between two emergency exits in a tunnel. The distance is higher than indicated in other studies, however, for different environments.

What is also important for the operator of a road and rail tunnel is the direction the people in the tunnel is moving. Looking at the results and in particular the difference between the predicted and the real positions in the experiment the first impression is that the predicted locations are scattered along the travel paths, cf. figure 8. But looking at the data more precisely there is a trend that the predicted locations follow the subject as he/she moves in the tunnel. This pattern will most likely be clearer in a larger scale, when the distance moved exceeds the range for an access point. Having a longer experimental travel distance the trend would be more obvious and, as mentioned, the distance between emergency exits in a real tunnel can be one magnitude higher.

All the results presented in the paper assumes there is an active communication between the device and the WLAN. This implies the user to have agreed to connect to the tunnel network. In many cases this cannot be expected and a passive connection between the network and the device is likely to be the normal situation. However, the difference in the current experiment conditions would be that the frequency of connections between the device and the network would be lower as the device then talks less often to the network in the passive mode. The ability to predict the specific position using the Wi-Fi technique would not change. But, having less information the ability to determine the precise location and direction of travel of an individual may be affected. Still, having more data points will provide a more certain prediction. The data available from the experiment will enable the analysis of passive versus active communication, hence this remain to be analyzed.

An initial analysis of group movement has been performed. Currently, the results look at the results from individual subject movement. However, there may be reason to investigate how the group’s true positional average compares to the Wi-Fi-based equivalent. This would likely lead to a reduction in uncertainty providing a more precise prediction and need further investigations. This could be valuable information as based on reports from tunnel fire incidents, it is likely that people move in groups.

In the experiment, all the data treatment was done after the experiment was terminated, i.e., the predictions of the subjects' positions were not presented at the time of the experiment. A lot of trial data analyses had to be performed in order to find an analysis technique that provided a reasonable accuracy. This means that there is still room for further refinements of the analysis technique to a) find a better alignment between predicted and real positions, and b) to get the predictions presented
with only a short delay between collection of data and presentation of locations. With such improvements it is reasonable to assume it will be possible to better determine in which direction people are moving and with what speed.

Given an emergency, such as a fire, in a road tunnel such information could thus be used by, for example, a traffic controller to direct the rescue services to a specific location in a parallel service tunnel and to provide information on how to use the forced ventilation to facilitate evacuation and rescue operations. Thus, enabling a prompt, efficient and safe intervention. With regard to the data collected, two aspects are positive in relation to this: 1) accuracy seem to improve when people are still (which they can be expected to be, particularly in the early events of an emergency), and; 2) accuracy does not seem to be particularly affected by the location of the device position (handheld or pocket).

FUTURE RESEARCH

The experiment shows that there are still room for providing a better understanding of the benefit of using Wi-Fi techniques for improving the base for decision for an incident commander in the case of a tunnel fire. The most important would be to find out how to improve the precision of the predicted position for a person carrying a mobile device. Initially there is a need to further clarify important aspects affecting the predictive position accuracy such as the difference between active and passive communication, localization algorithm/technique, etc. In the current experiment a few factors have been included but there is a need to get a better understanding of determining factors. In this effort a theoretical study using a variety of mobile phone devices should be included.

The overall improved accuracy would most likely be performed by using equipment having a better performance, but it can also need additional localization algorithms for predicting the position. Both are most likely to enhance the performance of the technique. In this effort also the use of triangulation as a predicting technique should be explored. The improved performance should also include the ability to determine the direction of movement and preferably strive to get as precise accuracy so the technique could be used for data collection of people movement for modelling purposes.

Another track for future research would be to explore combination of different wireless techniques to enhance the precision. Using both Wi-Fi and for example Bluetooth would be preferred. Using different technologies also put a focus on how to limit localization to relevant devices as the environment will most likely also include Wi-Fi-devices located in cars, tablets and computers.

As the technique to locate people is fairly new, the application of the technique from a practical point of view would also be needed to be investigated. The environment in a road or rail tunnel is very demanding for the electrical equipment is just one such problem needing to be solved. From a practical point of view also the problem of implementing the information gained into the current emergency procedures needs a clear identification of demands and requirements.

CONCLUSIONS

The experiment presented in this paper should be considered as an exploration of the Wi-Fi technology’s ability to locate and track people in a tunnel environment from a practical point of view. It complements earlier, more theoretical studies, related to what should be technically possible with hands on data regarding what is achieved when deployed in a realistic setting. The results indicate that the ability to predict a position for an individual is generally around 20 m on average, or less. It has, furthermore, been shown that the possibility to determine a person's walking direction was fairly good even if the results are associated with a significant uncertainty.

The analysis of the data demonstrates that, in general, and in a set up similar to the test environment (given relatively many access points and active connection to the network), the technology may be used to improve tunnel safety as additional information about the location and approximate number of
people between safe locations can be communicated to, e.g., fire rescue services. In the current form, the technology can, however, not replace traditional methods for data collection of people movement useful for research and modeling purposes. Nonetheless, and as indicated: there are room for future research which may put these conclusions in another perspective.

The findings presented in this paper are of value both when building new and upgrading existing tunnels. In both situations, the technology as such (Wi-Fi) will most likely be available in some form and, hence, it could possibly be used to track people both during normal operation and emergency situations. Knowing where people are, the sizes of groups, and in which direction they are moving is information that today cannot always be communicated via a CCTV-system, particularly not during fires. However, that information is highly important when a traffic commander is to, for example, decide on whether or not to activate a forced ventilation system, and in which direction to blow the smoke, etc. Particularly in bi-directional tunnels, as there is no predetermined “safe” exit direction. Obviously, there seems to be a great potential to upgrade tunnel safety in existing tunnels using relatively simple and inexpensive means based on new technology which may already be, or be planned to, installed.

ACKNOWLEDGEMENT

This project is funded by The Swedish Fire Research Foundation (Brandforsk), a nonprofit organization which instantiate and finance knowledge development within the field of fire safety (project number 319 002).

REFERENCES

Nonlinear analysis of a tunnel slab under a hydrogen explosion

Wenqian Liu¹, Frank Markert¹, Volodymyr Shentsov² & Luisa Giuliani¹
¹Technical University of Denmark, Lyngby, Denmark
²Ulster University, Newtownabbey, United Kingdom

ABSTRACT

Hydrogen explosions consequent to hydrogen-fuelled vehicle (HFV) accidents in a tunnel could cause great losses of lives and property due to its special characteristics, such as high pressure blast waves. Reliable predictions on the structural response of a tunnel impacted by blast waves are crucial to develop effective mitigation technologies to protect the integrity of the structure. This case study conducts a numerical analysis of a tunnel ventilation slab subjected to an explosion wave calculated by a CFD study on this specific scenario. The focus here is the mechanical structural response of a reinforced concrete (RC) slab caused by the pressure time history of the explosion wave in the case tunnel. Two different finite element codes (ANSYS Mechanical APDL and DIANA) are applied comparing the respective results. The effects of the reinforcement diameter, reinforcement position, concrete strength and boundary condition are studied and discussed. Numerical results show that the RC slab suffers significant damage under larger explosive impulses. The influences of reinforcement position and concrete strength on the RC slab deflection are very slight. However, reinforcement diameter and boundary condition play an essential role in the RC slab dynamic response. Improving reinforcement diameter and reducing the freedom of the RC slab can effectively enhance the properties of the RC ventilation slab under hydrogen explosion loads.

KEYWORD: reinforcement concrete, tunnel ventilation slab, hydrogen tank explosion, numerical simulation, parametric analysis

1. INTRODUCTION

1.1 Background

Tunnels are essential infrastructures that can provide a cost-effective solution to direct transport between two locations, e.g., separated by mountains, water, or heavily populated areas of urban cities. However, a tunnel structure may be heavily damaged in case of a severe explosion accident. The resulting pressure time history of the explosion wave inside the tunnel is more severe than comparable explosions in unconfined and/or uncongested environments as in open space due to the close-in effects in the tunnel [1]. For example, a methane explosion that occurred in Qishanyan (QSY) tunnel in China caused the tunnel to collapse and trapped 12 workers [2]. In 2020, a mountain tunnel in Turkey collapsed due to an explosion caused by a gas leak, leading to 11 casualties [3]. In view of the consequences of tunnel accidents, it is crucial to study structural performance under explosion conditions to avoid structure collapse and reduce the potential hazards to public safety.

The main role of the tunnel is to provide normal and safe operation of transport. With the promotion of renewable energy, hydrogen vehicles are expected to be a common transport technology. Compared with conventional vehicles, the hazards from hydrogen vehicle accidents are somewhat different and may include gas explosion scenarios. An initial hydrogen leakage is expected to result in a hydrogen jet fire or hydrogen gas cloud explosion depending on the ignition time. An external fire could lead to a
hydrogen gas tank rupture in case the safety valve provided with any hydrogen pressure tank is malfunctioning. In light of LaFleur’s risk assessment of hydrogen vehicle accidents [4], the highest risk is the hydrogen tank rupture resulting in a blast wave and a fireball. A hydrogen explosion can lead to extremely dangerous impacts due to high energy and overpressure. Nevertheless, the probability of a tank rupture causing a blast wave in a hydrogen vehicle accident is very low (about 0.092%) [5, 6]. As explained before, the severeness of hydrogen explosions in a tunnel is more dangerous than that in the opening surrounding [7], because the explosive wave diameter is possibly larger than the tunnel height or width, and the explosive wave can impinge on the tunnel structure surface [8].

Presently, experimental and numerical analysis are two popular methods to predict the structural dynamic behaviour under explosions. However, owing to the complicated and expensive explosion experiment in a tunnel, FE (finite element) analysis is a preferred tool to investigate the nonlinear dynamic response of the structure. 

For example, Senpei Wang et al. [9] investigated the reinforcement concrete (RC) structures’ response under gas explosions using LS-DYNA based on different parameters, such as concrete compressive strength, reinforcement strength, and section type. The results showed that the RC response is dominated by the tensile membrane determined by the reinforcement steel strength, and different section types lead to different RC responses. M. Buonsanti et al. [10] performed the dynamic response of tunnel walls defining a liquefied petroleum gas (LPG) explosion by adopting ANSYS code, which illustrated that the position of the primary displacement is where the instantaneous impact is. Zhipeng Li et al. [11] studied the dynamic response and damage process of the concrete lining in the tunnel in line with the explosion wave by using LS-DTNA. Their results indicate that the maximum displacement is in 5m of the detonation site region, and the local damage zone developed along the longitudinal and circumferential directions of the concrete lining.

With reference to previous research [12-15], most of the work is concentrated on the explosion of the tunnel’s main structure other than the secondary structures (i.e., a ventilation slab or a smoke duct slab in a tunnel ventilation scheme). And yet secondary structures are easier to collapse under internal tunnel explosion scenarios because of the shortage of supports from surrounding rock or soil mass [16]. In addition, the internal tunnel explosion mainly focuses on typical fuel explosions, e.g., TNT, natural gas, methane, and LPG gas. However, hydrogen is gradually expected to be used in vehicles as an alternate fuel, and the hydrogen tank rupture from a vehicle’s fire is more hazardous than other common fuels due to the expected high explosion pressures. Therefore, to present the characterizing hazards of an explosion from a tank filled with hydrogen in the tunnel, the ventilation slab dynamic response to a hydrogen tank explosion will be investigated in this study.

1.2 Purpose and method
In terms of tunnel structural design, many types of secondary structures are found in a tunnel. In the present case study conducted within the HyTunnel CS project [17], a ventilation slab is chosen as the structure to be investigated. The aim of this study is to investigate if and to what extent a hydrogen tank blast could affect the integrity and functionality of the RC tunnel ventilation slab. Hence, this work first analyses the influence of the hydrogen tank blast impulse on the RC slab and then analyses the effects of different parameters on the RC dynamic response under the hydrogen tank rupture due to external fire. These parameters contain reinforcement diameter, reinforcement position, concrete strength, and RC slab boundary conditions. All analyses are carried out both in ANSYS Mechanical APDL and DIANA, and deflection response results are compared with some standards to forecast if the slab will collapse.

2. IMPLEMENTATION OF FE MODELS

2.1 Concrete material model
An appropriate model of the concrete material, including nonlinear behavior, softening, and cracking, is essential to model the collapse of a concrete element under exceptional loads is of interest. Herein,
the concrete compressive and tensile softening material models implemented in ANSYS and DIANA are the basis.

The ANSYS Mechanical APDL software provides the exponential HSD [18] (hardening, softening, and dilatation) model with Drucker-Prager concrete surface failure (HSD2-DP). This model is therefore used for the concrete material. The HSD2-DP model defines concrete tensile fracture energy, tensile and compressive dilatancy, and compressive and tensile strength. In the DIANA software, a Multi-linear curve model is selected to model the concrete compressive behavior together with the Hordijk tensile model [19] for concrete tensile response modeling. Comparing the stress-strain performance in both software, the Multi-linear curve in DIANA adopts the same stress-strain value of ANSYS. The tensile fracture energy value is defined the same in HSD2 and Hordijk models. Concrete compressive and tensile models in two software can be found in Figure 1.

![Concrete material model in ANSYS and DIANA][18, 19]

In Figure 1, $\Omega_c$ and $\Omega_t$ are the hardening and softening behavior of concrete yield surfaces, $k_{cu}$ is the plastic strain at the transition from power law to exponential softening, $k_{cm}$ is the plastic strain at uniaxial compressive strength, $\Omega_{cl}$ is relative stress at start of nonlinear hardening, $\Omega_{cu}$ is residual relative stress at $k_{cu}$, $\Omega_{cr}$ is the residual compressive relative stress, $\Omega_{tr}$ is the residual tensile relative stress, $G_f$ is concrete tensile fracture energy, $\Delta u_{n,ult}$ is concrete crack width, $f_t$ is concrete tensile strength. In this paper, $\Omega_{cr} = 0.1$, $\Omega_{cl} = 0.4$, $\Omega_{cu} = 0.7$, $k_{cm} = 0.003 - f_c/E_c$, $k_{cu} = 0.0045 - f_c/E_c$, $\Omega_{tr} = 0.01$, where $f_c$ is the concrete compressive strength, $E_c$ is the concrete elastic modulus.

2.2 Steel material model

In both software, steel yield strength, elastic modulus, and ultimate strain adopt the same values. The difference between the two software is the steel material model. In particular, the Multi-linear Kinematic Hardening model is chosen for defining the steel stress-strain curve in ANSYS, while the Von Mises plasticity with plastic strain-yield stress is used in DIANA[20].

2.3 Strain rate effect

The strain rate effect has an essential role in concrete structural dynamic behavior, resulting in material mechanical properties always being different from static loading when concrete structures suffer impacts from explosion waves [21]. Plenty of research indicated that higher strain rates result in higher strength and brittle failure processes [22, 23]. In order to show the material strength increase under a high strain rate, the dynamic increase factor (DIF) is applied to depict the relationship among the static strength, strain rate, and dynamic strength. In this study, DIFs of concrete compressive and tensile strength adopt expressions from CEB [24].

$$DIF_c = \begin{cases} 
\frac{f_{cd}}{f_c} = \left(\frac{\dot{\varepsilon}_c}{\dot{\varepsilon}_{c0}}\right)^{1.026\alpha_s} & \text{for } |\dot{\varepsilon}_c| \leq 30s^{-1} \\
\frac{f_{cd}}{f_c} = \gamma_s \left(\frac{\dot{\varepsilon}_c}{\dot{\varepsilon}_{c0}}\right)^{\frac{1}{3}} & \text{for } |\dot{\varepsilon}_c| > 30s^{-1}
\end{cases}$$

(1)
\[ DIF_t = \begin{cases} f_{td}^{c} = \left( \frac{\dot{\varepsilon}_t}{\dot{\varepsilon}_{t0}} \right)^{1.0165} \delta_s & \text{for } |\dot{\varepsilon}_t| \leq 30s^{-1} \\ f_{td}^{c} = \beta_s \left( \frac{\dot{\varepsilon}_t}{\dot{\varepsilon}_{t0}} \right)^{\frac{1}{3}} & \text{for } |\dot{\varepsilon}_t| > 30s^{-1} \end{cases} \]

Where \( f_{cd} \) is the concrete dynamic compressive strength, \( \dot{\varepsilon}_c \) is the compressive strain rate, \( \dot{\varepsilon}_{c0} = -30 \times 10^{-6} s^{-1} \), \( \alpha_s \) is the coefficient, \( f_{c0} \) is constant and equal to 10MPa, \( \gamma_s \) is the coefficient, \( f_{td} \) is the concrete dynamic tensile strength, \( f_t \) is the concrete static tensile strength, \( \dot{\varepsilon}_t \) is the tensile strain rate, \( \dot{\varepsilon}_{t0} = 3 \times 10^{-6} s^{-1} \), \( \delta_s \) and \( \beta_s \) are coefficients [24].

For the steel bars model, the DIF expression (Eq. (7) and (8)) from Malvar and Crawford [25] is used in this study, where \( \dot{\varepsilon} \) is the strain rate, and \( f_y \) is steel static yield stress.

\[ DIF = \left( \frac{\dot{\varepsilon}}{10^{-4}} \right)^a \]

\[ \alpha = 0.074 - 0.04 \frac{f_y}{414} \]

3 VALIDATION OF THE FE MODEL

3.1 Test study introduction

To validate the dynamic model of an RC structure that suffered an explosion, a simpler model of an RC beam studied in literature was first implemented and simulation results were compared with experimental data reported in Bin Rao [26]. The RC beam was tested with a 13.4kg TNT charge and 1.5 m stand-off distance. The cylindrical explosive was detonated at both ends. The beam was 2.5 m long and had a squared section with 0.2 m side. The concrete was C40 grade and the steel of the longitudinal steel bars was HRB 335, having a yield strength of 466.7MPa.

The RC beam has four 20mm longitudinal bars and average spacing of 150mm for 8mm stirrups. The tested beam was placed in a hole, so that the upper surface of a beam was level with the ground surface. Four rectangular steel plates and nuts are used to constrain the tested beam. In the interest of obtaining the explosive pressure on the beam, three pressure transducers were set parallel to the upper surface of a beam in this test. Furthermore, three displacement transducers were arranged on the tested beam bottom surface to detect the beam deflection response.

3.2 FE models in software

The external explosion pressure wave impact on the structure varies significantly along the structure surface and with time. Thus, it is challenging to map each resulting point pressure of the structure when analyzing the explosive behavior. To simplify the external surface load pattern, uneven loads have been divided into several uniform loads along the structure element surface, as shown in Figure 2. In this FE model, the explosive pressure was then simplified according to the test pressure position of sensors. Thus, the external load is predicted assuming that the overpressure is uniform between the half distance of the adjacent pressure sensors, and the pressure-time curve adopts the central pressure sensors value, as shown in Table 1.
To improve the calculation efficiency and reduce the simulation errors, the FE model was simplified to a 2D model with various uniform pressure. The respective 2D FE model in ANSYS and DIANA are summarized in Table 1. In ANSYS, the concrete is simulated by the PLANE182 element, a four-node element with two degrees at each node. And the reinforcing steel is simulated by the REINF263 element, a two-node element with two degrees of freedom at each node. It is worth noting that REINF263 uses a smeared approach and is defined by a mesh-independent method. In DIANA, the concrete uses a Q8MEM element with four nodes, and steel bars use an L2TRU element with two nodes. For both the FE software, reinforcements are embedded in the concrete and their element sizes are 0.02m. In these two FE models, mass damping ratios are considered in both software, while stiffness damping is only considered in DIANA. The mass matrix multiplier for damping is 0.001 in ANSYS. The Rayleigh damping coefficient for mass matrix is 5/s and factor for stiffness matrix is 10^{-9}s in DIANA.

Notably, the pressure unit is different in ANSYS and DIANA, and the actual input external force should be transformed into new data based on the real surface overpressure. For example, the explosion is applied on the top line of the 2D FE model, and this force is still a pressure which units is MPa in...
ANSYS when using PLANE182 element. But the line pressure unit is N/m in DIANA. Notably, the line pressure in DIANA is obtained by multiplying the real area pressure and the beam width.

![Figure 3 Input external force][26]

In Table 1, P1, P2 and P3 can be found in Figure 3, and P1 is in the beam central part with large peak pressure. The external loads of the RC beam in Figure 3 are from TNT explosion[26]. The mid-span point is the deflection measured point in both software, and this point is in the middle of the bottom surface. Two nodes in the beam bottom surface are fixed in vertical and horizontal directions, and another two in the beam top surface are only fixed in vertical directions, as shown in Table 1.

### 3.3 Comparison of FE results and test data

Figure 4 presents the x-component strain of the RC beam under the last time step in ANSYS. In that element strain contours, the elastic phase of the beam is from -0.000598 to 0.0000984, while other ranges indicate concrete cracking. The positive strain value means the beam is in tension and the negative strain value is the compression. It is worth noting that most of the concrete area is cracking due to tensile failure, only a few part closed to the support is still in elastic after the TNT blast.

![Figure 4 Concrete element failure diagram in ANSYS (X-component strain)]
To validate FE models, deflection time histories extracted from a mid-span point are compared with the test data. Following simulation results from ANSYS and DIANA, deflection responses are shown in Figure 5. It can be seen from Figure 5 that the maximum deflection value in both software is very similar, namely 0.04m in test, 0.037m in ANSYS and 0.0385m in DIANA. Thus, for the peak deflection of the RC beam, the FE models using ANSYS and DIANA compare well and are regarded valid to be applied in the following.

4. FE MODELING OF THE TUNNEL SLAB

4.1 FE model dimension and boundary

On the basis of the background of the HyTunnel CS project [17], the dynamic performance of an RC tunnel ventilation slab is explored in this paper. In this study case, the RC tunnel ventilation slab suffered a pressure wave due to the explosion of a hydrogen tank of 62.4L and 700 bar, with a total mass of 2.5kg in a tunnel with a cross-section area of 83m². This study adopts the hydrogen explosion force obtained through a CFD analysis of a tunnel involved in the HyTunnel CS project [17], the validated against experiments CFD model that was employed for simulation of blast wave is based on [27]. The pressure curve has 2 distinct peaks, the first one is leading shock that first touches the ceiling at 0.01 s and the second is reflected from walls and focusing at the middle of the ceiling hence increased by 50 kPa at 0.015 s.

The RC ventilation slab in a tunnel is simplified to a supported 2D RC beam, as shown in Figure 6. This is because the RC ventilation slab is a simply supported slab along a longitudinal direction of a tunnel, which caused consistent deformation of the whole slab when it suffered external force. Another main reason not mentioned is that the action considered does not vary along the length (most critical point). Based on these assumptions, the problem is planar and can be adequately represented in two dimensions and use of 3D model is less favourable in terms of computational efforts.
In this RC slab, a section of a spaced (150mm) longitudinal bar is extracted to form a simply supported beam with two steel bars. One bar is in the tensile zone; another bar is in the compressive zone. The length of the RC slab is 10m, and the height is 0.35m. It is worth noting that the force from the point that suffered the largest explosion is assumed to apply uniformly to the concrete slab. This is a simplification due to the fact that the maximum pressure recorded at the ceiling above the tank explosion location to account for the conservative estimation of the slab reaction in FEM analysis. As been previously show in [28] the series of blast waves are produced after explosion resulting in reflections and focusing. Authors aware of the physics behind and take this simplifications into account due to difficulty in realisation without two way coupling of CFD and FEM.

Line with the parameters of the concrete slab in the tunnel, Table 2 refers to the fundamental dimension of the 2D simplified supported beam. The concrete grade is C35, and the reinforcing steel is class C with a yield strength 500MPa. The FE model in ANSYS and DIANA can be found in Figure 7. Two nodes on the beam edges are constrained in these two FE models. One node is fixed in a horizontal and vertical direction; another node is only fixed in a vertical direction. The element mesh size of both FE models is 0.5m. The deflection response detected point is point A in two FE models, as shown in Figure 7.

<table>
<thead>
<tr>
<th>Dimension of concrete beam</th>
<th>Concrete cover(m)</th>
<th>Steel bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width(m)</td>
<td>Length(m)</td>
<td>Height(m)</td>
</tr>
<tr>
<td>0.15</td>
<td>10</td>
<td>0.35</td>
</tr>
</tbody>
</table>

![FE model in ANSYS](a)  
![FE model in DIANA](b)

**Figure 7**  
FE models in ANSYS and DIANA

### 4.2 Response of the slab under hydrogen explosion

According to the input pressure [17], the duration (0.024s) of the pressure impact caused by the hydrogen explosion) is shorter than the beam natural period (0.17s), which means that the beam is in the impulsive regime under the hydrogen explosion. When the structure element is in the impulsive regime under external load, the dynamic amplification factor of this structure is lower than one, which indicates that the dynamic response does not depend on the force peak value (152kPa). This means that it is not so important how the hydrogen pressure varies with time and that the structural response is relative to the explosion impulse.

Figure 6b shows that this given hydrogen explosion pressure stops at 0.024s with a pressure of 89 kPa. Thus, three different overpressure time histories (vertical drop, linear drop with the same slope of the last two data, and nonlinear drop) are simulated in this study to investigate the influence of the pressure impulse.

Figure 8 expresses the dynamic displacement response of different pressure waves at the same point (point A) in various software. The dashed line in the input data picture shows the different drop modes, and the solid line is the original hydrogen pressure data from the CFD simulation. The input data in both FE models is the whole line, including the original and drop lines. Regarding the deflection response under different input data, the impulse (area under pressure versus time curve) significantly influences the structure deflection. The larger the impulse value, the higher the slab deflection value.
In Figure 8, the displacement time history is very close between ANSYS and DIANA before the first wave valley in ANSYS arrives. However, the residual deflection of ANSYS is always greater than that value in DIANA. This is attributable to the different concrete material models in the two software. In ANSYS, it is hard to simulate the lower residual strength, and the software can adjust the residual strength based on the convergence, although the input residual strength is very lower. But it is easier to calculate the model with a very low residual strength in DIANA. Therefore, compared with ANSYS Mechanical APDL, DIANA is recommended for use when analysing the nonlinear behaviour of the structure under explosion.

In addition, the time corresponding to the peak displacement value is also delayed, which is larger than the external load duration (0.04s). This also means that a significant delay between the peak of the action and the peak of the response can be expected, as the elastic response of the structure was still growing when the action was ending. Taking Figure 8(b) as an example, the maximum displacement response of the mid-span of the tunnel slab is about 0.225m. Compared with the value in BS 476 [29] and ISO 834-1 [30], it revealed that the displacement is in control, and the slab can resist this explosion pressure without collapsing. However, the smaller residual displacement (0.1m in DIANA and 0.15m in ANSYS) is far from the origin and indicates significant permanent damage. Therefore, the slabs should be retrofitted and reinforced after the explosion to ensure safe use.
5. PARAMETRIC ANALYSIS

In this section, parametric studies are carried out to study the effects of reinforcement diameter, reinforcement position, concrete strength, and boundary conditions on the nonlinear performance of an RC ventilation slab in a tunnel with hydrogen explosion loads. Deflection time histories are compared to investigate the RC slab nonlinear behaviour. Furthermore, all of the displacement responses are obtained from two software, ANSYS and DIANA. Three reinforcement diameters (i.e., 12mm, 16mm, 20mm), three reinforcement positions (i.e., 25mm, 40mm, 55mm), and three concrete strengths (i.e., C25, C35, C45) are considered into 9 cases with two software. FE models have the same mesh size and material models for the parametric analysis in chapter 2. The input pressure is selected from the CFD data with a linear drop, see Figure 8(b). All deflection time histories are extracted from the point A on the slab bottom surface, which is the same point as chapter 4.

5.1 Influence of reinforcement

Figure 9 shows the deflection time history of the RC slab with different steel bar diameters. The difference in maximum deflection between the two software increases with the steel bar diameter decrease. Moreover, the smaller the steel bar diameter, the larger the maximum mid-span deflection. For example, when the reinforcement diameter is 12mm, the maximum displacement is 0.315m and 0.29m in DIANA and ANSYS, respectively, which is larger than 0.175m in DIANA and 0.165m in ANSYS when the bar diameter is 20mm. This phenomenon is caused by the RC slab tensile membrane effect, and the RC slab is easier to collapse when the steel bar diameter is small. Thus, in the case of meeting the design code, using a large-diameter steel bar is suggested in practice engineering.

![Figure 9 Deflection time history in different reinforcement diameters](image)

5.2 Influence of reinforcement position

The reinforcement position in this section indicates the distance between the concrete surface and the steel bar center, and the beam section size is the same as in chapter 4. The displacement time histories under different reinforcement positions can be seen in Figure 10. The maximum deflection in distinct cases is very close, and the deflection has a little improvement with the distance between the concrete surface and the steel bar center decreasing, which means that the reinforcement position is not the dominant influence factor. Compared with the two software, it can be seen that the residual deflection of ANSYS is higher than that in DIANA. Both the residual deflection in ANSYS and DIANA exceed 0.1m. Thus, the RC slab is damaged under this type of hydrogen explosion load, and this damage to the slab is permanent.
5.3 Influence of concrete strength

According to Figure 11, the deflection time histories curves for different concrete strengths almost overlapped with each other in the same software. For example, the maximum displacement is around 0.225m in DIANA, although the concrete grade changes from C25 to C45. Furthermore, the maximum deflection has a little discrepancy with concrete strength in ANSYS, from 0.21m to 0.219m. Hence, it can be concluded that the influence of concrete strength on the middle point deflection of the RC slab is minor.

5.4 Influence of boundary condition

In real engineering applications, the boundary of an RC ventilation slab in the tunnel depends on the construction technology. Thus, there are many kinds of boundary conditions for the RC slab. Herein, four different boundary conditions are discussed in this section, as shown in Figure 12. In Figure 12, support 1 indicates that the node is constrained in a vertical and horizontal direction, and support 2 demonstrates that the node is constrained in a vertical direction.
RC slab middle point displacement responses under various boundaries are presented in Figure 13. The deflection time histories of boundary (a) and (b) in the same software are almost overlapped. It is because of the similar natural period of the RC slab under boundaries (a) and (b). Depending on the maximum deflection of these four boundary conditions, the RC slab under boundary (a) and (b) has the largest value, followed by boundary (d), and the minimum value is shown in boundary (c). The reason for this phenomenon is that the natural period is different in these boundary conditions. Under boundary (c), the RC slab with less freedom has the smallest natural period and largest stiffness among these boundary conditions, which leads to lower deflection when the external load is the same.

Figure 13  Deflection time history of different boundary conditions in Figure 12

6. CONCLUSION

In this paper, the nonlinear performance of the RC ventilation slab under a hydrogen tank explosion is studied by numerical analysis with two software. The conclusions obtained from this study are summarized as follows:

(1) The simplified 2D FE models are developed in ANSYS and DIANA, and these FE models are validated by comparing them with experimental data. These numerical models can be used to predict the RC structure deformation under explosions.

(2) In terms of the RC ventilation slab construction technology, a 2D simplified supported beam can substitute a 3D simplified supported ventilation slab in a tunnel.

(3) Under a hydrogen tank explosion, the RC ventilation slab deflection is relative to the explosion impulse when the RC slab is in the impulsive regime. And the larger the impulse, the greater the RC slab deflection. Furthermore, slabs should be retrofitted and reinforced after an explosion to ensure safe use when the external impulse is very larger.
(4) Parametric analysis states that the reinforcement diameter and structure boundary conditions have a significant influence on the structure’s dynamic performance. Increasing the reinforcement diameter or reducing the freedom of the structures can reduce structural deformation to some extent. However, the effects of reinforcement position and concrete strength on structural deflection are limited.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support provided by the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 826193. The authors gratefully acknowledge the support from the European Union’s Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

REFERENCES

3. Negligence in tunnel collapse that killed 11 workers was covered up: Turkish court of accounts. 2021: https://stockholmcf.org/negligence-in-tunnel-collapse-that-killed-11-workers-was-covered-up-turkish-court-of-accounts/.
18. I, A., ANSYS Mechanical APDL Material Reference. 2022, ANSYS, Inc


Explosions in road tunnels Part 3: Target failure probability and design values

Mirjam Nelisse & Ton Vrouwenvelder
TNO Netherlands Organisation for Scientific Research, Delft, The Netherlands

ABSTRACT

With the introduction of the Eurocodes [1-6], countries are encouraged to take into account explosion loads in the design of their road tunnels. From “Explosions in road tunnels, Part 1: A study into the explosion scenarios” [7] it has been concluded that 1) the loads as mentioned in the Eurocode are not representative for the total spectrum of explosion loads and 2) based on the Eurocode it is not possible to design tunnels satisfactory for explosion loads. To be able to design tunnels for explosions, it is necessary to have an understanding of all the possible explosion scenarios that can take place, the probability of occurrence of these scenarios and their consequences in terms of pressure and impulse. In “Explosions in road tunnels, Part 2: A quantitative risk analysis” [8] a quantitative risk analysis (QRA) has been performed, resulting in an overview of all possible LPG induced scenarios and their respective risk. In this “Part 3: target failure probability and design values”, we present a method to calculate the design values for the peak pressure and impulse, based on an economic analysis [9,10]. Given the Quantitative Risk Analysis [8] as basis, the following steps are taken:

1. Determining the explosion characteristics for the various scenarios in terms of peak pressures and impulses. This was done on the basis of existing reports and, where necessary, on estimates;
2. Determining the desired target failure probability. The target failure probability has been determined based on a simple economic consideration. No complex calculations have been done and available literature has been used instead, including the JCSS Probabilistic Model Code;
3. Determining the design values for the loads, depending on some relevant parameters (importance, type of traffic, length) and the conditions to which this applies. This has been done based on a relatively simple analysis.

The research has resulted in an overview of the explosion characteristics of the various explosions that can occur with an LPG truck in a tunnel. The explosion characteristics are shown in Table 10. The target failure probability that has been derived based on an economic analysis is \(1.2 \times 10^{-3}\) per year and \(1.3 \times 10^{-2}\) over the lifetime. The design values for the load is shown are derived based on a simple analysis and is shown in Figure 5.

Research into explosions in tunnels has been carried out over the course of several years, which in this (final) publication has led to a first draft text for the ROK for the design of category A tunnels for an explosion load as a result of the transport of LPG in bulk. The design values that are recommended for these specific conditions concern a dynamic peak pressure of 400 kPa and an impulse of 20 kPa·s.

KEYWORDS: Explosions, road tunnels, scenarios, quantitative risk analysis, QRA, probability of occurrence, consequences, pressure, impulse, peak pressure, design value, target failure probability, Eurocode, accidental actions, exceedance probability, reliability, economic analysis
INTRODUCTION

With the introduction of the Eurocodes on Accidental Actions EN1991-1-7 [1-6], countries are encouraged\(^1\) to take into account explosion loads in the design of their road tunnels. From “Explosions in road tunnels, Part 1: A study into the explosion scenarios” [7] has been concluded that 1) the loads as mentioned in the Eurocode are not representative for the total spectrum of explosion loads and 2) based on the Eurocode it is not possible to design tunnels satisfactory for explosion loads. To be able to design tunnels for explosions, it is necessary to have an understanding of all the possible explosion scenarios that can take place, the probability of occurrence of these scenarios and their consequences in terms of pressure and impulse. In “Explosions in road tunnels, Part 2: A quantitative risk analysis” [8] a quantitative risk analysis (QRA) has been performed, resulting in an overview of all possible LPG induced scenarios and their respective risk. In this (last) “Part 3: target failure probability and design values”, we present a method to calculate the design values for the peak pressure and impulse, based on an economic analysis [9,10].

Aim

The goal of the research presented in this paper, is to determine a desired target failure probability and the resulting design values for the explosion load. Based on these results, countries are able to take into account realistic explosion loads in the design of their tunnels and formulate regulation for the design of tunnels. The target failure probability should be based on a consideration of on the one hand the costs necessary for the required strength of the structure against explosions and on the other hand of the costs of damage or even collapse and rebuilding of the tunnel. Since the Eurocodes govern the design of tunnels for explosions, we have used the reliability approach in the Eurocodes to also base the economic analysis on. We assume that the collapse of the tunnel does not result in more casualties than the casualties as a result of the explosion itself.

Approach and methods

Given the Quantitative Risk Analysis [8] as basis, the following steps are taken:

1. Determining the explosion characteristics for the various scenarios in terms of peak pressures and impulses. This was done on the basis of existing reports and, where necessary, on estimates;
2. Determining the desired target failure probability. The target failure probability has been determined based on a simple economic consideration. No complex calculations have been done and available literature has been used instead, including the JCSS Probabilistic Model Code;
3. Determining the design values for the loads, depending on some relevant parameters (importance, type of traffic, length) and the conditions to which this applies. This has been done based on a relatively simple analysis.

EUROCODES

The Eurocodes, in particular EN 1990 and EN 1991 in principle give directions with respect to the target values for a safe and economic design. The next paragraphs show the applicable directions for this particular subject.

The basis for design EN 1990

In the Eurocode the following paragraphs from EN 1990 [1] are of importance:

\(^1\) Citation: (1)P Explosions shall be taken into account in the design of all parts of the building and other civil engineering works where gas is burned or regulated, or where explosive material such as explosive gases, or liquids forming explosive vapour or gas is stored or transported (e.g. chemical facilities, vessels, bunkers, sewage constructions, dwellings with gas installations, energy ducts, road and rail tunnels). Furthermore the Eurocode states that: (4) For construction works classified as CC2 or CC3, key elements of the structure should be designed to resist actions by either using an analysis based upon equivalent static load models, or by applying prescriptive design/detailing rules. Additionally for structures classified as CC3 a dynamic analysis should be used. Tunnels are usually classified as CC2 or CC3 constructions.
2.1 (1)P: “A structure shall be designed and executed in such a way that it will, during its intended life, with appropriate degrees of reliability and in an economical way:
– sustain all actions and influences likely to occur during execution and use, and
– remain fit for the use for which it is required”
This article poses requirements on the economical analysis in the design of a structure.

2.1 (4)P: “A structure shall be designed and executed in such a way that it will not be damaged by events such as:
– explosion,
– impact, and
– the consequences of human errors,
to an extent disproportionate to the original cause”.
This article draws the relation between the size of the explosion and the cause thereof and refers in the notes to EN1991-1-7 and recommends a project specific analysis.

2.2 (3) “The choice of the levels of reliability for a particular structure should take account of the relevant factors, including:
– the possible cause and/or mode of attaining a limit state;
– the possible consequences of failure in terms of risk to life, injury, potential economical losses;
– public aversion to failure;
– the expense and procedures necessary to reduce the risk of failure”.
This article relates to the influence of the consequences and the costs of prevention. In the note is referred to Annex B, which is limited to the consequence classes.

In the (informative) Annex B [1] the following definition has been given of CC3 (Consequence class 3): “High consequence for loss of human life, or economic, social or environmental consequences very great”. As examples are given grandstands, or public buildings where consequences of failure are high (e.g. a concert hall).

The Netherlands Guidelines for the Design of Engineering Works (ROK) [11] contain requirements that the design and implementation of a new engineering structure, such as a bridge, lock or tunnel, must meet. The ROK also applies to new parts of existing structures or if structures are expanded. The ROK contains amendments, additions and explanations to the Eurocodes with National Annexes for the new construction of all structures that are commissioned by The Dutch Ministry of Infrastructure (Rijkswaterstaat). In the ROK tunnels “in and under highways and under main waterways are classified as Consequence Class 3.

A possible alternative would be Consequence Class 2. This class is defined as: “Medium consequence for loss of human life, economic, social or environmental consequences considerable”. Examples are residential and office buildings, public buildings where consequences of failure are medium (e.g. an office building).

In Annex B of [1] Reliability classes are mentioned: RC1, RC2 and RC3. These can be associated with the three consequence classes CC1, CC2 and CC3. Table B3 gives recommended minimum values for the reliability index $\beta$ associated with reliability classes.

<table>
<thead>
<tr>
<th>Reliability Class</th>
<th>Minimum value for $\beta$ (ultimate limit states)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 year reference period</td>
</tr>
<tr>
<td>RC3</td>
<td>5.2</td>
</tr>
<tr>
<td>RC2</td>
<td>4.7</td>
</tr>
<tr>
<td>RC1</td>
<td>4.2</td>
</tr>
</tbody>
</table>
The accidental actions EN 1991

In the Eurocode EN-1991-1-7 [6] the following paragraphs are relevant:

3.1 (2) note 4: “Notional values for identified accidental actions (e.g. in the case of internal explosions and impact) are proposed in this part of EN 1991. These values may be altered in the National Annex or for an individual project and agreed for the design by the client and the relevant authority”.

3.1 (2) note 5: For some structures (e.g. construction works where there is no risk to human life, and where economic, social or environmental consequences are negligible) subjected to accidental actions, the complete collapse of the structure caused by an extreme event may be acceptable. The circumstances when such a collapse is acceptable may be agreed for the individual project with the client and the relevant authority”.

3.2 of the National Annex [10]: “The general target level of the acceptable failure probability in exceptional design situations is 10^{-5} per year. A distinction based on the consequences of failure is recommended”.

3.4 (2) of EN-1991-1-1-7: “Accidental design situations for the different consequence classes given in 3.4 (1) may be considered in the following manner for CC3: an examination of the specific case should be carried out to determine the level of reliability and the depth of structural analyses required. This may require a risk analysis to be carried out and the use of refined methods such as dynamic analyses, non-linear models and interaction between the load and the structure. To the opinion of TNO a risk analysis should be executed in this particular case.

COST OPTIMIZATION

Reliability indices

We take the values from Table 2 as a starting point. The last line contains the reliability indices from the Eurocode [2, page 87, Table B2]. It is assumed on basis of comparison to other calculations that they belong to the category “Low cost”. Eurocodes lack the possibility to take the costs of safety measures into account. Therefore Table 2 has been enlarged with two rows for medium and high costs of safety measures. Tunnels are foreseen to be in the combination of CC3 and high costs. To enlarge the table we have used steps of 0.5 for the betas. In that way a structure is formed that has also been used in ISO 2394 [12] and Rackwitz [13].

Table 2: Reliability indices (last line according to Eurocode [1])

<table>
<thead>
<tr>
<th>Lifetime (50 years)</th>
<th>CC1</th>
<th>CC2</th>
<th>CC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>High costs</td>
<td>2.3</td>
<td>2.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Medium costs</td>
<td>2.8</td>
<td>3.3</td>
<td>3.8</td>
</tr>
<tr>
<td>Low costs</td>
<td>3.3</td>
<td>3.8</td>
<td>4.3</td>
</tr>
</tbody>
</table>

When we transform Table 2 into annual values, we get Table 3. For explosions in tunnels we should probably lower from 5.1 (standard Eurocode, RCL/CC3, yearly basis, see Table 4) to 4.3 on yearly basis (from 4.3 to 3.3 on lifetime basis).

Table 3: Reliability indices per year (last line according to Eurocode [1])

<table>
<thead>
<tr>
<th>Yearly basis</th>
<th>CC1</th>
<th>CC2</th>
<th>CC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>High costs</td>
<td>3.5</td>
<td>3.9</td>
<td>4.3</td>
</tr>
<tr>
<td>Medium costs</td>
<td>3.9</td>
<td>4.3</td>
<td>4.7</td>
</tr>
<tr>
<td>Low costs</td>
<td>4.3</td>
<td>4.7</td>
<td>5.1</td>
</tr>
</tbody>
</table>

We compare the Eurocode based table with the reliability indices used in ISO [12] and JCSS [14] (Table 4).
Table 4: Tentative target reliabilities (one year reference and ULS, based on economic optimization)

<table>
<thead>
<tr>
<th>Yearly basis</th>
<th>CC1</th>
<th>CC2</th>
<th>CC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>3.1</td>
<td>3.3</td>
<td>3.7</td>
</tr>
<tr>
<td>Medium</td>
<td>3.7</td>
<td>4.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Small</td>
<td>4.2</td>
<td>4.4</td>
<td>4.7</td>
</tr>
</tbody>
</table>

The reliability indices based on the Eurocode turn out to be a little higher in all cases and therefore a little more safe (lower probability of failure) than the values used in ISO and JCSS. We choose a conservative approach as a starting point and decide to continue with the values from Table 3.

**Costs**

An alternative approach is to calculate the values of the reliability indices based on a cost function. Table 5 shows the calculation of the background of these values, assuming the following cost function:

\[ C_{\text{tot}} = [C_0 + C_1 \gamma] + P(F) \frac{C_s}{r} \]

in which:
- \(C_{\text{tot}}\) = total capitalized costs
- \(C_0\) = basic construction costs
- \(C_1\) = construction cost gradient
- \(C_s\) = damage costs in case of failure
- \(r\) = annual interest
- \(\gamma\) = (central) safety factor
- \(P(F)\) = annual probability of failure

The probability of failure is equal to \(P(Z<0)\) with \(Z = R - S\), where \(R\) represents the strength (resistance) and \(S\) represents the load (solicitation). In this section, normal distributions are assumed for \(R\) and \(S\) with numerical values chosen: \(\mu(S) = 1, \mu(R) = \gamma, V(R) = 0.1\) and \(V(S) = 0.2\).

The calculations are made for \(C_s = 100, 1000\ and \(10000\), corresponding to CC1, CC2 and CC3. \(C_0=10\) has been taken for the basic construction costs. For \(C_1\) is taken \(C_1= 100, 10\ and \1\), corresponding to relative costs of safety being high, medium and low. All these costs only have relative significance, not absolute ones. A graphical presentation of the cost optimization from Table 5 is given in Figure 1.

---

2 Based on table G4 from [12] and table 1 from [14]
3 The value 1 for \(\mu(S)\) is an arbitrary chosen ratio. The value \(V(R) = 0.1\) is a generally accepted value in the Probabilistic Model code of JCSS [8]
The bottom 3 x 3 lines of Table 5 show the combinations of RC and CC. The minimum cost combinations are shaded; the optimal β value is then higher in that column. The resulting table of reliability coefficients then becomes as follows:

<table>
<thead>
<tr>
<th>Life time (50 year)</th>
<th>CC1</th>
<th>CC2</th>
<th>CC3</th>
<th>Yearly basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC High</td>
<td>2.7</td>
<td>3.5</td>
<td>4.0</td>
<td>RC High</td>
</tr>
<tr>
<td>RC Medium</td>
<td>3.5</td>
<td>4.0</td>
<td>4.5</td>
<td>RC Medium</td>
</tr>
<tr>
<td>RC Low</td>
<td>4.0</td>
<td>4.5</td>
<td>5.1</td>
<td>RC Low</td>
</tr>
</tbody>
</table>

Tunnels fall into the high cost and high damage category (RCH/CC3) and according to Table 6 have an optimal beta of 5.0 on an annual basis. When we compare the results from Table 6 with Table 7, it appears that the beta from the Eurocode is lower and therefore allows a higher probability of failure. The calculation with the cost consideration function thus broadly confirms the previous analysis, but does not contribute to a defensible further reduction of the beta.
Table 7: Reliability indices based on the Eurocode (Table 2 and Table 3 combined)

<table>
<thead>
<tr>
<th>Lifetime (50 jaar)</th>
<th>CC1</th>
<th>CC2</th>
<th>CC3</th>
<th>Yearly basis</th>
<th>CC1</th>
<th>CC2</th>
<th>CC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>High costs</td>
<td>2.3</td>
<td>2.8</td>
<td>3.3</td>
<td>High costs</td>
<td>3.5</td>
<td>3.9</td>
<td>4.3</td>
</tr>
<tr>
<td>Medium costs</td>
<td>2.8</td>
<td>3.3</td>
<td>3.8</td>
<td>Medium costs</td>
<td>3.9</td>
<td>4.3</td>
<td>4.7</td>
</tr>
<tr>
<td>Low costs</td>
<td>3.3</td>
<td>3.8</td>
<td>4.3</td>
<td>Low costs</td>
<td>4.3</td>
<td>4.7</td>
<td>5.1</td>
</tr>
</tbody>
</table>

At most, given that there are no (additional) casualties due to the collapse of the tunnel, we would perhaps drop even further in the target safety level for some tunnels by placing the tunnels under CC2/RCH. The beta then moves to 3.9 on an annual basis (2.8 on a lifetime basis)

Optimization

Until now a load with a normal distribution has been assumed. However, many extreme value processes, such as the occurrence of explosions in tunnels, but also, for example, the probability of extreme high water levels or major fires [17], have an exponential probability distribution. In other words, there is a linear relationship between the load (peak pressure) and the logarithm of the recurrence time.

The probability distribution (given an explosion) for the peak pressure can be written as (see next chapter):

\[ F(p) = \begin{cases} 1 - \exp\left(-\frac{(p-a)}{b}\right) & \text{for } p > 100 \text{ kPa} \\ 0 & \text{for } p < 100 \text{ kPa} \end{cases} \]

with \(a = 100 \text{ kPa}\); from \(F(p) = 10^{-2.6}\) for \(p = 600 \text{ kPa}\) it follows that \(b = 100 \text{ kPa}\).

For this distribution holds that the average pressure (given an explosion) \(m(p) = a + b = 200 \text{ kPa}\) and the standard deviation \(s(p) = b = 100 \text{ kPa}\).

Because the load now has an exponential distribution instead of a normal distribution, the probability calculation is slightly different. With a good approximation:

\[ P(F) = \exp \left[- \left\{ \frac{m(R) - a}{b} + \frac{1}{2} \left\{ \frac{s(R)}{a} \right\}^2 \right\} \right] \]

Because the spreadsheet (Table 9) uses the normalized value \(m(S) = 1\), we have to divide the pressures in the calculation by 200 kPa:

\[ S = \frac{p}{200} \]

Resulting in \(a = 0.5\) en \(b = s(S) = 0.5\); \(P(F)\) will be:

\[ P(F) = \exp \left[- \left\{ \frac{m(R) - 0.5}{0.5} + \frac{1}{2} \left\{ \frac{s(R)}{0.5} \right\}^2 \right\} \right] \]

This is the conditional probability of failure (i.e. given the occurrence of an explosion); the outcome must therefore be multiplied by the probability of an explosion, being equal to 0.017 for the lifetime.

Using a calculation procedure comparable to the one in the section on costs, we then find the optimal beta values for the lifespan and the values converted to an annual basis (see also Table 9 and Figure 2) presented in Table 8.
Table 8: Optimalisation reliability indices

<table>
<thead>
<tr>
<th>lifetime</th>
<th>CC1</th>
<th>CC2</th>
<th>CC3</th>
<th>Year basis</th>
<th>CC1</th>
<th>CC2</th>
<th>CC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCH</td>
<td>2.1</td>
<td>2.4</td>
<td>3.2</td>
<td>RCH</td>
<td>3.6</td>
<td>3.8</td>
<td>4.3</td>
</tr>
<tr>
<td>RCM</td>
<td>2.4</td>
<td>3.2</td>
<td>3.8</td>
<td>RCM</td>
<td>3.8</td>
<td>4.3</td>
<td>4.8</td>
</tr>
<tr>
<td>RCL</td>
<td>3.2</td>
<td>3.8</td>
<td>4.2</td>
<td>RCL</td>
<td>4.3</td>
<td>4.8</td>
<td>5.2</td>
</tr>
</tbody>
</table>

The results differ slightly from the earlier cost function, but the β values found are equal to those in the Eurocode. Let us assume an optimal β value on an annual basis of 4.3.

Table 9: Calculation for the determination of the reliability index based on cost minimisation.

<table>
<thead>
<tr>
<th>j</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>β</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>α</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>x</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>c</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>p</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>q</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>r</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>s</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 2: Reliability index for an optimisation based on the probability density function for explosion pressures

Resulting target failure probability

Table 8 was ultimately calculated on the basis of the optimized cost function in the section on optimization. For tunnels we initially assume CC3 and RC3, resulting in an annual β of 4.3.

When we then multiply β by the standard value for α for load parameters which is 0.7 [5], we arrive at αβ = 3.03. The associated probability of exceedance for the design value of the load P(p>pd) is therefore 1.2·10⁻³ per year and therefore 1.3·10⁻² over the lifetime.

261
CALCULATION OF PEAK PRESSURE AND IMPULSE

Introduction and starting points
Based on the event tree approach from [8], the consequences were estimated in terms of the type of explosion. The peak pressure and impulse of the type of explosion is estimated in this chapter. The following principles have been used for our “reference tunnel”:

- Tunnel length: 1000 m;
- Cross section: 13.5 x 5 = 67.5 m²;
- Ventilation speed: 2 m/s (in the direction of traffic);
- Accident location: middle of the tunnel;
- Tank: LPG truck with 60 m³ tank with a maximum capacity of 50 m³ LPG;
- Ignition gas explosions: worst case moment, at the maximum length of the explosive gas cloud.

The accident location is the most unfavorable and therefore conservative location at the beginning of the tunnel. However, few calculations are available for this location, which is why the middle of the tunnel was chosen. The calculations in [15] are also based on the middle of the tunnel.

Because calculations are not part of this study, an estimate has been made based on existing and available calculations. This means that in a number of cases calculations were used in which the length or cross-section of the tunnel differs from that used as the starting point for this study. Most calculations have been made for a cross section of 72 m² and even 130 and 210 m². However, we have to use these results for estimating the peak pressures of BLEVEs and GEEs, because no alternatives are available.

For a complete and consistent set of data, a large part of the calculations would have to be performed for the current assumptions. This improvement is definitely recommended for the future.

Explosion scenarios
The normative explosions are:

- Gas Expansion Explosion for “empty tank” (GEE0), half full (GEE50) and full tank (GEE100)
- Gas Explosion Instantaneous for “empty tank” (GEI0), half full (GEI50) and full tank (GEI100)
- Gas Explosion Continuous release for “empty tank” (GEcont,0), half full (GEcont,50) and full tank (GEcont,100)
- BLEVE (T > 326K) for “empty tank (BLEVE0), half full (BLEVE50) and full tank (BLEVE100)

In addition, a number of combinations of the above effects are also possible.

The temperature at which the consequences occur is also important. A BLEVE can only occur above the homogeneous nucleation temperature (for LPG that is 326 K). In the TNO calculations one has applied 326 K and 340 K (the 340 K in order to check the sensitivity). Because the dataset with 326 K is larger than the dataset with 340 K, it was decided to use the peak pressures at 326 K. These peak pressures are therefore the minimum peak pressures at which a BLEVE can occur. Further refinement is possible.

In the event tree [8] this choice is shown as follows:
- If a fire starts and a temperature increase larger than 50 degrees occurs, the consequences will occur at 326 K (represented by @326K);
- If no fire and/or a temperature increase less than 50 degrees occurs, the consequences will occur at 288 K (represented by @288 K).

---

4 BLEVE: Boiling Liquid Expanding Vapour Explosion.
5 Gas Expansion Explosion
6 We assume the ambient temperature to be 288 K.
Note: BLEVEs and GEEs are both physical explosions. Because calculations are now based on 100%, 50% and 1% LPG tank filling, combinations of explosion types may occur. We have never calculated this and can therefore only make a first-order estimate.

**Peak pressure and impulse**

Table 10 provides an overview of the peak pressures and impulses used for the explosion consequences from the event tree [8]. The identification of the consequence is given in the first column, followed by the description in the second column. In the third and fourth column, the peak pressure and impulse associated with the effect in question are listed. The source of these numbers is indicated in column 5 and column 6 refers to an explanation of the peak pressure and impulse used. The numbers referred to are listed below the table (under the heading “Explanation”).

**Table 10: Overview of peak pressures and impulses used for explosion consequences.**

<table>
<thead>
<tr>
<th>ID</th>
<th>Consequences</th>
<th>Peak pressure (kPa)</th>
<th>Impulse (kPa.s)</th>
<th>Source</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CQ0</td>
<td>No consequences</td>
<td>0</td>
<td>0</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>CQ1</td>
<td>Jet fire</td>
<td>0</td>
<td>0</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>CQ2</td>
<td>Gas cloud, continuous release</td>
<td>0</td>
<td>0</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>CQ3</td>
<td>Gas cloud, instantaneous release</td>
<td>0</td>
<td>0</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>CQ4</td>
<td>GEE, 0 @288K</td>
<td>200</td>
<td>2</td>
<td>[15]</td>
<td>2</td>
</tr>
<tr>
<td>CQ5</td>
<td>GEE, 0 @326K</td>
<td>500</td>
<td>6</td>
<td>[15]</td>
<td>2</td>
</tr>
<tr>
<td>CQ6</td>
<td>GEE, 50 @288K</td>
<td>300</td>
<td>10</td>
<td>EJ</td>
<td>3</td>
</tr>
<tr>
<td>CQ7</td>
<td>GEE, 100 @288K</td>
<td>300</td>
<td>20</td>
<td>EJ</td>
<td>4</td>
</tr>
<tr>
<td>CQ8</td>
<td>GEE, 0 @288K + GE, I,0 (a.g.v. GEE)</td>
<td>575</td>
<td>38</td>
<td>EJ</td>
<td>1, 5</td>
</tr>
<tr>
<td>CQ9</td>
<td>GEE, 50 @326 K + BLEVE 50</td>
<td>600</td>
<td>30</td>
<td>EJ</td>
<td>5</td>
</tr>
<tr>
<td>CQ10</td>
<td>GEE, 100 @326 K + BLEVE 100</td>
<td>600</td>
<td>50</td>
<td>EJ</td>
<td>1, 5</td>
</tr>
<tr>
<td>CQ11</td>
<td>GEE, 50 @288K + GE, I, 50 (a.g.v. GEE)</td>
<td>300</td>
<td>20</td>
<td>EJ</td>
<td>1, 6</td>
</tr>
<tr>
<td>CQ12</td>
<td>GE, I, 0</td>
<td>575</td>
<td>38</td>
<td>[15]</td>
<td>-</td>
</tr>
<tr>
<td>CQ13</td>
<td>GE, I, 50</td>
<td>150</td>
<td>20</td>
<td>[15]</td>
<td>-</td>
</tr>
<tr>
<td>CQ14</td>
<td>GE, I, 100</td>
<td>130</td>
<td>17,5</td>
<td>[15]</td>
<td>-</td>
</tr>
<tr>
<td>CQ15</td>
<td>GE, cont, 0 (a.g.v. gas cloud)</td>
<td>0</td>
<td>0</td>
<td>[15]</td>
<td>-</td>
</tr>
<tr>
<td>CQ16</td>
<td>GE, cont, 50 (a.g.v. gas cloud)</td>
<td>1800</td>
<td>275</td>
<td>EJ</td>
<td>1, 7</td>
</tr>
<tr>
<td>CQ17</td>
<td>GE, cont, 100 (a.g.v. gas cloud)</td>
<td>1800</td>
<td>275</td>
<td>[15], EJ</td>
<td>1</td>
</tr>
<tr>
<td>CQ18</td>
<td>BLEVE, 0</td>
<td>500</td>
<td>6</td>
<td>[15]</td>
<td>8</td>
</tr>
<tr>
<td>CQ19</td>
<td>BLEVE, 50</td>
<td>600</td>
<td>30</td>
<td>EJ</td>
<td>1, 9</td>
</tr>
<tr>
<td>CQ20</td>
<td>BLEVE, 100</td>
<td>600</td>
<td>50</td>
<td>[15]</td>
<td>10</td>
</tr>
<tr>
<td>CQ21</td>
<td>GEE, 50 @326K</td>
<td>600</td>
<td>30</td>
<td>EJ</td>
<td>1</td>
</tr>
<tr>
<td>CQ22</td>
<td>GEE, 100 @326K</td>
<td>600</td>
<td>50</td>
<td>EJ</td>
<td>1</td>
</tr>
<tr>
<td>CQ23</td>
<td>GEE, 100 @288 K + GE, I, 100</td>
<td>300</td>
<td>20</td>
<td>EJ</td>
<td>1</td>
</tr>
</tbody>
</table>

Note 1: CQ0 = CQ19 = CQ21. CQ20 = CQ22. CQ5 = CQ18. May be merged.

Note 2: CQ9 and CQ10 can both be followed by a gas explosion provided ignition occurs. The GE effects conform to CQ13 and CQ14 and are therefore lower than those of the GEE and BLEVE effects (the latter are therefore normative).

Source:
- [15]. The peak pressures and impulses are based on TNO-models [15]. It should be noted that the calculations from [9] were performed for a tunnel with a cross-section of 72 m² and a ventilation speed of 1 m/s. The calculated values for peak pressure and impulse will therefore be different from our reference tunnel.
The rationale behind the values for the gas explosion is as follows: take the average explosive cloud length (lead & trail) in combination with the “explosion rule of thumb” that gives the pressure and impulse (see result of 2010 [15] and 2001 [16]);

For GEE and BLEVE, the proposed design pressures from [15] have been adopted. For T < 326 K it is assumed that no BLEVE occurs. For BLEVE and GEE, only the explosion load is given for the zone near the point of explosion. The remaining part of the tunnel is loaded by a lower explosion load (see [15]).

In case of a continuous outflow, the worst case has been assumed. The explosion conditions depend on the flow rate, the ventilation speed and the tunnel cross section. There is then always the chance of the critical conditions for a detonation. A detonation has therefore been conservatively assumed here.

\cdot \text{EJ (expert judgement). When “EJ” is stated as source, it means that the values for peak pressure and impulse are estimated by J. Weerheijm based on his extensive knowledge and experience with explosion research.}

Explanation:
1. The values for the impulses have been entered on the basis of estimates, because no calculations were available. For a combination of two explosions, the larger value for the impulse was taken. For the gas explosions in which a detonation occurs (CQ16 and CQ17), a global estimate of the impulse has been made, based on the location 500 m from the point of ignition.
2. Calculated with TNO GEE model.
3. To arrive at an estimate, this explosion type has been schematized into a BLEVE as a result of 50% LPG as a liquid and a GEE as a result of 50% LPG in gaseous form. The quantitative estimate is based on available calculations with the TNO BLEVE and GEE models for 1% and 100% filling at a temperature of 288 K.
4. Here are the results of a BLEVE at 288K (fast expansion of the LPG) used for the “physical explosion” GEE100.
5. This is a combination of two explosion types.
   a. In the case of a GEE followed by a GE, it was decided to use the peak pressure and impulse of the most severe explosion for the combination as a whole and not to sum it up. This was chosen because the explosions follow each other in time and do not occur simultaneously. The GEE occurs first followed by the gas explosion, provided ignition occurs. For the structure, this choice may not be conservative, because the structure is weakened after the occurrence of the first explosion and, as a result, is less resistant to the second explosion than originally.
   b. In the case of a GEE and a BLEVE, it was decided to sum the peak pressure and impulse of both explosions, because the explosions occur simultaneously. For CQ9, an estimate was made based on a BLEVE100 and a GEE0 @326K. The peak pressures of these explosions are of the same order. The maximum value is included in the table. The impulse values are very different, however. Therefore, not the maximum, but a value in between the two impulse values has been selected.
6. The same philosophy has been used here as under 5a, with the difference that the maximum peak pressure originates from one explosion type and the maximum impulse from the other explosion type.
7. For this explosion type it is assumed that the peak pressure and impulse are the same as for a GEcont, 100.
8. A BLEVE0 does not occur. The effects are determined by a GEE0 @326K.
9. For a BLEVE50 it is assumed that the peak pressure values are the same and for the impulse slightly lower than for the BLEVE100.
10. Calculated with TNO BLEVE model.

\textbf{Calculation of probability distributions for peak pressure and impulse}

The following steps were performed to calculate the design values for the peak pressure and impulse:
1. The peak pressures or impulses associated with the scenarios are sorted from low to high. Where the peak pressure or impulse is equal to zero, it has been replaced by the value 1 kPa·s. This has been done because the calculation with the value zero is not feasible.

2. Subsequently, the exceedance probability of each scenario was calculated by adding up the probabilities from the bottom up. For example, the probability of a pressure greater than 300 kPa is $1.16 \times 10^{-4}$ in a year. The probability of the upper scenario is therefore the probability of an accident with an LPG car, with or without an explosion ($1.72 \times 10^{-4}$ per year).

3. Then these exceedance probabilities are divided by the probability of an accident with an LPG truck ($1.72 \times 10^{-4}$ per year), which results in the conditional probability of the pressure exceedance, given an accident with an LPG truck.

4. Finally, the negative logarithm of the conditional exceedance probability (step 3) is calculated, i.e. -$\log(P)$. The peak pressure and the negative logarithm are plotted in Figure 3, with the negative logarithm of the conditional exceedance probability on the vertical axis and the pressure on the horizontal axis: so the 2 means 0.01 and the 4 means 0.0001. The distant points of 1800 kPa are not taken into account here. This results in a more accurate picture in the range of lower pressures and thus a more realistic picture in the area we are really interested in.

Note: The jumps at 300 and 600 kPa are due to the rough estimates of the peak pressures. Refined calculations could possibly improve this.

Looking closer at the graph, and given the often used exponential model for these type of processes, it seems plausible to draw a line of type $\log(P) = a + b \cdot p$. This is estimated to produce the red line in Figure 3.

Given the annual target $\beta = 4.3$ corresponding to a target probability $8.5 \times 10^{-6}$ per year and dividing by the probability of the explosion $P(E) = 1.72 \times 10^{-4}$ per year we arrive at a conditional failure target of $P(F|E) = 0.05$. This corresponds to $\beta = 1.64$. Using $\alpha S = 0.7$ we have $\alpha S \cdot \beta = 0.7 \times 1.64 = 1.15$ corresponding to an exceedance probability of the explosion design load of 0.12. Taking the negative logarithm results in a value of 0.91. When this value on the vertical axis is plotted against the red line, a peak pressure of 400 kPa results as a design value.

The same can be done for the impulse (Figure 4) which results in a design value of 19 kPa·s.

![Figure 3: Peak pressure plotted against conditional probability of exceedance](image-url)
Sensitivity analysis
A sensitivity analysis is important to gain insight into the variation that occurs in the design values as a result of uncertainty in the peak pressures and impulses associated with the considered explosion scenarios. However, the peak pressures and impulses reported in this report are based on calculations only to a limited extent. Part of the results have been estimated on the basis of expert judgement. Since it is difficult to perform a well-founded sensitivity analysis without a better and calculation-based insight into the peak pressures and impulses, the idea has been abandoned here for the time being.

PROPOSED NORMATIVE TEXT FOR THE NEXT ROK IN THE NETHERLANDS

The requirement is that explosions as a result of the transport of LPG in bulk must be taken into account in new category A tunnels. The design values to be considered are 400 kPa dynamic peak pressure and an impulse of 20 kPa∙s. The pressure-time diagram to be used assumes a sudden increase of the load to the initial peak load at t=0 and a linear decrease of the load over time (triangular shape, see Figure 5).

With these values for peak pressure and impulse, the probability of exceedance is $2.5 \times 10^{-5}$ per year. This is based on a $\beta$ of 4.0 and an $\alpha$ of 0.7. The $\beta$ of 4.0 is based on an economic analysis and the choice to take the $\beta$ for class CC3 and RCH (high cost of safety measures).

CONCLUSIONS AND RECOMMENDATIONS

Research into explosions in tunnels has been carried out over the course of several years, which in this (final) publication has led to a first draft text for the ROK for the design of category A tunnels for an explosion load as a result of the transport of LPG in bulk. The design values that are recommended for this concern a dynamic peak pressure of 400 kPa and an impulse of 20 kPa∙s.
For tunnels that fall outside the scope of the current study, the methodology used in this report, together with that from [8], can be used to determine the (specific) explosion load that must be taken into account when designing tunnels.

The research has a number of limitations. It is recommended to investigate this further before definitively including the text in the ROK:

1. The number of calculations where the design values for peak pressure and impulse are based upon, is limited. For a large part of the scenarios, the loads have been determined on the basis of engineering judgement. It is recommended to substantiate the values used for these scenarios on the basis of additional calculations.

2. The design values given are based on a so-called reference tunnel with a length of 1000 m and a width of three lanes. These design values are expected to be conservative for shorter tunnels as well as for multi-lane tunnels. However, for tunnels with a greater length and smaller width, the given design values very likely lead to an unsafe design. To be able to make a well-founded statement for such tunnels, additional analyses are necessary.

Finally, the peak pressure and impulse design values refer to the ultimate limit state (ULS) where tunnel failure is dictated by the collapse of part or all of the tunnel. However, if the starting point (as, for example, with a fire) is that the tunnel must be repairable after the explosion, then this concerns a so-called serviceable limit state (SLS). It is plausible to assume that this criterion leads to a lower design load (pressure and impulse) than for the ULS. On the other hand, the degree of accepted damage is less than for the ULS, which is reflected in a more stringent criterion regarding strength. In order to make a statement about the design explosion load for an SLS criterion, the research from this report and from [8] must be reconsidered.

REFERENCES

1. NEN-EN 1990 (en) Eurocode, Basis of structural design, December 2002
Experimental study of smoke characteristics in a double-deck tunnel with multiple point extraction by using branch pipe

Zhan Wang1,5, Zhi Tang1,5, Zheng Fang1,5, Zhiming He2, Tao Yang3, Ming Zhou2, Enshi Wang3, Yinhang Xu4, Pei Yu1,5, Qinwen Li1,5
1 School of Civil Engineering, Wuhan University, Wuhan, Hubei Province, 430000, China
2 Wuhan Investment Group CO.,LTD., Wuhan, Hubei Province, 430000, China
3 Wuhan Zhongjiao Traffic Engineering Co., Ltd., Wuhan, Hubei Province, 430000, China
4 Wuhan Municipal Engineering Design & Research Institute Co., Ltd., Wuhan, Hubei Province, 430000, China
5 Engineering Research Centre of Urban Disasters Prevention and Fire Rescue Technology of Hubei Province, Wuhan 430072, P.R. China

ABSTRACT

A reduced scale 1:8 double-deck tunnel model was built to study smoke control performance of a semi-transverse ventilation system using a branch pipe to connect the lower deck tunnel to the upper smoke duct. 41 experiments were conducted to analyze the effects of different activation modes of smoke vents, heat release rates, and exhaust smoke rates on smoke spread distance. An optimum smoke control mode was found by activating two vents near the fire source when the heat release rate is 44.19 kW (8 MW at full scale) and a smoke extraction rate is 0.66 m³/s (120 m³/s at full scale) by using branch pipe. Results showed a linear relationship between smoke spreading distance and the volumetric flow rate of the fan, leading to the development of calculation equations. Furthermore, fire smoke spread characteristics were quantified under a typical ventilation design.

KEYWORD: tunnel fire, double-deck tunnel, semi-transverse ventilation, branch pipe, fire smoke, smoke exhaust

INTRODUCTION

Since the mid-20th century, tunnels have become increasingly important in modern transportation systems, owing to their high practicability and flexibility in mountainous areas and their ability to solve urban land shortages. However, as a major infrastructure hazard, tunnel fires cause huge economic losses and casualties every year[1]. More research has been conducted in tunnel fires to alleviate and limit the threats of toxic and smoke due to that around 85% of casualties result from the smoke[2, 3]. The mechanical exhaust system can carry a large amount of smoke and heat to the outside of the tunnel and improve the safety environment for personnel evacuation and fire fighting[4-6].

Several studies have been conducted on the characteristics of fire smoke under different smoke ventilation techniques[7-9]. The goal of the ventilation system is to manage smoke spread and minimize harm to evacuees as much as possible. In an uncongested tunnel, longitudinal ventilation is regarded as an appropriate and economic way as it pushes smoke downstream where there are usually no evacuees. However, it is a challenge in congested tunnels where evacuees will struggle to leave the downstream region polluted by smoke. To take this challenge, it is alternative to use semi-transverse ventilation to extract smoke from the vicinity of a fire into the smoke duct along the tunnel. The behavior of smoke movement under smoke semi-transverse system depends on factors such as the
size and interval of exhaust vents, smoke exhaust rate, and heat release rate (HHR) of the fire[10-13]. Xu et al. studied the dimensionless relationship between the heat exhaust coefficient, heat release rate, exhaust vent size and exhaust velocity. They found the lateral smoke exhaust caused strong air entrainment on the downstream of the exhaust vent and boundary layer separation on the upstream[14]. Yi et al. studied the heat exhaust coefficient of transversal smoke extraction system in a 1:10 model tunnel and found that activating small number of the exhaust inlets is beneficial for enhancing the heat exhaust coefficient of the smoke duct[15].

The attenuation of temperature along the tunnel is one of the central aspects in the research of tunnel fire[16, 17]. Temperature field can be significantly impacted by fire heat release rate (HRR) and smoke ventilation system[18-21]. He et al. proposed a simplified prediction model for the downstream smoke temperature to account for the entrainment effect near a mechanical exhaust vent in a tunnel fire[22]. Zhu and Tang studied the effect of lateral smoke extraction on the transverse temperature distribution and maximum smoke temperature beneath the ceiling and proposed the correlation of the maximum smoke temperature under the influence of lateral smoke extraction[18, 23].

As introduced above, the previous studies on smoke semi-transverse relate to smoke exhaust duct with ceiling vents or lateral vents. With the developing of urban tunnels, double-deck tunnels are more commonly in Chinese city and a new design of smoke semi-transverse ventilation for the lower deck tunnel involves using a branch pipe to connect its lateral exhaust vents to the smoke exhaust duct above the upper deck tunnel, as shown in Figure 1(c). This layout can save tunnel space because there is no need to set additional smoke duct on the side. So this study aims to explore the smoke characteristics under this form of semi-transverse ventilation, an area that has not been experimentally investigated previously. A series of experiments are conducted by considering different the smoke vents quantity, vents interval, heat release rates (HRRs), and smoke exhaust rates. This paper will first introduce the experimental configurations of a reduced-scale tunnel built, and then the way for determining the smoke spreading distance will be demonstrated. Then, the smoke movement features under the considered factors will be presented and analyzed. A conclusion will be made after the quantification of fire smoke spread characteristics under a typical ventilation design.

**DESCRIPTION OF EXPERIMENTS**

A series of experiments were carried out in a 1:8 reduced-scale model tunnel (in Figure 1), which was built up based on the Froude similarity law. The length, width and height of the model tunnel were 36 m, 1.80 m and 1.42 m respectively. The tunnel had a 0.9 m shield diameter with fireproof glass and arc frame for its outer boundary. The upper smoke duct was 0.26 m high. An exhaust fan and a smoke hood were installed at the tunnel’s outlet with the exhaust fan’s volumetric flow rate controlled by a frequency modulator. The upper deck and lower deck were 1.28 m wide and 0.58 m high, separated by a calcium silicate plate.

As shown in Figure 1, the branch pipe, made of iron sheet, connects the lower deck and the upper smoke duct. The entrance of the branch pipe was located at the top of the lower deck’s side wall, and the exit was at the upper smoke duct. The vertical partition plate with branch pipe was made of silicon calcium plate, and the other side was made of fireproof glass for convenience of experimental observation during the experiments.

(a) The photo of reduced scale tunnel
A propane gas burner with dimensions of 0.2 m (length) × 0.2 m (width) × 0.12 m (height) was used to generate as a fire source, providing steady HRR controlled by a mass flow meter. The mass flow meter had an accuracy of ±0.21x10^-4 kg/s, which corresponds ±1.01 kW for propane gas fire. A 40 mm-thick layer of glass wool was fixed beneath the ceiling wall (1.0 m x 0.8 m) near the fire source for protection. Since the propane combustion process produced very little smoke particles, smoke tracers were used in experiments. A laser sheet with output power of 3 W was used to observe the smoke flow [24].

As shown in Figure 2, five branch pipes for smoke extraction were set up connecting the lower deck tunnel to the smoke duct on the top of the upper deck tunnel. The fire source was positioned at the center of the model tunnel, in the middle of Vents 2 and 3. Five velocity probe points (named P1, P2, P3, P4, P5) were set in the smoke duct, and the velocity of the points is approximately the average velocity of the cross-section. The volume flow rates at the five cross-sections could be calculated by the product of velocity and cross-sectional area. For example, the product of velocity and cross-sectional area at P5 means the flow rate of the fan. The difference between the volumetric flow rate at P5 and P4 represents the volumetric flow rate of Vent 5 if Vent 5 is open. Similarly, the volumetric flow rate of other Vents could be calculated. A total of 42 type K thermocouples were arranged along the longitudinal centerline of the lower deck ceiling in the tunnel. Meanwhile, four thermocouple trees with 12 thermocouples each were placed in the tunnel, with a spacing of 2 cm for the top 5 thermocouples, 4 cm for the next 5 thermocouples, and 5 cm for the remaining 2. T-B (d=4.2 m) and T-C (d=4.2 m) were 4.2 m away from the fire source, T-A (d=12.2 m) was 12.2 m away from the fire source, while T-D (d=13.0 m) was 13.0 m. Two velocity probes were installed on the lower deck, positioned 15 cm away from both the ceiling and the floor at T-D.
were set up in this work: Vents 2/3 (mean of opening Vents 2 and 3), Vents 2/3/4, Vents 1/4, Vents 1/2/3/4. Four mass flow rates of fuel were considered, each corresponding to a different heat release rate (HRR) of 16.57 kW, 27.62 kW, 44.19 kW and 82.26 kW. These HRRs are equivalent to full-scale HRRs of 3.0 MW, 5.0 MW, 8.0 MW and 15 MW, based on the Froude law. Three levels of volumetric flow rates of exhaust fan were set up: 0.33 m$^3$/s (60 m$^3$/s at full scale), 0.50 m$^3$/s (90 m$^3$/s at full scale), 0.66 m$^3$/s (120 m$^3$/s at full scale). Two cameras and a laser sheet were used to record the spread distance of the smoke, which can also be calculated by the ceiling temperature. During the experiments, the smoke exhaust fan was activated before the ignition. According to the experimental data, the temperature in the tunnel reached a stable state about 5 min after ignition. In this study, the ignition and combustion lasted for 7 min under each condition, and the data of 6-7 min was taken as the steady-state data to analysis.

Table 1 Summary of the tests.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>The branch pipe exhaust opening</th>
<th>HRR (kW)</th>
<th>Volumetric flow rate of exhaust fan(m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-9</td>
<td>Vents 2/3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>16.57, 27.62, 44.19</td>
<td>0.33, 0.50, 0.66</td>
</tr>
<tr>
<td>10-18</td>
<td>Vents 2/3/4</td>
<td>16.57, 27.62, 44.19</td>
<td>0.33, 0.50, 0.66</td>
</tr>
<tr>
<td>19-27</td>
<td>Vents 1/4</td>
<td>16.57, 27.62, 44.19</td>
<td>0.33, 0.50, 0.66</td>
</tr>
<tr>
<td>28-36</td>
<td>Vents 1/2/3/4</td>
<td>16.57, 27.62, 44.19</td>
<td>0.33, 0.50, 0.66</td>
</tr>
<tr>
<td>37-39</td>
<td>No Vents</td>
<td>16.57, 27.62, 44.19</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>Vents 2/3</td>
<td>82.26</td>
<td>0.66</td>
</tr>
<tr>
<td>41</td>
<td>Vents 2/3/4</td>
<td>82.26</td>
<td>0.66</td>
</tr>
</tbody>
</table>

<sup>a</sup> ‘Vents 2/3’ means the branch pipes 2 and 3 are opened.

THE IDENTIFICATION OF SMOKE SPREADING DISTANCE THROUGH TEMPERATURE AND SMOKE OBSERVATION

Smoke generated by the fire spreads upstream and downstream along the tunnel under the force of hot buoyancy. The smoke spreading distance is determined by measuring the longitudinal distance from the fire source to the frontier of the smoke layer, both upstream and downstream. There is no doubt that gas temperature distribution below the tunnel ceiling has a sharp decrease at the end of the smoke [25], but the specific criteria for the sharp decrease is not clearly defined. So we determine the standard of smoke arrival by matching the video and temperature data. As shown in Figure 3, both thermocouples and laser sheet have been used to determine smoke spreading distance in the experiments. The temperature rise will be analyzed and compared when the smoke spreads to 6.9 m, 8.7 m and 10.5 m downstream of the fire source.

Figure 3 Smoke picture with laser sheet and thermocouple positions.

Since smoke movement is visually tracked by smoke tracers, it is also necessary to study the effect of different smoke tracers on the smoke movement. Figure 4 shows the placement of one smoke tracer and two smoke tracers. The smoke tracers are placed above the burner and ignited by the fire source. Figure 5 shows the temperature rise as the smoke spreads to the three positions. When HRR is constant, the temperature rise upon smoke arrival decreases as the distance from the fire source increases. Meanwhile, as the HRR increases, the temperature rise at all three positions increases. It is
also observed that the quantity of smoke tracers and the exhaust flow rate have a minimal impact on the temperature rise upon smoke arrival at the same location.

![Figure 4 The placement of smoke tracers](image)

---

Given that the smoke can still spread up to 10.5 m downstream of the fire source under the effect of mechanical system, the temperature rise at this point is analyzed to establish the correlation between the smoke arrival and temperature rise. Figure 6 shows the temperature rise with time at T3 (d=10.5 m), and the volumetric flow rate of exhaust fan is 0.66 m$^3$/s. At 150 s after ignition, the video show that smoke has reached this location, where the temperature rise is 1.13 K. The smoke continues to spread downward and the temperature increases to 1.85 K at 180 s. Therefore, this paper uses the temperature rise of 1 K as the characteristic for the presence of smoke. Care should be taken when using this criterion. As shown in Figure 5, the temperature rise at the time of smoke arrival is closely related to the HRR and the distance from fire source. In Liu’s research[26], the temperature rise of 10 K is taken to define the smoke back-layering distance. The 1:3 scaled tunnel model was used in Liu's experiments. The HRR is about 210 kW (3.0 MW at full scale), which is relatively close to that in this study at full scale. However, the measurement point is 1.1 m (3.3m at full scale) upstream of the fire source, where the thermal radiation from the flame may cause the temperature rise. While the measuring point in this paper is 10.5 m (84 m at full scale) away from the fire source, the effect of radiation from the flame can be ignored and it is acceptable that the temperature rise of 1 K as the criterion for the presence of smoke.

![Figure 5 The temperature rise as the smoke spreads to the three locations.](image)

During the experiments, as described in section 2, a total of 41 thermocouples were arranged on the tunnel ceiling. Based on the criterion of 1 K as the representative of smoke arrival, it is clear that the smoke is located between two thermocouples with temperature rises greater than 1 K and less than 1 K. The linear interpolation for the temperature of the two points is used in this paper to calculate the position with 1 K temperature rise, and thereby determine the smoke spreading distance.
Figure 6 The temperature rise with time at T3(d=10.5 m). HRR:16.57 kW, $V_m$:0.66 m³/s, Vents 2 and 3 are opened.

RESULTS AND DISCUSSION

Effect of the activation mode of smoke vents

Figure 7 shows the smoke spreading distance upstream and downstream from the fire source when the volumetric flow rate of exhaust fan volume is 0.66 m³/s and HRR is 44.19 kW. A comparison with no mechanical exhaust condition is also displayed in Figure 7. As can be seen from Figure 7, the smoke spreads throughout the entire tunnel and all five smoke exhaust pipes are within the smoke range for no-exhaust condition. When Vents 2 and 3 are opened, some smoke with heat was removed, reducing the smoke’s mass and momentum as it continues to spread forward. As shown in Figure 7, the smoke spread distances upstream and downstream are 9.02 m and 12.54 m, respectively, which correspond to 72.16 m and 100.32 m at full scale. The longer smoke spread distance downstream is due to the proximity of the smoke exhaust fan to Vent 3.

The intersection between the smoke exhaust vent and the smoke duct as well as the smoke exhaust valve louvers could not be completely sealed in tunnels, and the air leakage phenomenon in tunnels is inevitable. During the construction of the small-scale tunnel model, there are slight gaps between the curved glass and the stainless steel bracket, which results in air leakage in the smoke duct. Figure 8 shows the gas volumetric flow rate at five cross-sections in the exhaust duct when Vent 1 is opened. It can be seen that due to the air leakage, the volumetric flow rate in the exhaust duct decreases continuously from the section P5 to P1. The air leakage of the exhaust duct is related to the frequency of the exhaust fan. The higher the frequency of the exhaust fan, the larger the air leakage. Due to the difference in the installation process of the tunnel model, the air leakage in different sections of the exhaust duct is different. The air leakage in the section P4 to P3 of the exhaust duct is the most serious. When the frequency of the exhaust fan is 50 Hz, the air leakage reaches the 20% of the exhaust fan’s volumetric flow rate. While it is 18% when the exhaust fan frequency is 32Hz. Under different fan frequencies, the air leakage in the remaining sections is between 4% and 6%.
Figure 8 The air leakage in smoke duct under various exhaust fan’s frequencies when Vent 1 is opened.

Considering the influence of air leakage in each section of the smoke duct, the volumetric flow rate at the exhaust outlet can be calculated by Eq. (1):

$$Q_{\text{vent}(i)} = Q_{P(i)} - Q_{P(i-1)} - Q_{\text{leak}(i,i-1)}$$  \hspace{1cm} (1)

where $Q_{\text{vent}(i)}$ represents the gas volumetric flow rate (m$^3$/s) at the $i$-th exhaust vent, $Q_{P(i)}$ represents the gas volumetric flow rate (m$^3$/s) at the $i$-th section in the smoke duct, $Q_{P(i-1)}$ represents the gas volumetric flow rate (m$^3$/s) $i$-1-th section in the smoke duct. $Q_{\text{leak}(i,i-1)}$ is the air leakage between the section $i$ and $i-1$ in the smoke duct.

Figure 9 (b) shows that the volumetric flow rate of Vent 3 (0.24 m$^3$/s) is larger than that of Vent 2 (0.18 m$^3$/s). Thus, it is logical that Vent 3 with larger exhaust gas flow induced the smoke likely moving toward downstream. Compared with the activation mode of Vents 2 and 3, tests with the activation mode of Vents 1 and 4 means that the Vents interval enlarged from 7.2 m to 22.8 m, corresponding to the 57.6 m and 182.4 m at full scale. With the vent interval increase 216%, the smoke spread range increased 22.7%. Figure 7 also shows an interesting trend where smoke control performance worsens as more vents opened. The velocity distribution in the smoke duct and volumetric flow rate of each vent can explain these phenomena, as displayed in Figure 9 (a) and Figure 9 (b), respectively. When just Vents 2 and 3 are opened, the volumetric flow rates of the closest vents to the fire source (vents 2 and 3) are much higher than that with other activation modes of smoke vents. As the vents close to fire source are more likely to exhaust smoke rather than air, leading to a more efficient exhaust. Therefore, it is not surprise to see that the best smoke control is achieved when Vents 2 and 3 opened.

Figure 9 Velocity in smoke duct and volumetric flow rate of exhaust pipes. HRR:44.19 kW, $V_m$:0.66 m$^3$/s.
Figure 10 shows the temperature rise of the four thermocouple trees. When Vents 1 and 4 are opened, a temperature rise can be observed at T-A and T-D. However, no significant temperature rise in the other three vents activation modes. This indicates that opening Vents 1 and 4 is not effective in controlling smoke, as illustrated above. At T-B and T-C, the vertical temperature at the tests with the activation mode of Vents 2 and 3 is lower than the other three modes, supporting the conclusion that the best smoke control performance comes from the activation mode of Vents 2 and 3.

(a) T-A (d=12.2 m)  
(b) T-B (d=4.2 m)  
(c) T-C (d=4.2 m)  
(d) T-D (d=13.0 m)

Figure 10 The temperature rise with multiple branch pipe exhausts. HRR:44.19 kW, $V_m$:0.66 $m^3/s$.

Figure 11 shows the measured velocities at the location of T-D in the tunnel when the volumetric flow rate of exhaust fan is 0.66 $m^3/s$ and HRR is 44.19 kW. When there is no smoke exhaust system, Ve1 and Ve2 increase rapidly after ignition, and the velocities of the two points are relatively close. The velocities of Ve1 and Ve2 are finally stable at 0.5 m/s and 0.45 m/s. As the exhaust fan is activated before ignition, induced wind is generated in the lane. The speed decreases slightly after the ignition when the Vents 2/3 are opened. Finally, the velocities of Ve1 and Ve2 are finally stable at 0.7 m/s and 0.4 m/s. However, the velocities of both Ve1 and Ve2 have a little fluctuation when Vents 2/3/4 or Vents 1/2/3/4 are opened. As can be seen from Figure 7, when the smoke exhaust is activated, the smoke spreads downstream to the vicinity of Vent 4, and the little smoke spreads downstream through T-D position, which results in little fluctuation in velocity before and after the ignition.

(a) No exhaust system  
(b) Vents 2/3
Effect of HRR
As opening Vents 2 and 3 were identified as the optimum activation mode in section 4.1, this vents activation mode will be used as the basis to study the impact of other factors, such as HRR. Figure 11 represents the smoke spreading distance under different HRRs when the Vents 2 and 3 are opened and volumetric flow rate of exhaust fan is 0.66 m$^3$/s. It can be seen that when the HRRs are 16.57 kW (3 MW at full scale) and 27.62 kW (5 MW at full scale), the smoke spreading distances in the upstream and downstream are almost equal. This relationship also holds true when comparing the smoke spread distances between 44.19 kW (8 MW at full scale) and 82.26 kW (15 MW at full scale). This suggests that the smoke spreading distance is not significantly impacted by HRRs within the range of 16.57 kW to 27.62 kW or the range of 44.19 kW to 82.26 kW. However, when HRR increases from the range of 16.57 kW to 27.62 kW to the range of 44.19 kW to 82.26 kW, the smoke spread distance increases from 15.5 m (124 m at full scale, made up of 50.4 m for upstream and 73.6 m for downstream) to 21.9 m (175.0 m at full scale, made up of 74.0 m for upstream and 101.0 m for downstream). It can be observed that HRR rises from 16.75 kW (3 MW at full scale) to 82.26 kW (15 MW at full scale), resulting in a moderate 29.1% increase in smoke spread distance. So the effect of HRR on smoke spread distance is modest in fires with HRR lower than 15 MW, despite the fact that larger HRR fires are expected to produce more buoyant flow.

![Figure 11: The smoke spreading distance under different HRRs. Branch pipe exhausts: Vents 2/3, $V_m$:0.66 m$^3$/s.](image)
Figure 12 shows the ceiling temperature distribution along the tunnel under different HRRs when the Vents 2 and 3 are opened and volumetric flow rate of exhaust fan is 0.66 m$^3$/s. It can be seen that the ceiling temperature gradually decreases as the distance from the fire source increases. The higher the HRRs, the higher the temperature. Interestingly, the ceiling temperature of 82.26 kW is very close to that of 44.19 kW in the upstream of the fire source. However, there are obvious differences in the downstream of the fire source. The temperature downstream is slightly higher than that of the upstream at the position of the same distance from the fire source. This is due to the smoke exhaust fan, which causes more smoke spread to spread downstream, resulting in a higher temperature rise in the downstream. These findings indicate that the spreading distance of the smoke in downstream is greater than that upstream, as shown in Figure 11.

Figure 12 The ceiling temperature distribution along the tunnel for various HRRs. Branch pipe exhausts: Vents 2/3, $V_m$:0.66 m$^3$/s.

Figure 13 shows the temperature rise at thermocouple trees of T-B and T-C. The data reveals that the temperature rise decreases as the HRR decreases, and the temperature rise at T-C is higher than at T-B. This suggests that the temperature is strongly linked to HRR.

Figure 13 The temperature rise under different HRRs. Branch pipe exhausts: Vents 2/3, $V_m$:0.66 m$^3$/s.

**Effect of volumetric flow rate of exhaust fan**

Figure 14 shows the smoke spreading distance under different volumetric flow rates of exhaust fan when the branch pipe Vents 2 and 3 are opened and the HRR is 44.19 kW. When the volumetric flow rate is 0.33 m$^3$/s, the smoke spreading distance in the upstream and downstream is almost the same as that without mechanical exhaust. The smoke spreading distance decreases with the increase of volumetric flow rate gradually. When the volumetric flow rate is 0.50 m$^3$/s, the smoke is limited between the smoke exhaust pipes 1 and 5. And the smoke is limited between the smoke exhaust pipes 1 and 4 when the volumetric flow rate is 0.66 m$^3$/s. It is worth noting that when there is no smoke exhaust, the smoke spread to both ends of the tunnel, the spreading distance is the distance between the ends of tunnel and the fire source.
Figure 14 The smoke spreading distance under different volumetric flow rates of exhaust fan. HRR: 44.19 kW, branch pipe exhaust: Vents 2/3.

Figure 15 illustrates the spreading distance and volumetric flow rate of the exhaust fan with the fire scales of 16.57 kW (3 MW at full scale), 27.62 kW (5 MW at full scale) and 44.19 kW (8 MW at full scale). The smoke spreading distance increases with the increase of HRRs, and decreases with the increase of the volumetric flow rates of exhaust fan. Further analysis of the experimental data was carried out by taking the tunnel width and height into account. The dimensionless volumetric flow rate $Q^*$, dimensionless HRR $Q^*$ and smoke spreading distance $D^*$ are defined as:

$$ Q^* = \frac{Q}{Wg^{1/2}H^{3/2}}, \quad Q^* = \frac{Q}{\rho_c g^{1/2}H^{3/2}}, \quad D^* = \frac{D}{H} $$

where $Q$ is volumetric flow rate of exhaust fan (m$^3$/s), $Q$ is HRR (kW), $D$ is the total smoke spreading distance, $D_u$ and $D_d$ are the smoke spreading distances upstream and downstream of the fire. $W$ is the tunnel width (m), $H$ is the tunnel height(m), $\rho_c$ is the ambient density (kg/m$^3$), $c_p$ is the thermal capacity of air (kJ/kg K), $g$ is gravitational acceleration (m/s$^2$).

Figure 15 The smoke spreading distance under different volumetric flow rates of exhaust fan. HRRs: 16.57 kW, 27.62 kW and 44.19 kW, branch pipe exhausts: Vents 2/3.

Figure 16 illustrates the relationship between dimensionless smoke spreading distance and dimensionless volumetric flow rates of exhaust fan when Vents 2/3 are opened using branch pipe exhausts. It is observed that the dimensionless smoke spreading distance has a linear relationship with the dimensionless volumetric flow rate, and the correlation lines are almost parallel. The slope of the correlation lines ranges from -96.98 to -93.73 and the mean value is -95.01. This relationship can be expressed as Eq (2):

$$ D^* = -95.01Q^* + C $$

where $C$ is a constant value that is related to the HRR value.
Figure 16 Dimensionless smoke spreading distance vs. dimensionless volumetric flow rates of exhaust fan. Branch pipe exhausts: Vents 2/3

Figure 17 shows the parameter $C$ as a function of the dimensionless HRRs when the Vents 2 and 3 are opened. It is observed that parameter $C$ has a linear relationship with the dimensionless HRRs. This relationship can be expressed as Eq. (3):

$$C = 57.66 + 91.12Q$$

Figure 17 The parameter $C$ under different dimensionless HRRs, branch pipe exhausts: Vents 2/3

By combining Eq. (2) and Eq. (3), the dimensionless smoke spreading distance can be calculated by Eq.(4):

$$D' = -95.01Q^* + 91.12Q^2 + 57.66$$

Figure 18 shows the ratio of the smoke spreading distance on either the upstream or downstream side of a fire to the total smoke spreading distance under various exhaust volumetric flow rate conditions. The ratios remain relatively constant regardless of the volumetric flow rate of exhaust fan. Based on this trend, we can define the ratio of the upstream dimensionless smoke spreading distance to the total dimensionless smoke spreading distance as $\phi$, and calculate it as follows:

$$\phi = \frac{D_u^*}{D^*}$$

In this study, $\phi$ was found to be approximately 0.4 based on Figure 18.

Figure 18 The ratio of the smoke spreading distance on either the upstream or downstream side of a fire to the total smoke spreading distance. Branch pipe exhausts: Vents 2/3.
Using Eqs (4) and (5), the dimensionless smoke spreading distances upstream and downstream of the fire, $D_u^*$ and $D_d^*$, can be calculated by Eqs. (6) and (7).

$$D_u^* = \phi (-95.01Q_v^* + 91.12Q_v^* + 57.66)$$

$$D_d^* = (1 - \phi) (-95.01Q_v^* + 91.12Q_v^* + 57.66)$$

To validate the proposed simple equations, comparisons with the experiments are shown in Figure 19, which illustrates good agreement. It should be noted, however, that the equations only account for variations in HRR and exhaust volumetric flow rate considered in the study. The sensitivity of the equations to other factors, such as the quantity of activated vents, vents interval and geometry of tunnel, have not been investigated in this paper. Care should be taken when extending the use of these equations.

![Figure 19](image)

*Figure 19 The smoke spreading distance under different volumetric flow rates of exhaust fan. Branch pipe exhausts: Vents 2/3.*

Figure 20 shows the temperature rise of four thermocouple trees with the fire scales of 44.19 kW (8 MW at full scale). The presented temperature is the averaged value over 6 min to 7 min after ignition. It can be seen from the figure that the temperature rise decreases with the increase of the volumetric flow rates of exhaust fan. The larger the volumetric flow rates, the more heat and smoke will be taken away through the smoke exhaust pipe, which results in the decrease of the temperature in the tunnel.

![Figure 20](image)
Figure 20 The temperature rise under different volumetric flow rates of exhaust fan. HRR: 44.19 kW, branch pipe exhausts: Vents 2/3.

Fire smoke spread characteristics under a typical ventilation design
Most urban tunnel in China only allows cars passing through, leading to maximum HRR of 15 MW usually adopted in fire design, corresponding to 82.26 kW in the current experimental configuration. Additionally, a commonly used design standard of an axial fan capability is to generate a volumetric flow rate of 120 m$^3$/s (equivalent to 0.66 m$^3$/s in current experiments). This section will analyze the fire smoke risk for the mentioned typical design, focusing on tests with a HRR of 82.26 kW and a smoke extraction rate of 0.66 m$^3$/s.

Figure 20 (a) shows the time of smoke arrival along the tunnel under the typical conditions (82.26 kW, 0.66 m$^3$/s) with two vents activation modes of Vents 2/3 and Vents 2/3/4. Comparing the two cases, the duration for smoke to spread downstream remains relatively unchanged, however, the smoke spreads more rapidly and farther upstream when Vents 2/3/4 are opened. This highlights that opening Vents 2 and 3 results in a better smoke control performance again. When Vents 2 and 3 are open, smoke overflows exhaust pipes 2 and 3 located 3.6 m away from the fire (28.8 m at full scale) at around 11 s (31 s at full scale) after ignition. The smoke stop spreading upstream 7.9 m (63.2 m at full scale) from the fire source at 160 s (453 s at full scale) after ignition. In contrast, the smoke begins spreading downward across exhaust pipe 4 (96 m away from the fire at full scale) at about 110 s (311 s at full scale) after ignition, and stop spreading further downstream at about 13.6 m (108.8 m at full scale) at 180 s (509 s at full scale). The smoke arrival time demonstrated in Figure 20 (a) can be conservatively judged to be Available Safe Egress Time (ASET) at the location. However, It is important to keep in mind that the actual ASET may be much longer due to the relative slow fire growth in a real fire and the stratification of smoke layer.

Figure 20 (b) shows the velocity of smoke as it spreads along the tunnel. It was discovered that the smoke spread speed was significantly reduced after passing through the smoke vents, which implies that reducing the distance between smoke vents is crucial for reducing the smoke spreading speed to increase ASET for evacuees. Combined with the finding that the smoke spread range can also be shortened with the decrease in smoke vent interval, as displayed in Figure 7, the significance of smoke vents for ASET is therefore identified. Figure 20 (b) also reveals that the smoke spreads more rapidly in the downstream direction than in the upstream direction in the current experimental configurations. The difference in the smoke flow speed is attributed to the fan being located only on the downstream side. This type of ventilation scenario is similar to real-life tunnels of having the one side of the smoke duct activated with a fan, or having the fire closer to one side of the shaft with the exhaust fan than the other side.

To demonstrate how the stratification of smoke layer can result in a prolonged ASET, Figure 21 is drawn to present the temperature rise at a height of 0.29 m (equivalent to 2.28 m in full scale) at various locations from the fire source. Given the assumption that the start time of temperature rise at a position can indicate the descent of smoke there, it can be deduced that smoke descending to 0.29 m height at the 6.3 m upstream and 6.9 m downstream of the fire are 70 s (198 s at full scale) and 55 s (156 s at full scale), respectively. Comparing the smoke arrival times at 6.3 m upstream and 6.9 m downstream of the fire, 58 s and 30 s respectively, the corresponding times from the smoke arrival to descent to the height of 0.29 m is 12 s and 25 s (34 s and 71 s at full scale).

Additionally, it is noteworthy that there was no temperature rise at 8.7 m upstream and 13 m downstream before the fire was put out. However, a temperature rise was observed after the fire was extinguished. As there was no ongoing fire source to provide constant heat, the smoke gas is likely to settle during its spread, causing the temperature rise at the lower parts of the tunnel. In the actual tunnel fire rescue scenarios, it is important to keep in mind that the negative effect on the smoke descent during the fire-fighting stage.
CONCLUSIONS

A reduced-scale 1:8 double-deck tunnel model was built to examine smoke movement under a semi-transverse ventilation by using branch pipes. Experiments were conducted by varying the activation modes of smoke vents, HRRs and exhaust smoke rates. Four activation modes of smoke vents and three different volumetric flow rates of the exhaust fan were considered. The HRRs ranged from 16.57 kW to 82.26 kW, equivalent to 3.0 MW to 15.0 MW in full scale. Based on the discussions on the effects of these parameters on the smoke control performance of the ventilation system, fire smoke spread characteristic under a typical ventilation design was quantified. The key findings are:

- Smoke control worsens as more vents are opened. The most effective smoke control for the fire scenarios studied was achieved by opening just two vents closest to the fire source (Vents 2 and 3), as their higher volumetric flow rates and proximity to the fire source result in more efficient exhaust.
- The smoke spread distance was not significantly impacted by HRRs in current tests. The smoke spread distance increased by 29.1% when HRR increased from the range of 16.57 kW to 82.26 kW (3 MW to 15 MW at full scale).
- It is found that the decreasing the interval between smoke vents is crucial for enhancing ASET, due to the significant reduction of the smoke spread speed passing through and the modest reduction of the smoke spread distance.
- The smoke spreading distance decreased linearly with an increase in volumetric flow rate of the exhaust fan. Equations were proposed to calculate smoke spreading distances and the results agreed well with experiments. However, care should be taken when extending the use of these equations as the they are proposed based on the observation of current experimental data.
ACKNOWLEDGEMENT

The research is funded by Wuhan Investment Group CO., LTD. under the project of "Wuhan two lakes tunnel". The authors would also like to acknowledge the National Natural Science Foundation of China (Grants No. 51508426 and No. 51978536), the Key Research and Development Program of Hubei Province of China (Grants No. 2020BAB118 and No. 2021BCA217) and China Scholarship Council (Grant No. 202206270120).

REFERENCES


Influence of blockage on smoke control in tunnels

Ying Zhen Li & Haukur Ingason
RISE Research Institutes of Sweden, Borås, Sweden

ABSTRACT

Smoke control in a longitudinally ventilated tunnel with various blockage conditions was investigated experimentally. A total of 28 tests were conducted with a focus on single blockage with a short distance from the fire source, continuous blockage and semicontinuous blockage. Both gas and pool fires were used. The aim was to understand the influence of blockage on critical velocity and backlayering length. The results confirm that blockage ratio is a critical parameter when determining the critical velocity and backlayering length. The blockage location in relation to the fire source also influences the values of critical velocity and backlayering length. The experiments presented are in scale 1 to 3.3 and represents a medium sized tunnel. The focus was on free flow conditions, blockage ratios of regular sizes. For the various tested scenarios with single blockage, the reduction ratio of critical velocity appears to be slightly less than the blockage ratio. However, when the blockage is attached to the upstream side of the fire source, the reduction ratio of critical velocity approximately equals the blockage ratio.

KEYWORDS: Critical velocity, backlayering, smoke control, blockage, medium scale tunnel

INTRODUCTION

Smoke control in longitudinally ventilated tunnels has been extensively investigated mainly by using model scale tunnel fire tests. Two important parameters for longitudinal ventilation systems are focused on, i.e., the critical velocity and the backlayering length. The critical velocity is defined as the minimum longitudinal ventilation velocity to prevent reverse flow of smoke upstream of a fire in the tunnel. The backlayering length is defined as the distance between the front of backlayering (smoke reverse flow) and the fire center, and the corresponding longitudinal velocity is called confinement velocity by Li et al. [1]. The confinement velocity was originally defined as the velocity corresponding to a backlayering length of 4 times tunnel height beyond an extraction vent by Vauquelin [2] for a smoke extraction system.

Different correlations were proposed, but most of them have only minor differences. They can be categorized into two types: the critical Froude model and the nondimensional equations. It has been found there are imperfections in the critical Froude model. The original model with critical Froude number of 1 by Thomas [3, 4] was calibrated based on data from one rectangular tunnel/corridor. The modified model with critical Froude number of 4.5 [5] was based on one single data point from Lee et al.’s model scale test [6] for a relatively large fire in full scale. In the past decade, it has been proven that there exists no constant critical Froude number [7]. More importantly, the critical Froude model does not appropriately account for the effects of tunnel width and tunnel height [8]. It is evident that the critical Froude number itself is a variable, i.e., it significantly depends on many other parameters such as fire size and tunnel geometry. It is not suitable to be used as the foundation for predicting the critical velocity. By contrast, the nondimensional equations are more appropriate and flexible in accounting for these effects, as shown in Li and Ingason [8].
Most research has been focused on free tunnel cross section (no effects of blockages) where the fire source was placed at the floor level, e.g., [1, 3-5, 8-10] or at a raised height [11]. In real world situation blockages may exist in various forms in a tunnel, e.g., the fire source self-blockage, the vehicles behind (upstream of) a fire vehicle and a train/tram carriage. The blockage has been found to be a parameter that affects the smoke control in tunnels. Issues related to blockage were studied by numerous authors and is shortly summarized and introduced in the following.

Oka and Atkinson [9] tested smoke control using raised gas burners and obtained some useful data, although their test set up with water sprays acting on the exteriors of the tunnel influenced the results as pointed out by Li et al. [1]. The authors stated that in a tunnel of this shape, a vehicle with a height of around half the tunnel height occupying around 12% of the tunnel cross section should cause a decrease of around 15% in the critical velocity, and if the vehicle occupies 32% if the tunnel cross section, the critical velocity should be reduced by 40-45%. This statement was made by Oka and Atkinson based on a comparison of data from test 8, test 9 and the reference test 7 with a blockage ratio of around 9%. A more careful analysis (using no blockage scenario as the reference) may indicate the corresponding blockage ratio is around 14% and 31% respectively. It should be noted that these tests (tests 7-9) refer to a fire source height of 0.13 m above the floor of a 0.244 m high horse-shape tunnel. The data for critical velocity from test 7 are higher than those in test 5 where the fire source was placed on the floor. If test 5 in Oka and Atkinson is used as the reference, the decrease of the maximum critical velocity will be around 8% for a blockage ratio of 21% and 38% for a blockage ratio of 37%. In these tests by Oka and Atkinson, both the gas burner blockage and raised fire source height have effects on the critical velocity and their effects are difficult to distinguish. Further, the exterior water cooling affects the results and the uncertainties related are difficult to estimate especially if one focuses on a parametric study of the blockage effects.

Li et al. [1] tested different fire sizes under a long train tunnel model in a tunnel, and found evidence that the reduction of the critical velocity is directly related to and approximately equal to the blockage ratio, regardless of the fire sizes. It was concluded there exists a local critical velocity. They also found that the backlayering length varies more significantly with the velocity within the blocked region. Correlations for both critical velocity and backlayering lengths in tunnels with long blockage and without long blockage were proposed. It should be noted that the correlations for blockage were proposed only for the specific blockage scenario and may need to be modified for other blockage scenarios. A definition of different type of specific blockages are given in Figure 1.

Lee and Tsai [12] conducted small scale tunnel fire tests with gasoline pools as the fire sources. The fire sources were either placed along the centerline or behind one vehicle models. The burning rates in tests with various blockage configurations varied especially when the fire source was placed behind one vehicle model. Their results show that the critical velocity increases with blockage ratio for fire source placed behind the vehicle model, probably due to the increase in burning rates, while it decreases when the fire source was placed along the centerline and directly exposed to incoming air flows. The former may not be of much interest as it was concluded by a direct comparison of data between tests with different fire sizes. Overall, the results from the tests with relatively stable fire sizes (fire source was exposed to wind) show a reduction of critical velocity approximately equal to the blockage ratio.

Li et al. [13] conducted a numerical study to investigate the effect of fire source blockage on the critical velocity for a blockage ratio in a range of 0-70%. The fuel surface was set on top of a blockage, height of which varies to achieve the desire blockage ratio. They concluded that the decrease of critical velocity is approximately equal to the blockage ratio.

Jiang et al. [14] conducted tunnel fire tests with a long vehicle model placed right upstream of a methanol pool. They tested various blockage ratios and concluded the critical velocity decreases even when the pool was behind a vehicle model, and the reduction ratio is lower than the blockage ratio. As no information about the burning rates of the methanol pools was reported, the effect of varying fire sizes is not possible to estimate.
Note that most of the above mentioned literature refer to only fire source blockage [9, 13] or only upstream blockage [12, 14], but in Li et al. [1] both fire source and upstream blockage were considered. From the work where blockage exists at the fire source [1, 9, 13], it is relatively clear that the reduction ratio of critical velocity should be closely related to the blockage ratio. However, from the work with only upstream blockage [12, 14], quite significant differences can be found. This may be attributed to not only the blockage configuration, but also the use of liquid pool as the fire source in both experiments. Gas burner was used as fire source in the experiments reported in Li et al. [1] and Oka and Atkinson [9], while sprays were applied in [9] and only one blockage configuration was tested in [1].

There is a need for a more systematic study to investigate the influence of different type of blockage on smoke control. The focus is on influence of geometrical type, size and distance between the fire source and the projected area by the blockage ratio.

THEORETICAL CONSIDERATIONS

In the following the theory behind every type of blockage scenario is given. Several typical blockage scenarios are identified and defined here, including single blockage, continuous blockage and semicontinuous blockage. In Figure 1 the different blockage scenarios are defined. The blockage ratio is defined here as the ratio between the projected area of the blockage in the direction of the longitudinal flow and the total free cross-sectional area.

(a) blockage far away from the fire. Closely no influence as flow becomes fully developed.

(b) general case. Influence depends on distance.

(c) blockage attached to or very close to fire. Full influence on smoke control.

Figure 1. Schematic diagrams of single blockage upstream of the fire in the tunnel.
No blockage
In the case of no blockage, the critical velocity for smoke control in a tunnel can be estimated using the following correlation [1, 8]:

\[
u_c = \frac{u_c}{\sqrt{gH}} = \begin{cases} 0.81(Q^* \varphi^{-1/3})^{1/3} & Q^* \varphi^{-1/4} \leq 0.15 \\ 0.43 & Q^* \varphi^{-1/4} > 0.15 \end{cases}
\]

(1)

where

\[Q^* = \frac{Q}{\rho_o c_p T_o g H^{5/2}} \varphi = \frac{W}{H} \]

The backlayering length in a tunnel without blockage can be estimated by [1]:

\[\frac{l}{H} = 18.5 \ln\left(\frac{u_c}{u_o}\right) \]

(2)

or

\[\frac{u_o}{u_c} = e^{-0.054l/H} \]

(3)

where \(Q\) is heat release rate (kW), \(u_c\) is critical velocity in free tunnel (m/s), \(u_o\) is longitudinal tunnel velocity (m/s), \(g\) is gravitational acceleration (m/s²), \(l\) is backlayering length (m), \(c_p\) is thermal capacity of air (kJ/kg·K), \(T_o\) is ambient temperature (K), \(H\) is tunnel height (m), \(\varphi\) is tunnel aspect ratio, and \(\rho_o\) is air density (kg/m³). Superscript * refers to dimensionless terms. The above correlations have been widely used and verified to a large extent using both experimental data and numerical results.

Single blockage
General case
When a blockage exists at a certain distance upstream of the fire, the supplied air flow velocity increases at the location with blockage, simply according to the mass conservation:

\[u_{o,local} = \frac{u_o}{1-\alpha} \]

(4)

where \(u_o\) is longitudinal air flow velocity (free flow) and \(\alpha\) is blockage ratio (the blocked cross-sectional area to free cross-sectional area of the tunnel). Subscript local refers to the blocked region.

As the momentum of incoming air flows controls the movement of smoke backlayering in a given scenario, the increased momentum according to the above equation indicates that the smoke flow becomes easier to be controlled in such a scenario, i.e., a lower longitudinal air flow velocity is required to obtain a same controlled backlayering condition. The reduction ratio of critical velocity due to blockage is defined as [1]:

\[\varepsilon = \frac{u_c - u_{c,blockage}}{u_c} = 1 - \frac{u_{c,blockage}}{u_c} \]

(5)

where \(u_{c,blockage}\) refers to the critical velocity in the free tunnel cross section in the case of blockage. By simply comparing this reduction ratio with the blockage ratio, the magnitude of the blockage influence can be known.
It is worthwhile to point out that, in theory, there is no local critical velocity in the case of blockage. Two mechanisms are necessary to be considered. The blockage affects the local flow velocity and profile and the local velocity is therefore a representative parameter. However, the blockage also affects the fire plume, and thus the critical condition or required critical velocity for smoke control may vary due to the blockage. Therefore, the reduction ratio may not be equal to the blockage ratio. In other words, the remaining question is, in practice, whether there exists a local critical velocity for smoke control, regardless of the blockage, or a correlation is needed for estimating the critical velocity with blockage based on that without blockage.

Flow pattern and recirculation zone
As shown in Figure 1(b), the velocity of the fully developed longitudinal air flow increases suddenly at the blockage section, but it takes a certain length to become fully developed again. Behind the blockage, there exists a recirculation regime or zone. The length of the zone is mainly dependent on the dimensions of the blockage and tunnel, and the relative locations and the flow velocity.

The scenario is similar to a ceiling beam in a tunnel. A recent study [15] shows that the length of recirculation zone induced by a ceiling beam is mainly dependent on the beam depth and tunnel height, while the longitudinal airflow speed has a negligible effect on it. A correlation for the recirculation length, \( l_{\text{recirculation}} \) (m), was proposed as follows:

\[
 l_{\text{recirculation}} = 6.03h_Be^{1.43(1-h_B/H)} \]

(6)

where \( h_B \) is the curtain/blockage height (m) and \( H \) is tunnel height (m).

Although the work studied the ceiling beam covering the whole tunnel width, differing from a typical vehicle blockage on the floor level, the results provide useful references for the scenario of key interest in the current study. For scenarios with a typical tunnel blockage, the above correlation indicates that the recirculation length is around 10-20 times of the blockage dimension. This complies well with the knowledge from study of jet fan flows in tunnels or obstructions in inlet of a pipe flow. It is known that for a jet fan installation in a tunnel, the flow becomes fully developed after around 10 to 20 times tunnel height or hydraulic diameter. This recirculation length may be applied to estimate the influence of blockage on smoke control between the blockage and the fire source.

Within the recirculation zone, the effective tunnel cross sectional area for fresh air flow movement becomes smaller compared to a free tunnel cross section. This area becomes larger as the air flows travels further away and it equals the free tunnel cross sectional area when the regime ends. It is therefore evident that the blockage location in relation to the fire source (longitudinal) plays an important role in the results.

A typical upstream vehicle blockage in a tunnel creates three dimensional flow behavior, which is somewhat different from two dimensional phenomenon related to a ceiling beam. The shape of the recirculation regime should therefore also be different. For example, if the upstream blockage was placed in such a way that the fire source is exposed to wind, the whole fire plume may be exposed to the accelerated flow, and counterwise, the lower part of the fire plume could be in the recirculation regime. Consequently, the blockage dimensions (shape and size), its location in relation to the fire source (transverse) also may have certain influence although it may be minor.

Both the longitudinal and horizontal distances between the blockage and the fire source are parameters of investigation in this study.

In summary, the blockage dimensions (shape and size) and location in relation to the fire source (transverse and longitudinal) all influence the values of critical velocity and backlayering length in relation to free flow conditions (no blockage/obstructions upstream the fire).
Blockage far away from the fire
When a blockage is far away from the fire, as shown in Figure 1(a), the flow that passed the blockage region may become fully developed again, and thus the influence of blockage on the smoke control between the fire and the end of the recirculation regime is limited. In other words, there is closely no influence on the critical velocity for smoke control at the fire site. Therefore, the critical velocity to prevent any smoke backlayering at the fire site should be closely the same as that without blockage, i.e., \( v_{c, \text{local}} \approx u_c \).

There are two scenarios are of interest here, i.e., before and after the smoke passes the blockage. When the smoke backlayering is within the fully developed fresh air flow regime (between the fire and the end of recirculation regime), it can be expected that the backlayering length should be the same as that without blockage. The key question is what the critical condition is, and how the smoke backlayering varies with the velocity after the smoke flow passes the blockage.

Blockage attached or close to the fire
When the blockage is directly attached/connected to the fire, as shown in Figure 1(c), the velocity profile at the fire source is highly influenced by the blockage, and the local velocity at the blockage region could be representative of the velocity for control of smoke flow at the ceiling. The vertical fire plume may probably lie in the same tunnel section as the recirculation regime (lower part), i.e., the air flow velocity at most part of the boundaries of fire plume, which affects the fire plume entrainment, is probably close to the local velocity at the blockage cross section. Therefore, a local critical velocity may probably exist. In other words, the reduction of critical velocity due to blockage is expected to approximately equal the blockage ratio. The main remaining question is how the smoke backlayering varies with the velocity after the smoke flow passes the blockage.

Continuous blockage
A continuous blockage is similar to a single blockage but has a greater length, such as a long truck or a train as shown in Figure 2. In the whole tunnel area with blockage (e.g., around a train), the flow accelerates due to the continuous blockage. Same situation is experienced as for single blockage, if the continuous blockage is positioned upstream far from the fire, i.e. the influence may be limited. Here we consider only the case with a short distance (much less than 10 times the tunnel height).

The upstream section may not be fully blocked, but it may be considered as a continuous blockage if the area of key concern refers to the blocked area (smoke backlayering ends within the blocked area), regardless of whether the further upstream is blocked or not.

A study conducted by Li et al. [1] with a train model placed in a model scale tunnel showed that the reduction ratio of critical velocity due to blockage is slightly greater than the blockage ratio of 20 %, independent of the heat release rate. It was also found that, in the area blocked by the train model, the backlayering length varied less significantly with the longitudinal velocity in the free tunnel section. In that study, the fire source section was also blocked, compared to the case without blockage. This should be mainly related to the fact that the effective air flow velocity in such a case is the local velocity in the annular region rather than the longitudinal velocity in the free tunnel section.

Figure 2. A diagram of continuous blockage upstream of the fire in the tunnel.
Semi-continuous blockage
The scenario becomes more complex when the blockage is semi-continuous, i.e., many blockages distributed upstream of the fire as shown in Figure 3. This blockage scenario is expected to lie between a single blockage case and a continuous blockage case. One may expect that there are many recirculation regimes behind blockages and in some cases they may interact with each other. If the distance between blockages is short, the downstream blockage may be within the starting part of the recirculation regime of the upstream one. This blockage scenario could be regarded as close to a continuous blockage.

Figure 3. A diagram of semi-continuous blockage upstream of the fire in the tunnel.

MATERIAL AND EXPERIMENTAL CONDITIONING

The experimental study focuses on single blockages with a short distance from the fire source (Figure 1 (b) and (c). The main aims are to understand the influence of upstream blockage on critical velocity and backlayering length. Both gas and pool fires were used as fuels in the test series. The blockage dimensions (shape and size) and location in relation to the fire source (transverse and longitudinal) all may influence the values of critical velocity and backlayering length in relation to free flow conditions and thus were tested.

Tunnel
The tunnel consisted of ordinary steel container modules and was 49.3 m long, 2.39 m high and 2.35 m wide, as shown in Figure 4. The tunnel ceiling and the upper parts of the tunnel walls (a height of 0.6 m) were protected with 10 mm thick Promatect H boards, within -2 m and +4 m. Within -1.5 m and 1.5 m, the floor was also protected to avoid damage. The tunnel tunnel is regarded as 1:3.3 scale of a road tunnel.

Figure 4. The experimental tunnel used.

Ventilation
Various velocities were tested, ranging from 0.6 m/s – 5 m/s. However, in most of the tests, the velocity was in the range of 1-2 m/s.

Two electric fans (HT71JM/25/4/9/34 and BRV-710) were placed outside of the tunnel inlet to create longitudinal flows in the tunnel. The fans were placed at around 0.8 m above floor, close to the centre of the tunnel cross section. In some tests with high velocity (>2.5 m/s), one or two mobile fans (provided by Guttasjö rescue service) were also used. Frequency regulator was adjusted to obtain the design values within 0.6 m/s – 2.1 m/s in most of the tests. Two perforated steel nets (70 % opening area) with thickness of 2 mm were used in order to even the air flow directly when entering the tunnel.
Fire source
The fire sources were placed at the centerline of the tunnel, and at 26.5 m from the left tunnel portal, close to the middle point of the tunnel, as shown in Figure 4.

Two different types of fire sources were tested, including gaseous fires and pool fires. For gaseous fires, a gas burner with dimensions of $0.45 \, \text{m (W)} \times 0.45 \, \text{m (L)} \times 0.30 \, \text{m (H)}$, where $L$, $W$ and $H$ refer to longitudinal, transverse and vertical directions, respectively, was placed on the floor. Propane was used as the fuel. The inlet of the gas supply into the tunnel was about 0.3 m from the floor level. In pool fire tests, either one or two pools were used in tests, and the corresponding fire HRR in full scale was estimated to be around 20 MW and 50 MW. Each pool had dimensions of $0.8 \, \text{m (L)} \times 0.5 \, \text{m (W)} \times 0.12 \, \text{m (H)}$. For each pool, 35 litres of heptane was used as the fuel. In tests with two pools, they were attached to each other in the longitudinal direction, and the combined pool has dimensions of $1.6 \, \text{m (L)} \times 0.5 \, \text{m (W)} \times 0.12 \, \text{m (H)}$.

General blockage design
The ratio of the blocked area (projected area in the direction of the longitudinal flow) to the total cross sectional area is called blockage ratio. This is a key parameter to vary in the test series. It varies as 0%, 10%, 20%, 30% and 40%, respectively. In Figure 5 a sketch over the arrangement for the centered placed blockage is shown.

The objects or the blockages consists of boxes made of Promatect H boards. As it is in operational tunnels, the objects are located at the floor level. Each box has dimensions of $0.8 \, \text{m (W)} \times 0.7 \, \text{m (H)} \times 0.4 \, \text{m (L)}$ with the shortest side placed along the tunnel. The blockage area is 0.56 m$^2$, approximately 10% of the tunnel area.

The distance between the neighboring edges of the fire source and the objects was varied as 0 m, 0.5 m, 1.35 m and 2.5 m, respectively. This parameter was tested at first in order to choose a default distance for the other tests and the analysis is given later. In most of the gaseous fire tests, the distance was fixed to 0.5 m while it was 1.35 m in pool fire tests to avoid too much heat exposure to the blockage. Also, the effects of the distance was more sensitive in the gaseous fire tests. In other words, most of data refer to a distance between 0.5 m and 1.35 m, corresponding to 1.65 m and 4.5 m in full scale. This distance is considered as being realistic in a queue situation or when a vehicle has to stop behind an incident vehicle. A drawing of the scenarios in Figure 1(b) and (c) for centre placed blockage is shown in Figure 5.

![Diagram showing general blockage design](image)

Figure 5. Configurations of centre placed blockage. The distance from blockage to fire was 0 m, 0.5 m, 1.35 m and 2.5 m, respectively.
INSTRUMENTATION

A total of 125 channels were used for measurements. Ceiling temperatures were measured along the tunnel. All these ceiling thermocouples were placed 15 cm below the ceiling. Thermocouple trees were placed at around 3.3 m upstream of the fire, and at 9.7 m (Pile A) and 16.7 m (Pile B) downstream of the fire. The gas analysis probes were placed at the centerline of the tunnel, and the bi-directional tubes and thermocouples were placed horizontally 5 cm from the gas analysis. Gas velocities were measured using bi-directional pressure tubes at 10 m and 16.7 m downstream of the fire.

Gas analyses were conducted at 10 m station (Pile A) and at the measurement station (Pile B). The gas analyzers at Pile B were used to calculate the heat release rates (HRRs). The heat release rates were calculated using the oxygen consumption method [16]. The cross section at Pile B was divided into five sections in the calculation of the heat release rate. Flow profile surveys were conducted before and after the test series in order to validate the measurements and control the flows. The ceiling thermocouples were used to analyses the backlayering lengths, see Figure 6. Following the methodology proposed by Li et al. [1], a sharp decrease of the ceiling smoke temperature can be found at the front of smoke backlayering, and thus the backlayering length was determined as the distance between the smoke front and the fire center.

![Image](image_url)

*Figure 6. Instrumentation and measurements.*

FIRE TESTS

A total of 28 tests (see Table 1) were conducted to investigate the effects of blockage on smoke control in a tunnel with longitudinal ventilation. In the case of single blockage, the blockage ratio tested included 10 %, 20 %, 30 % and 40 %. The influence of the distance between the upstream object and the fire source was initially tested with various blockage ratios. Thereafter, various effects of fire sizes were tested.

In tests 1-16, the gas burner was used as the fire source. Tests 5, 10 and 13 were used as references tests for comparison as there were no blockage in these tests. In the other tests, either one or two pools were used instead.

The key parameter tested was the blockage conditions (e.g., blockage ratio and distance between fire and blockage). In most of the tests with blockage, the blockage was placed along the centerline, so the fire source may be in the flow recirculation region if the distance is short. But in tests 31-34, the blockage was placed aside (1/4 tunnel width from one side wall) and thus the fire source is directly exposed to wind. In test 33, the object 3 in Figure 5(c) was placed above the object 1 and both of them
were located on the left side and the object 2 was placed on the right side. In test 34, the object 1 and 4 in Figure 5(d) were placed on the left side and the other two on the right side.

The distance from fire varied and it is given in Table 1. The distance refers to the free length between the neighboring edges of the blockage and fire source. The actual distances between the fire source center and the neighboring edges of the blockages should be the values in Table 1 plus 0.225 m for gas fires, and 0.4 m for pool fires, respectively.

According to Equation (6), the recirculation lengths are estimated to be 11.6 m and 15.3 m for 0.7 m and 1.4 m high blockage, respectively. The corresponding ratios of recirculation length to tunnel height is 4.9 and 6.4 respectively, in good agreement with Vogel and Eaton’s measurements downstream of a backward-facing step [17] which gives a value of about 6.6. As in the tests the distance tested varied in a range of 0 m and 2.5 m, the fire source should be in the upstream part of the recirculation zone, indicating the blockages should have large influences on the results. The degree of influence, however, may vary with the distance, and this will be investigated later.

Table 1. Summary of fire tests for smoke control in the tunnel.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Fire source</th>
<th>Fire size</th>
<th>Blockage ratio</th>
<th>Blockage</th>
<th>Distance from fire (m)</th>
<th>Compare to</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gas</td>
<td>1</td>
<td>0.2</td>
<td>2 boxes</td>
<td>0</td>
<td>Reference test</td>
</tr>
<tr>
<td>2</td>
<td>Gas</td>
<td>1</td>
<td>0.2</td>
<td>2 boxes</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Gas</td>
<td>1</td>
<td>0.2</td>
<td>2 boxes</td>
<td>1.35</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Gas</td>
<td>1</td>
<td>0.2</td>
<td>2 boxes</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Gas</td>
<td>0.5</td>
<td>0</td>
<td></td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Gas</td>
<td>0.5</td>
<td>0.1</td>
<td>1 box</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Gas</td>
<td>0.5</td>
<td>0.2</td>
<td>2 boxes</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Gas</td>
<td>0.5</td>
<td>0.3</td>
<td>3 boxes</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Gas</td>
<td>0.5</td>
<td>0.4</td>
<td>4 boxes</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Gas</td>
<td>1</td>
<td>0</td>
<td></td>
<td>NA</td>
<td>Reference test</td>
</tr>
<tr>
<td>11</td>
<td>Gas</td>
<td>1</td>
<td>0.1</td>
<td>1 box</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Gas</td>
<td>1</td>
<td>0.3</td>
<td>3 boxes</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Gas</td>
<td>2.5</td>
<td>0</td>
<td></td>
<td>NA</td>
<td>Reference test</td>
</tr>
<tr>
<td>14</td>
<td>Gas</td>
<td>2.5</td>
<td>0.1</td>
<td>1 box</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Gas</td>
<td>2.5</td>
<td>0.2</td>
<td>2 boxes</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Gas</td>
<td>2.5</td>
<td>0.3</td>
<td>3 boxes</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>2 Pools</td>
<td>-</td>
<td>0</td>
<td>No</td>
<td>-</td>
<td>Reference test</td>
</tr>
<tr>
<td>24</td>
<td>1 pool</td>
<td>-</td>
<td>0</td>
<td>No</td>
<td>-</td>
<td>Reference test</td>
</tr>
<tr>
<td>25</td>
<td>1 Pool</td>
<td>-</td>
<td>0.2</td>
<td>2 boxes</td>
<td>0.5</td>
<td>center</td>
</tr>
<tr>
<td>26</td>
<td>1 Pool</td>
<td>-</td>
<td>0.2</td>
<td>2 boxes</td>
<td>1.35</td>
<td>center</td>
</tr>
<tr>
<td>27</td>
<td>1 Pool</td>
<td>-</td>
<td>0.2</td>
<td>2 boxes</td>
<td>2.5</td>
<td>center</td>
</tr>
<tr>
<td>28</td>
<td>1 Pool</td>
<td>-</td>
<td>0.1</td>
<td>1 box</td>
<td>1.35</td>
<td>center</td>
</tr>
<tr>
<td>29</td>
<td>1 Pool</td>
<td>-</td>
<td>0.3</td>
<td>3 boxes</td>
<td>1.35</td>
<td>center</td>
</tr>
<tr>
<td>30</td>
<td>1 Pool</td>
<td>-</td>
<td>0.4</td>
<td>4 boxes</td>
<td>1.35</td>
<td>center</td>
</tr>
<tr>
<td>31</td>
<td>1 Pool</td>
<td>-</td>
<td>0.1</td>
<td>1 boxes, Side</td>
<td>1.35</td>
<td>center</td>
</tr>
<tr>
<td>32</td>
<td>1 Pool</td>
<td>-</td>
<td>0.2</td>
<td>2 boxes, Side</td>
<td>1.35</td>
<td>side</td>
</tr>
<tr>
<td>33</td>
<td>1 Pool</td>
<td>-</td>
<td>0.3</td>
<td>3 boxes, Side</td>
<td>1.35</td>
<td>side</td>
</tr>
<tr>
<td>34</td>
<td>1 Pool</td>
<td>-</td>
<td>0.4</td>
<td>4 boxes, Side</td>
<td>1.35</td>
<td>side</td>
</tr>
</tbody>
</table>

Five tests (tests 19-23) are not presented in Table 1 as they had a different focus. During each test, the velocity was reduced step by step to allow longer and longer backlayering on the upstream side of the fire. Therefore, the front of smoke backlayering can be easily traced by the smoke temperatures placed upstream of the fire. Thereafter, a graph showing how the backlayering length varies with the velocity can be plotted for each test. As an example see Figure 9. By extrapolation, the critical velocity referring to zero backlayering length is obtained. Note that for a fair comparison, this criterion is used, regardless of blockage conditions.
An ideal test is that the first estimated velocity results in no backlayering and the 2nd velocity results in a backlayering length within 0.5 - 2 m (thermocouples T1-T3), or directly the first estimated velocity results in a backlayering length within 0.5 - 2 m (thermocouples T1-T3). The velocity corresponding to a backlayering length within 0.5 - 2 m is considered as the most important case (starting point).

**RESULTS AND DISCUSSION**

The results and analyses presented here focus on the critical velocity and backlayering length with and without well defined blockages of different sizes. For these tests, backlayering lengths were determined based on temperature distribution curves upstream of the tunnel, and then the critical velocities were obtained through extrapolation.

**Fires with no blockage**

As a first step, test data with no blockages are compared with Equation (1). Figure 7 shows the critical velocities from the pool and gas tests (reference tests in Table 1). Good agreement is found between the data and Equation (1), which indicates that the reference frame for the equation fits well to the tunnel structure and the test setup presented here. Note that some additional data obtained from another series of tests “Formas tests” but in the same test setup are also included for comparison.

![Figure 7. Comparison of measured and predicted critical velocity in free tunnel flow.](image)

**Gaseous fires with blockage**

The reduction ratio of critical velocity due to the blockage is plotted as a function of distance between the 20 % blockage and the fire source edge in Figure 8. As the distance is not greater than 0.5 m (about 1.6 m in full scale), it is approximately equal to the blockage ratio of 20 %. When the distance is greater than 1.35 m (about 4.5 m in full scale), the reduction ratio is around 0.13.
Figure 8. Reduction ratio as a function of distance between the fire and the 20% blockage.

The backlayering length data for various fire sizes are normalized and plotted in a single graph in Figure 9. These data refer to a distance between the blockage and the fire source edge of 0.5 m. The data for other distances are also compared, as shown in Figure 10.

Good agreement between the test data and the Equation (2) can be found in Figure 9 and Figure 10.

Figure 9. Comparison of backlayering length with velocity for gas fire tests with a distance of 0.5 m.
Concerning the critical velocity, Figure 11 shows the reduction ratio of critical velocity with blockage ratio for various fire sizes. Most of the data refer to a distance of 0.5 m but the data for other distances are also plotted for comparison. A simple linear fitting line is given:

\[ \varepsilon = \frac{u_c - u_{c,\text{blockage}}}{u_c} = k\phi \]  

where \( k \) is the correlation factor. In other words, the critical velocity in the case of a blockage could be estimated by:

\[ u_{c,\text{blockage}} = u_c (1 - k\phi) \]  

The correlation factor \( k \) mainly lies in a range of 0.6 and 1.0. An average of value of 0.8 (slope of the line) is used in the plot for these tests.

It should be noted that a linear correlation may not be always suitable to describe the blockage ratio. When the blockage ratio is around 10 \%, the data are much lower than the equality line, regardless of the heat release rate. One reason could be that in the tests without blockage, the gas burner itself acts as a blockage and the blockage ratio is around 2 \%. Another reason could be that for a 10 \% blockage the recirculation regime behind the blockage is relatively small (the recirculation length is related to the characteristic dimension of the blockage) and its influence on the fire plume is also smaller compared to the other blockage cases with larger characteristic dimensions. This indicates that both the dimensions of blockage and its location relative to the fire may play certain roles in the reduction ratio of critical velocity, not only the blockage ratio. In case that the 10 \% blockage is placed closer to the fire source, the influence of blockage is supposed to be more obvious and significant.

Note that most of the test data refer to a distance of 0.5 m between the edges of blockage and fire. As shown in Figure 8, when the blockage is directly attached to the fire source, the reduction ratio of critical velocity is approximately equal to the blockage ratio.

Consequently, both the dimensions of blockage (size and shape) and its location relative to the fire (longitudinal and transverse) have influence on the reduction ratio of critical velocity, as concluded from the theoretical analysis.
Figure 11. Variation of critical velocity with blockage ratio for various fire sizes.

The above critical velocity refers to the free area beyond the blockage. The physical meaning is clear when the distance is short. But when it is not, the main use is to estimate the backlayering length or the confinement velocity corresponding to a certain backlayering length:

\[ u_{conf} = u_{c, blockage} \cdot e^{18.5l} \]  

It is worthwhile to mention that in order to prevent any smoke backlayering upstream of the fire source center, the velocity could be between \( u_{conf} \) and \( u_{c, no blockage} \), mainly depending on how far the distance between the blockage and the fire is. It may be expected that when the distance is several times the characteristic dimension of blockage, the influence of blockage on \( u_c \) is limited and same velocity is required to prevent any backlayering upstream of the fire center.

The equation for backlayering length works well for all the scenarios tested (up to 9 times the tunnel height), with the critical velocity with blockage as the reference value.

For the various tested scenarios with single blockage, the reduction ratio of critical velocity appears to be slightly less than the blockage ratio. However, when the blockage is attached to the upstream side of the fire source, the reduction ratio of critical velocity approximately equals the blockage ratio.

**Pool fires with blockage**

In tests 28, 26, 29, and 30, the blockage was placed right in front of the fire source at a distance of 1.35 m (fire source not directly exposed to air flow). The fire HRRs varied from one to another, but during most of the test periods, the fire HRRs were higher than 1.5 MW (relatively large fires in full scale). Consequently, the data obtained from these periods can be used for estimations of critical velocities. These data are compared with the critical velocities based on extrapolation of the reference tests. The results are shown in Figure 12, indicating that most data lies around the equality line. This means that the gas and pool fire tests represent the same results obtained assuming correction factor k equal to one in Equation (8).
Figure 12. Variation of critical velocity with blockage ratio for various pool fire sizes (front blockage).

CONCLUSIONS

Three typical blockage scenarios were identified and defined: single blockage, continuous blockage and semicontinuous blockage. A total of 28 tests were conducted to investigate the effects of blockage on smoke control in a tunnel with longitudinal ventilation, with a focus on single blockage within a short distance from the fire source. Both gaseous and pool fires were tested. The focus of the analysis is on the smoke control beyond the first upstream blockage.

The blockage dimensions and location in relation to the fire source (transverse and longitudinal) all influence the values of critical velocity and backlayering length in relation to free flow conditions. For single blockage, as the distance increases from 0 to 2.5 m, the reduction ratio decreases slightly for gas fires but it remains almost unchanged for pool fires. It is also found that when the blockage at a distance of 1.35 m is put aside and the pool fire is directly exposed to the air flows, the reduction ratio becomes slightly less.

For the various tested scenarios with single blockage, the reduction ratio of critical velocity appears to be slightly less than the blockage ratio. However, when the blockage is attached to the upstream side of the fire source, the reduction ratio of critical velocity approximately equals the blockage ratio.

The correlation factor, $k$, is equal to 1 when the blockage is attached to the fire source. The factor, $k$, is slightly lower when a single blockage is at a certain distance from the fire source, and it has an average value of 0.8 for the scenarios tested with a distance between the fire source and the single blockage in a range of 0.5 m and 2.5 m, corresponding to a full scale distance between 1.65 m and 8.25 m. The pool fires appear to be less sensitive to the distance between the fire and the blockage, and the reduction ratio is approximately equal to the blockage ratio even when the distance is 1.35 m (4.5 m in full scale).

The equation for backlayering length works well for all the scenarios.
REFERENCES

Review of Design Fire Heat Release Rate for Tunnels with Fire Suppression Systems

Yunlong Liu, Sean Cassady, Eric Jones, Petr Pospisil
HNTB Corporation, USA

ABSTRACT

Heat release rate (HRR) is one of the major components when developing design fire for fire engineering design. Though numerous efforts have been taken during the past decades, there is no consensus on nomination of a peak heat release rate when considering fire suppression effects for various type of fire loads, such as flammable liquid cargo (FLC) tankers, heavy goods vehicles (HGV), battery electric (BE) and hybrid drive cars, etc. The purpose of this paper is to initiate an open discussion to develop credible design fire HRR, which may help engineers in designing tunnel fire & life safety systems and structural fire engineering solutions.

KEYWORDS: Design fire, Fixed Fire Suppression, Fire Control, Shielded Fire, Heat release rate, Tunnels

INTRODUCTION

Control of combustion processes developed during emergency fire scenarios using water-based suppression agent including foam is a subject with many ongoing and active developments. Effectiveness of the system configurations for fire control and/or suppression is influenced by several parameters that need to be evaluated through testing and analysis. The designer of the tunnel system requires to know the maximum heat release rate (HRR) if the tunnel will be provided with suppression system. However, there is still no consensus on the design fire heat release rate for design purpose. Peak HRR can be significantly reduced when fire suppression systems perform to expectations for each type of tunnel fire loads, such as internal combustion engine (ICE) cars, battery electric (BE) and hybrid drive cars, buses with ICE or BE / hybrid drives, heavy goods vehicles (HGV) with ICE, BE or hydrogen powered fuel cells, Flammable Liquid Cargo (FLC) tankers, hazardous goods, etc.

Previous work has ranged from component performance tests of spray nozzles to determine droplet size and spray characterization to full scale gallery tests of overhead multiple sprinkler spray head arrays on defined solid and liquid fuel packages. F. Tarada et al had recommended that heavy goods vehicles fire peak heat release rate can be reduced by around 35% with the deluge operation [ISAVFT 15]. Ingason and Maevski have contributed significant efforts on road tunnel vehicles fires, based on which NFPA 502 recommended some peak HRR values under fixed firefighting system (FFFS) for several type of vehicles in tunnel. There is also extensive practical experience with the application of deluge FFFS, particularly from Japan and Australia where such systems had been in operation for decades. However, there is no widely accepted conclusions on the maximum fire heat release rate which should be capped at for various type of vehicle fire scenarios when a suitable type of suppression system is in full operation.

The main objective of this paper is to summarize the fire growth rate, peak heat release and the peak temperature of different types of vehicles with a suitable type of fire suppression system corresponding to its type of fire load. This work may serve as a start point for developing design fire parameters for tunnel fire-life safety and structural fire durability design.
FREE BURN FIRE HRR WITHOUT FIRE SUPPRESSION

Free burn of fire without any suppression will develop a heat release rate controlled by ventilation and the fuel, and its HRR is usually higher than the case with suppression system. In this paper, the free burn fire will serve as the base cases to understand the suppression effects of various of fire suppression systems.

Igor Maevski [1,2] has completed a comprehensive review of highway tunnel fires and published a NCHRP Synthesis 415 in 2011. Based on tunnel fire incidents from 1949 to 2011, the review includes 45 tunnel fires where fire temperature of more than 1000 °C were achieved. PIARC Design Fire Characteristics For Road Tunnels[29] also summarized the heat release rates for various type of vehicles. Based on PIARC[21] as shown in the Table below that there are 8 truck fires happens for every 100 million driven kilometres, and at least one of them involves damages to the tunnel.

<table>
<thead>
<tr>
<th>Classification of Fire</th>
<th>Cases of Fire for 10^9 veh x km (approx. 10^9 veh x miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Cars</td>
<td>Fires of any importance</td>
</tr>
<tr>
<td>Trucks Without</td>
<td>Fires of any importance</td>
</tr>
<tr>
<td>Dangerous Goods</td>
<td>Fires with some damage to the tunnel</td>
</tr>
<tr>
<td>Trucks Transporting</td>
<td>Very serious fires</td>
</tr>
<tr>
<td>Dangerous Goods</td>
<td>Fires with involvement of the dangerous goods</td>
</tr>
<tr>
<td></td>
<td>Estimation 0.3 (0.48)</td>
</tr>
</tbody>
</table>

*Source: PIARC (21).*

Table 2.3.3 of PIARC Fire and Smoke Control in Tunnels 05.05B, La Defense, France, 1999 [21].

Since fire characteristics of each type of vehicle fire are different, fire HRR of each type of vehicles are discussed separately.

*Heavy Goods vehicles (HGV)*

The most known fire tests which represent heavy goods vehicles is Ingason’s tunnel vehicle fire tests[3], which recorded a peak fire heat release rate of 203 MW. HRR grew approximately at a t-squared ultra-fast rate. Tunnel gas temperature reached 1365 °C. Figure 1 shows the 2003 Runehamar tunnel fire HRR development curve of HGV tests [28].
Flammable Liquid Cargo (FLC)
Fire growth rate of Flammable Liquid Cargo (FLC) fire can be very fast, peak HRR of 300 MW can be reached within 90 seconds to 120 seconds after fire ignition\(^4, 30\). Its HRR growth rate can be as high as 165 MW/min linearly for a fully developed flammable liquid pool. Tunnel gas temperature can be as high as 1200 °C.

Battery Energy Vehicle (BEV) Car
The battery electric vehicle (BEV) uses an electric motor and relies on electric power for propulsion. The involvement of batteries in the fire may result in different toxic species, special consideration should be given to the design fire HRR and smoke species for analysing the fire ventilation for life safety in underground spaces. Based on a review of the recent publications on electrical vehicle (EV) fires, it is widely agreed that the fire heat release rate will not be higher than that for a conventional vehicle, which is around 7 MW\(^2, 5, 31\). In general, most of the EV fire accidents are caused by the thermal runaway of Li-ion battery (LIB), resulting for instance from mechanical damage after a collision. During the burning of LIBs, the generation of flammable/explosive gases and toxic smokes, such as hydrogen (H2), methane (CH4), carbon monoxide (CO), and hydrogen fluoride (HF), can pose a threat to those involved. According to the fire test on EV\(^6-10\), HRR growth rate roughly follows the standard t-squared medium growth curve. Peak HRR of 6 to 7 MW can be reached at 500-700 seconds after fire ignition\(^31\).
Figure 1: a Renault-Samsung electric vehicle model ‘SM3.Z.E’ fire while driving 2016 Korea

**Multiple ICE Cars**

Cecilia Lam et al. [5] published test results for Internal Combustion Engine (ICE) Vehicles at the 5th Int conference on Fire in Vehicle in 2016. It recorded a time of 6-8 minutes to the peak heat release rate of approximately 7 MW to 10 MW, with a peak gas temperature of approximately 800 – 900°C. Peak heat release rate of two internal combustion cars can be as high as 10-20 MW [10, 21]. HRR growth rate roughly follows t-squared medium growth curve [7].

**ICE Buses**

According to statistics [11] in the United Kingdom, there are 3 to 7 bus fires per 1000 vehicles during the period of 1964 and 2013. As shown in Figure 3, bus fire peak HRR can be as high as 20-36 MW [12] and its HRR growth rate can be approximated with ultra-fast t-squared curve [25]. Gas temperature can reach 700°C according to PIARC [21].

![Figure 3: HRRs for buses in tunnel](Image)

**Train Cars**

Xavier Ponticq, Joel Guivarch et al. [13] and Niclas Åhnberg, Axel Jönsson, et al. [14] published their test and research data, which suggested that train fire peak HRR would mainly be in the range of 10 MW to 40MW. It was reported [15] that the design fires used in Swedish railway tunnels are 12 MW to 20 MW with a t-squared medium to fast growth rate. White [16] reported that Queensland train fire tests recorded a gas temperature of around 1100 °C.
Based on NFPA 72, if HRR is assumed to grow following a t-squared curve, the fire growth classification is given in Table 1 with coefficient α as shown in equation HRR = αt^2. Table 2 shows the peak HRR, fire growth rate as well the gas temperature that can be reached for structural fire durability design.

**Table-1: Fire intensity coefficients (kW/s^2) for t-squared fire growth rate based on NFPA 72**

<table>
<thead>
<tr>
<th>α</th>
<th>0.00293</th>
<th>0.01172</th>
<th>0.0469</th>
<th>0.1876</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRR growth</td>
<td>Slow</td>
<td>Medium</td>
<td>Fast</td>
<td>Ultra-fast</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of Fire Load</th>
<th>HRR growth rate</th>
<th>Peak HRR without fire suppress</th>
<th>Linear HRR growth coeff. α1 (MW/min)</th>
<th>t squared HRR growth coeff. α2 (kW/sec^2)</th>
<th>Peak Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGV</td>
<td>Ultra-fast</td>
<td>200 [1, 3]</td>
<td>---</td>
<td>0.1876</td>
<td>1365°C [1, 3]</td>
</tr>
<tr>
<td>FLC</td>
<td>Linear</td>
<td>300 [1, 4]</td>
<td>165MW/min</td>
<td>---</td>
<td>1200°C [20]</td>
</tr>
<tr>
<td>BEV</td>
<td>Medium</td>
<td>7 [5-7]</td>
<td>---</td>
<td>0.01172</td>
<td>1000°C [27]</td>
</tr>
<tr>
<td>Multiple ICE Cars</td>
<td>Medium</td>
<td>10 – 20 [1]</td>
<td>---</td>
<td>0.01172</td>
<td>700°C [10, 20]</td>
</tr>
<tr>
<td>ICE Bus</td>
<td>Ultra-fast</td>
<td>34 [11-12]</td>
<td>---</td>
<td>0.1876</td>
<td>700°C [20]</td>
</tr>
<tr>
<td>Train</td>
<td>Medium</td>
<td>10 – 35 [13-16]</td>
<td>---</td>
<td>0.01172</td>
<td>1100°C [16]</td>
</tr>
</tbody>
</table>

**SUPPRESSION SYSTEM VS VEHICLE FIRE**

Till now there is no widely accepted design fire heat release rate (HRR) curve for tunnel fires where fire suppression system is considered. Especially with the new energy vehicles, which add to the complexity for tunnel fire control. This paper only attempts to propose a set of design fires for tunnels assuming properly designed suppression system to accommodate various type of vehicles, and to recommend design fire curves under fire suppression conditions, which can serve as a start point for proposing reference HRR curves for tunnel system design.

Fires that involve different types of vehicles call for different type of suppression system to control the fire efficiently. For example, a deluge system is less effective for flammable liquid cargo pool fires than an aqueous film forming foam (AFFF) which can generate a blanket on top of the fuel and isolate the oxygen from the fuel. A deluge system is less effective for buses or trains as these vehicles are shielded and the water is inaccessible to the fire seat inside the vehicle. An in-car water mist system would be more effective, though deluge system applied water can reduce the temperature of the released gases and can avoid the ignition of the neighbourhood vehicles. Table 3 summarizes fire suppression systems which is applicable for suppression of different types of vehicle fires.

**Table-2: Peak HRR (MW) growth rate and gas temperature (°C) in tunnel without fire suppression**

**Table-3: Applicable and effective fire suppression system vs vehicle types**

<table>
<thead>
<tr>
<th>Type of Fire load</th>
<th>HGV</th>
<th>FLC</th>
<th>BEV Car/Bus</th>
<th>Multiple ICE Cars or Buses</th>
<th>Train Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deluge</td>
<td>A</td>
<td>NR</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Foam</td>
<td>A</td>
<td>A</td>
<td>Questionable</td>
<td>Questionable</td>
<td>Questionable</td>
</tr>
<tr>
<td>Water mist</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>Questionable</td>
</tr>
<tr>
<td>In-car mist</td>
<td>A</td>
<td>NA</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

A – Applicable, NR – Not Recommended, NA – Not Applicable, Questionable – effectiveness of fire suppression depends on the design of the fire suppression system and fire origin

Some tunnels may not have restrictions on vehicle usage, some may prohibit certain type of vehicles to use it. Fire safety design should consider the vehicle fire which demands the most sophisticated
system for the subject tunnel. Fire suppression systems can be ranked from the simple to the sophisticated in the order of “no suppression”, “FFFS deluge”, “AFFF (foam)”, “water mist”, “in-car mist”, etc. Apart from the traditional cars, HGV and buses, flammable liquid cargo (FLC) fires and new energy fuel vehicles exhibit specific features and require different fire suppression systems for solid or cellulosic fuelled fires. Furthermore, the shielding effect is also an important factor to be considered, since most of HGVs are shielded and the response of fire suppression is different than these fires that are unshielded.

**SHIELD VS UNSHIELDED FIRE**

The impact of fire shielding should be factored in when considering the suppression effectiveness of water-based fixed fire suppression systems. Many existing studies observing effectiveness of FFFS utilize conditions where fire events are not shielded by freight cargo infrastructure. United States freight statistics indicate this approach may not best represent the current condition of freight operational characteristics for the nation’s truck population.

Of the five major modes of infrastructure freight transportation monitored in the US *(Roadway, Rail, Inland Waterways, Airways, and Pipelines)*: Trucks on roadway account for roughly 73% of all domestic freight transportation based on freight by weight [19]. Of the 73% roadway truck freight in the US, majority is transported via ‘dry van’, or more typically known as trailers/containers. Other freight transport methods not used as often include:

- Open-top container (used for raw mining materials, pipes, tools, cable spools, construction supplies, bulk cargo, scrap metal)
- Flatbed (typically used for oversized or large pieces of equipment, construction equipment, building supplies)

For purposes of this study, the following ‘dry van’ transport container are considered to have steel construction on top of the container:

- Tunnel Container
- Open or curtain sided storage container
- Insulated/Thermal, or refrigerated container
- Special purpose
- Intermodal
- Car Carriers
- Tankers (liquid storage)

The latest available data for physical and operational characteristics of various goods transport on freight trucks in the United States is based on a study in 2002 which shows that roadway freight cargo make up roughly 4.5% of freight traffic [20]. This is representative of open-top containers, and partially for freight covered by a tarpaulin. If flatbed cargo was also considered (which likely includes material not considered susceptible to immediate combustion or fast or medium growth fire curves), then this percentage increases to only 18%. The remaining roughly 82% of freight cargo transported on roadways at the time of these studies are container vehicles which may result in a shielded fire condition for any such emergency event. This representative percentage of shielded cargo loads on the US roadways is expected to increase when new data is issued in 2023.

This data would suggest that using open-top or flatbed containers as a basis to measure the performance of FFFS may not be the most plausible. Though these fire scenarios should be considered; a more useful and practical approach would be to use shielded fire conditions as a measure of FFFS effectiveness.
DESIGN FIRE HRR WITH FIRE SUPPRESSION

It is hard to accurately estimate the reduced HRR caused by the intervention of the fire suppression systems, and the design principle is to take a conservative approach. For different types of vehicle fires, fire control effectiveness varies with different type of suppression systems. Fire safety design should also consider a mitigation approach for the most severe scenarios, including failure of fire suppression system.

Apart from the type of fire suppression system, the peak fire HRR with the fire suppression operation will be influenced by various other parameters such as fire detection time, fire growth rate, location of fire origin, fire suppression system activation time, ventilation and the type of vehicles involved in the fire, etc. Major influencing factors of the peak HRR would be the type of fire suppression system and the time when fire suppression system is in full operation.

For fire suppression system activation time, it is determined by the fire detection time, positive alarm sequence, tunnel management control which determine the delay time to operate the fire suppression system. For example, the 2020 edition of NFPA 502 -2020 [6] Clause E4.2 stated that the maximum delay time to operate deluge system should not exceed three minutes.

For a given tunnel, fire can be detected if gas temperature rises quickly, or reach a threshold value, i.e., 68°C, if we assumed a delay time of three minutes for a dry FFFS operation, assuming HRR will be peaked within 20 seconds after FFFS operation for each type of fire with various type of fire load, based on the tested fire HRR growth, Table-4 summarizes peak fire HRR and fire detection time, fire suppression operation time, and the time when fire HRR is peaked.

To provide an overview of the maximum heat release rate that can be achieved in tunnels environment under low pressure deluge, high pressure water mist and foam systems, with the selected suppression systems that are applicable for different vehicle types as listed in Table-3, the peak fire HRR for HGV, FLC, BEV, ICE cars, ICE Bus, passenger train, etc. will be addressed separately.

Heavy Goods vehicles (HGV)
A heavy goods vehicle is a goods vehicle which exceeds 7.5 tonnes, permissible maximum weight according to definition. Ingason and Li et al [22-24] reported that HRR under deluge suppression can be as high as 20 - 40 MW, and all the fire suppression tests at Runehamar showed that fire HRR has been controlled at no more than 40MW, and stated that “after activation of the system the maximum temperatures at the ceiling were never higher than 400°C to 800°C” [23, 26]. Foam and water mist systems are both effective for HGV fires though these systems are more expansive to install or operative than the deluge system.

Flammable Liquid Cargo (FLC)
Fire HRR growth is very fast, according to the tests, its growth rate follows a bi-linear curve [4], based on a detection time of approximately 30 sec, the fire HRR peaked at 200 MW at 100 seconds under water mist suppression which started operation at approximately 60 second after detection. Gas temperature near the ceiling reach 1000°C. As shown in Figure 4, performance of AFFF behaves similar to that of the pure water mist according to Lakkonen [18]. Deluge system for FLC pool fire is not effective, and it is not recommended. M. Lakkonen et al [4, 17] compared the performance of high-pressure water mist and deluge system and suggested that high pressure water mist system is effective for FLC fires.
Battery Electric Vehicle (BEV) Car
Battery energy vehicle (BEV) is powered by batteries, and fire maybe caused by short circuit, etc, and fire may restart even after the car has been dumped, which means fire may restart on the next day after the initial car fire appears to have been extinguished. The suitable fire suppression system would be deluge, water mist or foam. HRR under suppression would be peaked at the time when fire suppression is in full operation. Gas temperature can be as high as 900°C.

Multiple ICE Cars
For traditional Internal Combustion Engine (ICE) cars, deluge water can cool the surrounding gases and avoid the ignition of neighbourhood vehicles. HRR under suppression operation could be capped at 10 - 15 MW, its fire growth rate can be represented with t-squared medium curve. Gas temperature would not exceed 700°C.

ICE Buses
Because of its shield nature of buses, deluge is not an effective type of suppression system for ICE bus fires. Based on ultra-fast HRR growth rate, fire can be detected at 1.5 minutes, considering a maximum positive alarm sequences of 3 minutes which delays the application of suppression system, HRR will be controlled at 15-20 MW under FFFS suppression system, gas temperature can be controlled at 700°C though deluge water is inaccessible to the seat of the fire inside the bus. The most effective approach is to employ an in-car water mist system to extinguish the fire originated from the inside of the bus.

Train Cars
The best train fire suppression approach is in-car fire suppression, HRR under properly designed suppression system can be controlled at 2 – 12 MW based on medium fire growth rate and its detection time of 4.6 seconds. A worst scenario would see a maximum gas temperature of 600-800°C. Trains are similar to the buses or HGVs which are shielded, and deluge water may not directly access the seat of the fire and effectively suppress the fire inside the carriage, though it is effective for cooling the air external of the bus.

Fire can be controlled within 2 minutes after suppression system is in full operation. Table-5 and Table-6 compares the peak HRR and the maximum gas temperature that can be reached with and without fire suppression, respectively. With a properly design fire suppression system, peak heat
release rate can be reduced by around 25 – 75%, and maximum gas temperature can be reduced by 10 – 45%. For cars or buses, the cooling effects of the fire suppression system can reduce the chance of ignition of neighbouring vehicles.

**Table-4: Fire peak HRR with properly designed and operated fire suppression involving different type of vehicles**

<table>
<thead>
<tr>
<th>Type of Fire load</th>
<th>Growth Rate</th>
<th>Type of suppression</th>
<th>Peak HRR Q_max (MW)</th>
<th>Maximum temperature (°C)</th>
<th>t_D (min)</th>
<th>t_S (min)</th>
<th>t_max (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGV</td>
<td>Ultra-fast</td>
<td>Deluge</td>
<td>15-50 [22,25]</td>
<td>400-800</td>
<td>1.5</td>
<td>4.5</td>
<td>4.8</td>
</tr>
<tr>
<td>FLC</td>
<td>Linear</td>
<td>mist/foam</td>
<td>200</td>
<td>800 [18]</td>
<td>0.5</td>
<td>3.5</td>
<td>3.9</td>
</tr>
<tr>
<td>BEV Cars</td>
<td>Medium</td>
<td>deluge/mist</td>
<td>3 - 7</td>
<td>800</td>
<td>4.6</td>
<td>7.6</td>
<td>7.9</td>
</tr>
<tr>
<td>ICE Cars</td>
<td>Medium</td>
<td>deluge/mist</td>
<td>10 - 15</td>
<td>700</td>
<td>4.6</td>
<td>7.6</td>
<td>7.9</td>
</tr>
<tr>
<td>ICE Bus</td>
<td>Ultra-fast</td>
<td>In-car mist</td>
<td>15 - 20</td>
<td>&lt;700 [26]</td>
<td>1.5</td>
<td>4.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Train</td>
<td>Medium</td>
<td>In-car mist</td>
<td>10 - 12</td>
<td>&lt;600 [15]</td>
<td>4.6</td>
<td>7.6</td>
<td>7.9</td>
</tr>
</tbody>
</table>

Q_max – the maximum total heat release rate, t_max – time when maximum HRR is reached, t_D – fire detection time, t_S – suppression system discharge time

**Table-5: Peak HRR (MW) with a properly designed suppression system* for different types of vehicles**

<table>
<thead>
<tr>
<th>Type of fire load</th>
<th>HGV</th>
<th>FLC</th>
<th>BEV Car</th>
<th>Multiple ICE Cars</th>
<th>ICE Bus</th>
<th>Train Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suppression effect</td>
<td>75%</td>
<td>33%</td>
<td>50%</td>
<td>25%</td>
<td>70%</td>
<td>65%</td>
</tr>
</tbody>
</table>

* Properly designed suppression system refers to the system listed on Table-3 and Table-4

**Table-6: Maximum gas temperature (°C) with properly designed suppression system* for fires involving different types of vehicles**

<table>
<thead>
<tr>
<th>Type of Fire load</th>
<th>HGV</th>
<th>FLC</th>
<th>BEV Car</th>
<th>Multiple ICE Cars</th>
<th>ICE Buses</th>
<th>Train Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free burning</td>
<td>1365°C [22-24]</td>
<td>1200°C</td>
<td>1000°C [27]</td>
<td>700°C</td>
<td>700°C</td>
<td>1100°C</td>
</tr>
<tr>
<td>With fire suppression</td>
<td>400-800 °C</td>
<td>800°C [18]</td>
<td>900°C</td>
<td>700°C</td>
<td>&lt; 700°C [26]</td>
<td>&lt; 600°C [15]</td>
</tr>
<tr>
<td>Suppression effect</td>
<td>41%</td>
<td>41%</td>
<td>10%</td>
<td>avoid fire propagation</td>
<td>avoid fire propagation</td>
<td>45%</td>
</tr>
</tbody>
</table>

* Properly designed suppression system refers to the system listed on Table-3 and Table 4

**SUMMARY**

Suppression of different type of vehicle fire requires selection of the most effective type of fire suppression system. Deluge system is effective for unshielded vehicle fires and can significantly reduce its design fire HRR. For shield type of vehicle fire, such as train or buses, in-car mist system is more effective than a deluge system. For FLC fire AFFF foam or water mist system are equivalently effective, but deluge system would not be effective for FLC fires.

If the suppression system operates as design expected, the maximum gas temperature for tunnel structural fire durability design would not exceed 800°C. The peak heat release rate would be reduced
by approximately 25 - 75%, and the gas temperature may be reduced by 10 – 45%. However, there is a probability of failure of the suppression operation which should be considered in the design.

ACKNOWLEDGMENT

The authors would like to thank Igor Maevski of Jacobs for the discussion on design fires HRR with FFFS. The author also would like to thank Max Lakkonen for the valuable comments on water mist system fire suppression, a final review and discussion with Dave Parker of HNTB are kindly acknowledged.

REFERENCES

6. NFPA 13 – 2020, 1 Batterymarch Park, Quincy, Massachusetts, USA 02169-7471
7. Hasan Raza, Matt Bilson, Silas Li, “Analysis of fire-life safety with battery electric vehicles in highway tunnels” 2022 ISAVFT19, page 762
12. Yoon Ko, “A Study of the HRR of tunnel fire and interaction between suppression and longitudinal air flow in tunnels”, PhD dissertation, Carleton University, April 2011
21. PIARC Fire and Smoke Control in Tunnels 05.05B, La Defense, France, 1999
CFD modelling of tunnel fires with low-pressure fire suppression systems

Ying Zhen Li¹, Lei Jiang² & Haukur Ingason¹
¹ RISE Research Institutes of Sweden, Borås, Sweden
² RISE Fire Research AS, Trondheim, Norway

ABSTRACT

CFD modelling was conducted to investigate the influences of low-pressure fire suppression systems on tunnel fires. The main purpose of this study is to evaluate whether CFD is capable of predicting the development of solid fuel fires in tunnels with and without the low-pressure fire suppression systems. To make the assessment, both small-scale and full-scale tests are selected for CFD modelling, including both free burn tests and fire suppression tests. In these two test series, wood cribs (small scale) and wood pallets (full scale) were used as the fire sources, respectively. In CFD modelling, both the simple ignition model and the Arrhenius pyrolysis model were used for the small-scale tests. For the large-scale tests, the fuel geometry was too complicated and thus simplifications using scaling correlations and the simple ignition model was used in CFD modelling. For the simple ignition model, the key empirical coefficient (Ecoefficient) that accounts for the suppression effects was assessed. The impacts of water surface spread velocities were also analysed.

KEYWORDS: CFD modelling, pyrolysis modelling, fire suppression, fire development

INTRODUCTION

Water-based fire suppression system has been widely used in buildings (sprinkler), as well as in road tunnels where it is usually named Fixed Fire Fighting Systems (FFFS). Several studies have been conducted to study the influences of water-based suppression systems on tunnel fires, both in small scale (e.g., [1]) and in full scale (e.g., [2]). Numerical studies have also been carried out to study suppression behaviours (e.g., [3]). Compared with fire experiments, CFD modelling provides cheap ways to do parametric studies and gives more detailed information than what can be directly measured in the tests, and therefore it is attractive to both researchers and engineers working on tunnel safety.

In this work, numerical studies are conducted to investigate the influences of low-pressure fire suppression systems on tunnel fires. The main purpose of this study is to evaluate whether CFD is capable of predicting the development of solid fuel fires in tunnels with low-pressure fire suppression systems.

EXPERIMENTS SELECTED FOR CFD MODELLING

To make the assessment, both small scale tests [1] and full scale tests [2] are selected for CFD modelling. These tests are selected as both free burn tests and fire suppression tests were conducted.

Small scale experiments
The small scale experiments were conducted in a 1:15 scale model tunnel [1]. The model tunnel was 10 m (L) × 0.6 m (W) × 0.4 m (H), as shown in Figure 1(a). Wood cribs were used as fire sources. The main purposes of these tests were to investigate the performance of the automatic sprinkler system while several free burn tests and tests with deluge systems were also carried out, some of which are selected for this study, including the free burn test (Test 26) and a test with water sprays (Test 24). The longitudinal velocities were 1 m/s and 1.5 m/s respectively.
The wood crib fire source is shown in Figure 1 (b). The ignited wood crib was 3.3 m from the tunnel entrance (the centre of the crib is x=0 m). A target was another wood crib, placed 1.8 m downstream of the first crib (the centre of the crib is x=1.8 m). The cross-section of the stick was 0.025 m × 0.025 m. The length of the crib was 0.8 m and the width was 0.2 m. The total weight of 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 ignition source was placed close to the front of the wood crib on the bottom of the weighing platform with a HRR of around 2.4 kW. The duration was estimated to be around 2 minutes.

Nine couples of full cone nozzles were installed in the second section of the model tunnel, as shown in Figure 1 (c). The interval between two neighbouring nozzles was 0.3 m. In tests with a deluge system, the nozzles were activated 75 s after ignition. The orifice diameter was 0.0007 m. The water spray was directed through a band between 0 and 60° from the vertical axis. The flow rate of each nozzle was 0.38 L/min.

Full scale experiments
The full scale experiments were conducted in Runehamar tunnel [2]. The tunnel is around 1600 m long, 9 m wide and 6 m high with a cross-section of about 47 m². The fire was located around 600 m from the east portal. Wood pallets were used as the fire source in these large scale tests. The initial purpose of this test series was to investigate the fire suppression effects using large droplet fire suppression systems. However, in one test the spray system failed to start due to a pipe breakage. Thus, this test is close to a free-burn test and is selected for this study. The instrumentation near the fire is shown in Figure 2 (a). The free burn test (Test 6) and a test with water sprays (Test 1) are selected for this study. The ventilation velocity was around 2.5 m/s during the test.

The fire source consisted of 420 wood pallets, as shown in Figure 2 (b). In addition, a target consisting of a pile of 21 wood pallets was positioned 5 m from the rear end of the fuel mock-up. The fire source was covered with steel plates on both the front and back, and above the pallets. The ignition source was two rectangular heptane pools (0.2 m × 0.8 m) placed on the bottom and at the front of the fuel. Together they produced a HRR of about 500 kW with a duration of about 5 min.

The position of nozzles in the tunnel cross-section is shown in Figure 2(c). Six side nozzles were placed in the vicinity of the fire with a spacing of 5 m. The orifice diameter was 24 mm. The water droplets were discharged to one side with a flow rate of 375 L/min for each nozzle.
CFD METHODOLOGY

Fire Dynamics Simulator (FDS) has become a widely used CFD tool in the fire community and its version 6.5.3 [4-5] is applied in this work. For vehicle fires with solid fuels which is the main concern of this study, it is known that the key mechanism of fire suppression for a low-pressure system is surface cooling. For the purposes of evaluating the fire suppression effects of such fire suppression systems, the pyrolysis of fuel needs to be suitably modelled which serves as the precondition for problem-solving.

Methods

There are different methods for pyrolysis modelling. For solid fuels like wood, the Arrhenius pyrolysis model is widely used in literature. For the Arrhenius pyrolysis model, the surface suppression effects can be directly accounted for, while the Arrhenius pyrolysis model contains many parameters that may be difficult to obtain or estimate. An alternative method is the simple ignition model. For the simple ignition model, a pre-set fire curve is used for the burning of ignited fuels and the suppression effects are accounted for by a semi-empirical model, while the determination of the key coefficient for this model may pose a problem for modelling. Both methods are used and assessed in this work.

Simple ignition model

In this method, the key parameters are HRRPUA (HRR per unit area, kW/m²) and ignition temperature (°C) besides the thermal properties. A study about wood ignition temperature in Babrauskas [6] suggests that the ignition temperature is around 250 °C for wood exposed to the minimum heat flux. Piloted ignition at heat fluxes sufficient to cause a direct-flaming ignition normally occurs at surface temperatures of 300 - 365 °C. In the current study, the ignition temperature was fixed at 300 °C. In the simulation, heat convection plays an important role in determining the surface temperature. The sample dimension was used as the convection length scale. In model scale, the HRRPUA was 190 kW/m² and it took 10 seconds to ramp up to this level. BLUK_DENSITY [4] was specified to make the total amount of mass independent of grid resolution.

Arrhenius pyrolysis model

In the Arrhenius pyrolysis model, the parameters for pyrolysis reactions need to be determined. The pyrolysis can be modelled as one global reaction [7-8] or reactions of several components [9-10]. For each reaction, the kinetic parameters include A, E in Arrhenius equation and heat of reaction. A is the pre-exponential factor in s⁻¹, E is the activation energy in kJ/mol. Typically, A and E can be derived from a common set of experiments, like TGA (thermogravimetric analysis). The heat of reaction is the amount of energy consumed, per unit mass of reactant that is converted into reaction products, i.e. enthalpy difference between the products and the reactant. Most solid phase reactions are
endothermic, i.e. take energy out of the system. An endothermic reaction is indicated by a positive value in FDS. Heat of reaction is usually not a constant during the thermal degradation process but changes its value and its sign [11].

Novozhilov et al. [11] conducted CFD study of wood combustion. In the study A was fixed at $5.25 \times 10^7$ s$^{-1}$ and E was varied at 125.6 kJ/mol and 110 kJ/mol. Heat of reaction was fixed at 0 kJ/kg. Alves and Figueiredo [12] used six components to model the pyrolysis of wet wood. The main components were Hemicelluloses (19%) and Cellulose (50%). For Hemicelluloses, $A=0.70 \times 10^5$ s$^{-1}$, $E=83$ kJ/mol and heat of reaction was -233 kJ/kg. For Cellulose, $A=0.20 \times 10^{10}$ s$^{-1}$, $E=146$ kJ/mol and heat of reaction was 322 kJ/kg. Di Blasi and Branca [7] found that a one-step global reaction was a degradation mechanism capable of capturing the main features of wood pyrolysis. The parameters were: $E=141.2 \pm 15.8$ kJ/mol and $ln A = 22.2 \pm 2.9$ s$^{-1}$ ($A = 2.41 \times 10^8 - 7.96 \times 10^{10}$ s$^{-1}$). Sinha et al. [13] conducted a review on the modelling of pyrolysis in wood. Sinha et al. found that most models have generally accounted for primary reactions through apparent kinetics and in some cases, some of the secondary reactions through multi-step reaction schemes. A one-step global reaction model was presented by Tinney [14], where the pyrolysis was divided into two stages, one before breakpoint and one after. Before the breakpoint, $A = 6 \times 10^{-7} - 7.5 \times 10^8$ s$^{-1}$ and $E=125$ kJ/mol, heat of reaction was 125 - 210 kJ/kg. After breakpoint, $A = 4 \times 10^5 - 2 \times 10^9$ s$^{-1}$ and $E=152 - 179$ kJ/mol, heat of reaction was 840 - 2300 kJ/kg. In the review the reported values of the heat of reaction of wood ranged from -1680 to 613kJ/kg. In the study of Vijee et al. [15], the pyrolysis of wood was divided into five reactions making use of four generic species: wood, gas, char and tar. Matala et al. [8] found that the scheme to model birch pyrolysis as a one-step reaction gave a better prediction of TGA curve than scheme modelling the pyrolysis as three one-step reactions of the components (Cellulose, Hemicellulose and Lignin). The kinetic parameters of the simple one-step reaction for birch were: $A=7.51 \times 10^{11}$ s$^{-1}$, $E=161$ kJ/mol and heat of reaction 230 kJ/kg. The kinetic parameters are model dependent and should be used only in models with similar structures. In the modelling of wood pyrolysis by Grieco and Baldi [16], the process was divided into primary pyrolysis and secondary reaction. In primary pyrolysis, wood changed into light gases and tars (low, mean and high molecular weight) with parameters $A=1.035 \times 10^7$ s$^{-1}$ and $E=87.5$ kJ/mol. In the secondary reaction, mean and high molecular weight tars underwent reaction into gases and char with parameters $A=1.18$ s$^{-1}$ and $E=45$ kJ/mol. Wang et al. [10] applied FDS pyrolysis model to predict HRR in small-scale forced ventilation tunnel experiments. Medium-density fireboard (MDF) was used as fire source and was represented by four components: Resin (10%), Hemicellulose (42%), Cellulose (36%) and Lignin (12%). For Resin, $A=6.24 \times 10^{15}$ s$^{-1}$, $E=130$ kJ/mol. For Hemicellulose, $A=7.64 \times 10^{12}$ s$^{-1}$, $E=157$ kJ/mo. For Cellulose, $A=6.78 \times 10^{13}$ s$^{-1}$, $E=192$ kJ/mol. For Lignin, $A=3.90 \times 10^{19}$ s$^{-1}$, $E=196$ kJ/mol.

In this study, the wood pyrolysis was modelled as a one-step reaction, with 88 % mass turning into combustible fuel, 7 % into water vapor and 5 % left as char. The thermal properties of char were from Richter et al. (2019), with density 162 kg/m$^3$, conductivity 0.084 W/(m·K) and specific heat 1.1 kJ/(kg·K). Based on the literature, the activation energy E was fixed at 100 kJ/mol and heat of reaction was fixed at 2200 kJ/kg. The pre-exponential factor A was determined through a series of numerical simulations, and it was found $A=3 \times 10^8$ s$^{-1}$ gave results close to the experiment. As indicated in Matala et al. [8], the kinetic parameters are associated with a specific reaction scheme having no fundamental physical significance, their values can indeed be chosen freely in order to get the best possible description of reality using the model in hand. In addition, Vaari et al. [17] found the actual values of the parameters A, E to be less important than the ratio between the parameters.

**Fire suppression modelling**

The nozzles discharge water droplets with sizes following a given pattern, which is usually described by a cumulative volume fraction (CVF) [4]. In the simulations, the default CVF curve was applied and the particles released per second per nozzle was set as 10000. By applying the same methodology as described in Ref. [18], the volumetric medium diameter of the water drops was estimated to be 223 µm for the small scale test 24, and 1910 µm for the full scale test 1.
In the simple ignition model, the way to account for the fire suppression by water is to characterize the reduction of the pyrolysis rate in terms of an exponential function [19,17,5]:

$$m_f'(t) = m_{f,0}'(t)e^{-\int k(t)dt}$$

(1)

where $m_{f,0}'$ (kg/s) is the burning rate per unit area when no water is applied and $k$ (1/s) is a function of the local water mass per unit area, $m_W''$, (kg/m$^2$) in FDS as follows [5]:

$$k(t) = E_{coef} m_W''(t)$$

(2)

This suppression coefficient, $E_{coef}$ (m$^2$/kg·s), is supposed to be obtained experimentally and serves as input into FDS. It is an empirical constant that is dependent on the material properties of the solid fuel and its geometrical configuration. Yu et al. [19] proposed a similar correlation from a global energy equation upon some assumptions, trying to characterize how water sprays affect the burning in the initial region and the fire spread region. The correlation is not directly applicable to local fuel surfaces, as it is in FDS. However, there was some evidence supporting this model [17,5]. Note that Yu et al.'s work [19] use the local water density while FDS uses the local water mass as the variable in the function of $k$. Consequently, the use in FDS is mainly based on comparisons between experimental and numerical results.

The local water mass per unit area, $m_W''$ in kg/m$^2$, is numerically calculated. So the unknown parameter is $E_{coef}$, which is assumed to be dependent mainly on type and configuration of fuels. So if this parameter is approximately known from a specific scenario by comparisons of experimental and numerical data, it might be applicable to other scenarios with the same type and configuration of fuels. It should be noted that this parameter is not a non-dimensional term and the physical meaning also indicates it is scale dependent. According to the Froude scaling, this suppression efficient follows:

$$E_{coef} \propto l^{-3/2}$$

(3)

This indicates that the ratio of $E_{coef}$ in 1:15 model scale to that in full scale is 0.017. If the former is 200, the latter is 3.4. This scale effect will be further explored in the following sections. Different values are used for a sensitivity analysis. It can be known from Eqs. (1) and (2) that the suppression efficient $E_{coef}$ should be equal to or greater than 0. The physical meaning is that the water suppresses the pyrolysis of the fuel and thus its burning.

In the Arrhenius pyrolysis model, there is no need to set any additional suppression parameters. It is assumed that water impinging on the fuel surface takes energy away from the pyrolysis process and thereby reduces the burning rate of the fuel.

In both models, the movement of water after hitting fuel surfaces affects the results. After hitting a horizontal surface, a liquid droplet is assigned a random horizontal direction and moves at a fixed velocity until reaching the edge where it drops down at a fixed velocity. The direction is downwards if vertical. By default, the horizontal velocity, $u_h$, and vertical water spread velocity, $u_v$, are set as 0.2 m/s and 0.5 m/s, respectively [4]. While attached to a surface, the “droplet” is assumed to form a thin film of liquid with a minimum film thickness of 0.01 mm. It is also assumed that the liquid is opaque with regard to thermal radiation. In the simulations, the spread underneath the objects is allowed by default.

**SIMULATION RESULTS OF SMALL SCALE EXPERIMENTS**

**Free burn test – Small scale**

**Simple ignition model**

The simulation domain was 2.5 m × 0.6 m × 0.4 m. The longitudinal velocity was 1.0 m/s. For wood, the conductivity is fixed at 0.11 W/(m K) and specific heat is 1.5 kJ/(kg K), which is adapted from
Due to the limit of computational capacity, a suitable mesh system should be adopted. Four mesh systems were studied. The mesh information is given in Table 1 and HRR is shown in Figure 3(a). Mesh 1 shows a much slower growing rate while the difference between other systems is small, and therefore mesh 2 was used in current study.

<table>
<thead>
<tr>
<th>Test</th>
<th>cell size (m)</th>
<th>Number of cells</th>
<th>Total cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>mesh 1</td>
<td>0.025 × 0.025 × 0.025</td>
<td>100 × 24 × 16</td>
<td>38400</td>
</tr>
<tr>
<td>mesh 2 (used)</td>
<td>0.025 × 0.0125 × 0.0125</td>
<td>100 × 48 × 32</td>
<td>153600</td>
</tr>
<tr>
<td>mesh 3</td>
<td>0.0125 × 0.0125 × 0.0125</td>
<td>200 × 48 × 32</td>
<td>307200</td>
</tr>
<tr>
<td>mesh 4</td>
<td>0.0167 × 0.0083 × 0.0083</td>
<td>150 × 72 × 48</td>
<td>518400</td>
</tr>
</tbody>
</table>

The HRR from the experiment and the simulation is shown in Figure 4(a). The fire growth rate and maximum HRR are well modelled, although the simulation shows a longer steady state period and a faster decay period. Part of the reason is that the flame extends to the outside of the domain when the full crib is burning. Nevertheless, this happens only within a short period of time and the influence on the result is small.

Arrhenius pyrolysis model

As in the simple ignition model, four mesh systems with the same size as in Table 1 were tested. The HRR curves are shown in Figure 3(b). Mesh 1 gives significantly slower fire growth rate, smaller maximum HRR and smaller total energy release. Results from Smokeview visualization show that the mass left after combustion in mesh 1 is larger than the other cases, thus the total energy is smaller. Differences are also found between mesh 2, mesh 3 and mesh 4, but due to the limit of computational...
power, mesh 2 was used in current study. Compared with the simple ignition model, the method of modelling combustion by complex pyrosis model is more sensitive to the mesh size.

HRRs from the experiment and simulation are compared in Figure 4(b). The fire growth rate is suitably modelled while it takes slightly longer to reach the maximum HRR in the simulation. Total energy release is smaller than the one in the simulation. One reason is that due to the water vapor and char defined in the numerical setup, the combustion of wood crib is not complete and there is crib left after HRR drops to 0 kW.

**Fire suppression test – Small scale**

*Simple ignition model*

HRR from the experiment and simulation (the simple ignition model) with various suppression coefficient $E_{\text{coef}}$ is shown in Figure 5. In the experiment, after activation of the water spray system, the HRR first increases slightly and then remains at a plateau of approx. 33 kW for about 20 seconds, after which it decays quite rapidly and drops to 0 kW at about 170 s.

By contrast, the decay trend of the numerical results is much slower. This applies to all the cases. No single value for $E_{\text{coef}}$ can produce results that exactly match the experimental data. Such phenomenon was also observed by Vaari *et al.* [17]. They also raised the question about the validity of the suppression coefficient model for suppression of wood pallet fires.

The simulation results vary significantly with the suppression coefficient. The trend is clear that as the suppression coefficient increases from 50 to 2000, the water sprays suppress the fire more rapidly. When the suppression coefficient is below 50, the maximum HRR is greater than the experimental value. The experimental data lie between $E_{\text{coef}} = 100$ and $E_{\text{coef}} = 500$. The value of 200 may be a good estimation.

![Figure 5. Comparison of small scale HRRs. Simple ignition model with default velocities.](image)

One reason could be the lack of water film model in FDS. Instead, fixed horizontal and vertical water spread velocity are applied, i.e., 0.2 m/s and 0.5 m/s, respectively. The vertical spread velocity may refer to the data of 0.55 m/s determined by injecting a coloured dye into a stream of water that cascaded down the side of a carton [22]. It is unclear where the 0.2 m/s comes from. It could be expected that both the vertical and horizontal spread velocities are related to the flow rate and the surface characteristics, and they may not be fixed values. In principle, there are scale effects on these parameters. Use of these default values may cause problem in case that the scales are different to the carton surface tested. Some materials behave as porous materials and allow water to penetrate through while materials like wood may absorb a certain amount of water. These behaviours differ from smooth surface. In reality, there may be no smooth surface for partly burnt surfaces, e.g., charring surfaces or folded plastics. It is expected that these velocities may probably be overestimated for small burning objects such as wood sticks in the small scale tests studied here.
To model fire suppression, the surface water spread can be important as it extends the area affected by water sprays, thus preventing flame spread through surfaces. Despite the fact that the use of horizontal and vertical water spread velocities reflects this important phenomenon, the sensitivity of these two parameters needs to be assessed in each scenario.

An extreme case is that the water does not spread along surface even if it survives from the fire plume and heating from surfaces, i.e., both water surface spread velocities \( u_h \) and \( u_v \) are set to 0. The results are shown in Figure 6(a) with three different values for the suppression coefficient and no surface water spread. The heat release rate continues to increase after activation of water sprays. The results indicate that applying no surface water spread highly underestimated the efficiency of the water spray suppression. The setting needs to be eased somewhat. Note that the simulations further than around 200 seconds were not conducted due to the long computation time and the clear trend already found.

Therefore, the impacts of horizontal surface spread and vertical surface spread on the results are further investigated for \( E_{\text{coef}} = 200 \). We may set only the horizontal velocity or the vertical velocity to zero. The results are shown in Figure 6(b). By reducing only one velocity to zero (\( u_h = 0 \) or \( u_v = 0 \)), the HRR after activation becomes much higher than the one with the default velocities, and the HRR with no horizontal spread (\( u_h = 0 \)) is much higher than the one with no vertical spread (\( u_v = 0 \)). Further, the HRR with no horizontal spread is similar to the one with no water spread (\( u_h = 0 \) and \( u_v = 0 \)). The significance of horizontal and vertical velocities can be known as follows. On one hand, if the default spread case is considered as a reference, only reducing the horizontal velocity to zero results in a greater increase in HRR, than only reducing the vertical velocity to zero. On the other hand, if the no spread case is considered as a reference, increasing the horizontal velocity to the default value (the case with \( u_h = 0 \)) cause a much greater reduction in HRR. Further, note that the change of horizontal velocity is 0.2 m/s in comparison with 0.5 m/s for the vertical velocity. Therefore, it is clear that the smaller change in horizontal velocity causes a more significant change in HRR. In other words, the horizontal spread has a more significant influence on the HRR than the vertical spread in this scenario.

Above all, the simple method using the suppression coefficient to consider the suppression effects only approximates the real scenarios and the decay trend is not well captured.

![Figure 6](image_url)

**Figure 6.** Comparison of small scale HRRs. Simple ignition model with various velocities.

**Arrhenius pyrolysis model**

HRRs from the experiment and simulation of Test 24 are shown in Figure 7. In the simulation with default water spread velocities, HRR immediately drops from 33 kW to about 13 kW after activation but increases slightly to around 18 kW at 2 min and drops to zero within a short period. The simulation results indicate that effective fire suppression is achieved, the same as in the experiment. However, the simulated suppression effect seems to be more prominent than in the experiment. Thereafter, the effects of water surface spread velocities are investigated (see Figure 7). The results
show that the suppression effect becomes less significant if either both water surface spread velocities are set to zero or only the horizontal velocity is set to zero. In the case of both velocities set to zero, the fire keeps burning after 2 min for a long period, which differs from the experiment results.

![Figure 7. Comparison of small scale HRRs. Arrhenius pyrolysis model with various velocities.](image)

Overall, it could be concluded that using the Arrhenius pyrolysis model is more capable of reproducing the whole heat release rate curve when using suppression model. The use of the simple ignition model is quite empirical and there appears no single value for the suppression coefficient that can be used to reproduce a test curve. However, it should be noted that it is possible that the pyrolysis method may have overestimated the suppression efficiency. A better scenario for such a study would be a case with stronger interaction between fire and water spray system, i.e., a case with the resulting fire curve that either decreases slowly after activation or increases slowly first and then decreases.

It is interesting to find that the horizontal spread velocity plays a key role in fire suppression in the simulated scenario and should be treated as such in simulations.

**SIMULATION RESULTS OF FULL SCALE EXPERIMENTS**

**Simplification of wood pallets – Full scale**

The fire source in the experiment is comprised of 420 wood pallets, with some wood boards having a thickness of 0.022 m. To simulate the combustion of such pallet piles, a very fine mesh is required. Due to the limit of computational resource and the size of the domain of concern in real fire scenarios, the structure of the wood pallets needs to be simplified.

To properly simplify the structure, four basic parameters need to be accounted for: maximum HRR, total energy release (integration of HRR), fire growth rate, and total mass, according to the work by Li and Ingason [20]. These four parameters are presented in Eq. (6) to Eq. (9). The simplified structure is expected to preserve these four parameters, or at least first three, if the total mass is difficult to be preserved. Besides, the external profile of the wood pallets should be preserved.

The fire growth rate in ventilated fires could be expressed as follows [21]:

$$\frac{dQ}{dt} \propto \frac{\dot{m}_f'' x \Delta H_c}{(kpc)_f} w_p u_0 = \frac{\chi \dot{q}_f''}{(kpc)_f} w_p u_0$$  \hspace{1cm} (6)

The maximum HRR is:

$$Q_{\text{max}} = \dot{q}_f'' A_{f,\text{ex}}$$  \hspace{1cm} (7)

Total energy release is:
\[ E = \rho V_f \Delta H_c \]  

Total mass:

\[ m = \rho V_f \]

where \( Q \) is heat release rate, \( t \) is time, \( \dot{m}_f' \) is burning rate per unit area, \( \chi \) is the fraction of heat received by fuel surface, \( \Delta H_c \) is the heat of combustion \( kpc \) is the thermal inertia, \( w_p \) is wet perimeter, \( u_a \) is air velocity, \( A_{f,ex} \) is exposed fuel surface area, \( V_f \) is fuel volume, \( \rho \) is density, and \( m \) is fuel mass. Note that \( \dot{q}_f' = \dot{m}_f' \Delta H_c \) is the HRRPUA. In a large tunnel fire, the longitudinal flame spread dominates the fire development [21]. It is preferred that fire growth rate remains the same along all three directions in the simplified fuel geometry, but the growth rate along \( x \) direction takes priority.

In a simplified structure, the geometry parameters are expected to be changed while the physical parameters should be changed as little as possible, to model realistic burning behaviours. By changing different parameters, different simplified structures can be developed. In this work, the thermal properties \( k \) and \( c \), and the density remain the same, and thus the thermal inertia is preserved. The methodology applied here is to establish an element and thus pile them up as for a wood pallet pile. Due to the limitation of grid size, the exposed area becomes less, and thus the HRRPUA increases. The latter indicates a smaller wet perimeter. It is found that the total mass is difficult to be preserved and thus ignored. To preserve energy, the total volume increases. In summary, the maximum heat release rate, the fire growth rate, and the energy content are approximately preserved. A summary of the parameters is shown in Table 2.

**Table 2. Parameters of the new wood pallet pile.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( A_{f,ex} )</th>
<th>( V_f )</th>
<th>( w_{p,x} )</th>
<th>( \Delta H_c )</th>
<th>( \dot{q}_f'' )</th>
<th>( \rho )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m(^2)</td>
<td>m(^3)</td>
<td>m</td>
<td>MJ/kg</td>
<td>kW/m(^2)</td>
<td>kg/m(^3)</td>
</tr>
<tr>
<td>Model</td>
<td>352</td>
<td>40</td>
<td>14</td>
<td>9.2</td>
<td>312</td>
<td>490</td>
</tr>
</tbody>
</table>

The new wood pile consisted of 48 elements, with 6 in \( x \) direction, 1 in \( y \) direction and 8 in \( z \) direction, as shown in Figure 8. The centre of pile is in the position \( x=0 \) m. The structure of one segment is also shown in Figure 8. The dimension of the element was 1.4 m (L) \( \times \) 2.4 m (W) \( \times \) 0.4 m (H). It can be divided into an upper part and a lower part. In the upper part, a hollow space (i.e. hole) at the centre was created to allow air going through. The width of the hole was 0.2 m and the length was 1.6 m. In the lower part, six blocks were defined. The four blocks at the front and rear were 0.4 m \( \times \) 0.4 m \( \times \) 0.2 m. The two blocks in the middle were 0.4 m \( \times \) 0.6 m \( \times \) 0.2 m. The target was modelled by 8 elements but with half of the width (1.2 m).

![Figure 8. Simulation geometry in FDS, full scale.](image-url)
Free burn test – Full scale
The tunnel geometry built in FDS is shown in Figure 8. To save computation time, tunnel length was reduced to 40 m ($x=20$ m to $x=20$ m), with fire source centre at $x=0$ m. HRR from the experiment and simulation is shown in Figure 9. Results from Smokeview show that the flame extends outside the right boundary. To determine a minimum tunnel length required to fully combustion, the computation domain downstream the fire source was extended to 25 m ($x=25$ m) and 30 m ($x=30$ m). It is found that even with outlet boundary $x=30$ m, flame can still extend to the outside of computation domain. Due to the limit of computation power, a longer tunnel was not studied. Instead, HRR is calculated from the generation rate of fuel gas (MLR_FUEL) and heat of combustion for the free burn test.

It can be seen from Figure 9 that HRR during the first 1000 s is well modelled. Visualization from Smokeview shows that at 1000 s the fire has spread to the target and most part of the wood pile. The total energy release is closely the same in the experiment and in the simulation. The maximum HRR in the simulation is 65 MW, slightly smaller than that in the experiment. This may partly be explained by the fact that some wood pallets may collapse during the test. Overall, the HRR development can be suitably modelled with the simplified structure for EUR wood pallets.

![Figure 9. HRRs from full scale experiment and simulation.](image_url)

Fire suppression test – Full scale
The results for HRR with default fixed water surface spread velocities are presented in Figure 10. Various values were set for $E_{\text{coef}}$. As mentioned above, the value for $E_{\text{coef}}$ is smaller. The 1:15 model scale value of 200 corresponds to a full scale value of 3.4. Therefore, the initial values investigated are 1 and 10. It is shown in the figure that as $E_{\text{coef}}$ decreases from 10 to $10^{-2}$, the HRR shows an increase trend, but it becomes insensitive to $E_{\text{coef}}$ after it is lower than $10^{-4}$. Therefore, further decreases is considered unnecessary. It is clear that the HRR is underestimated after 600 seconds, for all of cases, regardless of $E_{\text{coef}}$. This indicates the overestimation of the suppression efficiency by the CFD model. This is slightly different from the results shown in Figure 5 for a wood crib fire.

![Figure 10. HRRs from the full scale experiment and simulations with default velocities.](image_url)
Water movement along fuel underside

The above results force us to reflect on the choice of allowing the water spread underneath the objects. Some simulations were conducted, not allowing the water spread underneath the objects and the results are shown in Figure 11. However, the differences are not so significant as expected.

![Figure 11. HRRs from the full scale experiment and simulation with default velocities and no water spread underneath.](image)

No surface water spread

The use of surface spread velocities may cause additional problems. In the tests the wood pallets were packed in piles but there were small gaps between the piles which allow water dripping or spilling. However, in the numerical model, the surfaces were connected, due to the use of simplified structure and also due to the limitation of grid size. This may indicate that the unevaporated water on surface can continue to travel along the surface even to a far point that is unrealistic at a relatively high speed. If there is no fire and the surface spread is allowed, the whole fuel bed may be full of water after a while even if the only spray is from one top corner of the fuel, as the fuel bed in the simulations is connected together. Therefore, special cautions need to be taken here. In this case, we have a good argument to reduce or eliminate the surface spread velocities, especially the horizontal surface water spread.

At first, the water surface spread is turned off. The results with no surface spread and various suppression coefficients are given in Figure 12. Notice that by turning off the surface spread, the spread underneath the objects is also forbidden. It is obvious that the heat release rate starts to increase after the activation of water sprays, in contrast to the decay trends presented in Figure 10 with default water surface spread velocities.

The results show that the HRR is lower than the experimental data before 1000 seconds, but becomes higher afterwards. The results are insensitive to the suppression coefficient before 2000 seconds. The case with $E_{\text{coef}}=0.01$ appears to produce higher HRR after 2000 seconds, which is around 30 MW.

Note that the curve plotted refers to the heat released within the computation domain, and the calculation of possible HRR based on mass loss indicates a possible 20 % increase above 25 MW but it is uncertain whether it is because of the suppression effect or the unburnt fuel. This value is much
higher than the experimental result. Therefore, such a setting cannot reproduce the experimental data. This indicates that preventing all surface spread tends to have affected the suppression capacity too significantly in the simulations. This needs to be eased to a certain extent, the same as for the wood crib fire.

![Graph](https://via.placeholder.com/150)

**Figure 12.** HRR from the experiment and simulation, with no surface water spread velocities.

*Various surface water velocities*

Therefore, simulations with lower velocities have also been conducted and results are shown in Figure 13. The coefficient is set to be 0.01. The results show that using either 20 % or 50 % of the default velocities even results in lower heat release rate after water spray activation, compared to the case with the default velocities. The reason could be that for a smaller vertical velocity, more water may be accumulated on surfaces, causing more water flowing through horizontal surfaces.

Two additional simulations were conducted for comparison, one with no horizontal water spread and another with no vertical water spread. Rather similar trends can be found here as for the wood crib fire. By reducing only one velocity to zero (\(u_h=0\) or \(u_v=0\)), the HRR after activation becomes much higher than the one with the default velocities. The HRR with no horizontal spread is similar to the one with no water spread (\(u_h=0\) and \(u_v=0\)). The same analysis as for the wood crib fire scenario can be applied here. On one hand, if the default spread case is considered as reference, only reducing the horizontal velocity to zero results in a greater increase in HRR, than only reducing the vertical velocity to zero. On the other hand, if the no spread case is considered as reference, increasing the horizontal velocity to the default value (the case with \(u_v=0\)) cause a much greater reduction in HRR. Therefore, it is clear that the smaller change of horizontal velocity (0.2 m/s compared to 0.5 m/s) causes a greater change in HRR. In other words, the horizontal spread has a more significant influence on the HRR than the vertical spread in this scenario.
After turning off at least one water spread, the heat release rate curves are closer to the experimental curve before 1600 s, which is encouraging. The best results correspond to the case with only the horizontal water spread and no vertical water spread. To further explore the influence of the horizontal and vertical velocities, sensitivity analyses of the two velocities are conducted respectively in the following sections.

**Impacts of horizontal velocity of water on surfaces**

The results for various horizontal velocities of water on surfaces are shown in Figure 14. The used horizontal velocities refer to 100%, 50%, 20%, 10%, 2.5%, and 0% of the default value, and the vertical spread velocity is kept as the default. The results show that the HRR is not sensitive to the horizontal velocity between 0.02 m/s and 0.2 m/s. When it is reduced to 0.005 m/s, its influence on HRR becomes significantly higher. A further decrease to zero causes a huge increase in HRR. The correlation is clearly not linear.

**Impacts of vertical velocity of water on surfaces**

The results for various vertical velocities of water on surfaces are shown in Figure 15. The used vertical velocities refer to 100%, 50%, 20%, 10%, and 0% of the default value, and the horizontal spread velocity is kept as the default. The results show that the HRR decreases with the decreasing vertical velocity between 0.05 m/s and 0.2 m/s. However, a further decrease of the vertical velocity to 0 m/s significantly increases the HRR. The relationship is clearly not monotonic.
CONCLUSIONS

Two methods to simulate the fire development in tunnels with suppression systems were assessed, i.e., simple ignition model and Arrhenius pyrolysis model used in FDS. The suitability of the models for fire suppression modelling are investigated and discussed, including the sensitivities of some key parameters. Both small scale and full scale experiments with and without suppression systems are selected for this study. A simplification method is proposed to simplify the geometry of wood pallet piles used in the full scale tests. The links of CFD modelling between the small scale and large scale are explored.

For the free burn tunnel fire tests, both the simple ignition model and Arrhenius pyrolysis model can approximately reproduce the heat release rate curves. Note that the latter is only used for the model scale scenario.

For fire suppression tests, the simple ignition model using the exponential function to consider suppression effect with $E_{coef}$ and the default water surface spread velocities does not reproduce the fire development process. In the model scale scenario, the simulated decay period is much longer than that in the test. For the full scale scenario, no proper value for $E_{coef}$ with the default water velocities is found to well correlate with the experimental data.

The suppression coefficient $E_{coef}$ has a scale effect. It becomes smaller in a larger scale. In theory, it approximately follows $-3/2$ power of the length scale for a given configuration, while the comparison shows that the sensitivity to the length scale can be even greater than the $-3/2$ power of the length scale.

The sensitivity analyses show that the surface water spread plays a key role in suppression modelling. The relationship between the surface spread velocities and the results may not be monotonic. The most significant influence of the surface spread velocities on the results is found when either of them becomes zero. It seems to be that the horizontal spread plays a more significant role than the vertical spread in fire suppression for the scenarios investigated.

The surface water spread is a phenomenon of a different order of magnitude, typically much smaller than a grid size for tunnel flow modelling. A special sub model such as a film model is required to model the water transportation in order to accurately predict the water flow behaviour, which plays a key role in fire suppression. The obstacle to fire suppression modelling is not only the water film model but also the complex geometry of fuels involved in combustion in real fires and in fire testing.
Note that there are some parameters that have not been assessed but may be very important, e.g., the heat and mass transfer between the water and the fuel surface, the flammability in flow with dense water vapor, the water absorption of surfaces.

The work could serve as a reference for further research on modelling of water-based suppression systems in tunnel fires. It also helps improve the understanding of fire suppression modelling. The design of fire load equivalent to the wood pallets could be refined in future work. From the user’s point of view, the simple ignition model is robust in modelling fire development with limited parameters to be calibrated, but the related suppression coefficient model for water-based fire suppression system should be used with caution as not all the key physics are well considered. Further work should be conducted concerning the use of the Arrhenius pyrolysis model in modelling of fire development in tunnels with and without a water-based fire suppression system.

ACKNOWLEDGEMENT

The project was financially supported by Tunnel and Underground Safety Center (TUSC) which is gratefully acknowledged.

REFERENCES

Experimental study of the performance of a water mist system on fires in a full-scale tunnel

Lei Jiang, Robert Harley Mostad, Tian Li, Kemal Sarp Arsava, RISE Fire Research AS, Box 4767, NO-7465 Trondheim, Norway

ABSTRACT

A full-scale fire test was conducted to investigate the performance of a high-pressure water mist system in the Runehamar Test Tunnel in 2021 in Norway. The tunnel is approximately 1.6 km long, 9 m wide, and 6 m high. The main fire load consisted of 408 standardised wood pallets to represent a Class A fire of Heavy Goods Vehicles (HGV). The activation of the water mist system was determined by the gas temperature measurement above the mock-up, with a threshold value of 60 °C. The water mist pump unit was activated manually with a time delay of 3 min. It was found that the HRR (heat release rate) was reduced to 44 MW in the simulated HGV fire designed according to SOLIT² guidelines. Moreover, the system was able to prevent fire spread to a target placed 5 m away from the fire source. The tests conducted were based on SOLIT² guidelines but with minor modifications. Key measurements, such as gas temperature, gas concentrations, heat release rate and heat flux, are discussed. The guidelines for performing tunnel fire tests with water suppression systems are discussed, and recommendations are provided.

KEYWORD: Tunnel fire, Full scale, Ventilation, Water mist, Guidelines

INTRODUCTION

The use of water fire suppression systems in buildings has a long history, while the use of these systems in tunnels has also received attention in recent years [1,2]. Based on the water droplet size, the fire suppression system in tunnels can be divided into deluge sprinkler and water mist systems [3]. For water mist systems, the operating pressure is usually high (over 10 atm, 1 atm=1.01 bar), and the droplet size is small (usually less than 100 μm). The suppression mechanisms include latent cooling, volumetric displacement and dilution of oxygen [4]. For sprinklers, the operating pressure is usually low, e.g., several atmospheric pressure. The main fire suppression mechanism for sprinklers is heat extraction through direct cooling of the fire source and the thermal plume [4]. Compared with a sprinkler system, the water mist system uses significantly less water and reduces the water damage to the fire scene but requires much higher pressure [5].

One main concern of using water fire suppression systems in tunnels is the effect of ventilation. The activation and the fire suppression system can be negatively affected when the water droplets are blown downstream from the fire source by the ventilation flow. Sun et al.[6–8] studied the flow fields induced by longitudinal ventilation and water mist system in a reduced scale tunnel (1:10) and found that the water system could effectively reduce the gas temperature and prevent smoke from spreading in the absence of longitudinal ventilation. However, strong ventilation (0.8 m/s in the test, corresponding to 2.53 m/s in full scale) reduced the effectiveness of blocking the smoke spreading. It was also found that higher water pressure could make the cooling effect stronger. A small-scale (1:15) experimental study by Li and Ingason [9] showed that high ventilation and low water flow rates could result in the failure of an automatic sprinkler system in a tunnel fire. That is partly the reason why deluge systems (zone activation) are used in tunnels today. Water fire suppression can also affect
combustion products. A study in a small-scale tunnel (1:4) by Li and Ingason [10] showed that when the water density was too low, or activation was too late, the CO concentration and visibility could be worse than in the free-burn test.

In addition to small-scale experiments mainly for research purposes, large-scale tunnel fire tests can also be found, such as tests in Second Benelux Tunnel in the Netherlands [11], the Hagerbach tunnel in Switzerland [12], and tests carried out by Efectis commissioned by Land Transport Authority (LTA) Singapore [13]. Change et al. [14] conducted full-scale experiments in Dong-Aw tunnel in Taiwan by using a 6 m$^3$ heptane pool fire as a fire source. However, no mechanical ventilation was provided during the test. With water spray nozzles operating at 3.43 bar and a water flow rate of 360 l/min, the gas temperature directly above the fire could be lowered to below 500 °C within 30 s, and the gas temperature of the other ceiling area would also be lowered below 300 °C, and the heat flux would be lowered below 1 kW/m$^2$, therefore preventing subsequent fire spread. Deluge systems (water spray systems activated in zones) which could deliver 10 mm/min water in the activated zone were tested in the Runehamar Test Tunnel in 2013 [1]. It was found that the HRR was reduced to 20–45 MW compared to 100 MW estimated for a free-burn test. The fire spread to a 5 m away target was also prevented. During the test, the ventilation velocity was set at 3 m/s, close to the estimated critical velocity of 3.3 m/s. A similar study in the Runehamar Test Tunnel in 2016 [15] found that the suppression system with a large droplet (1-2.5 mm) could prevent fire spread to a target 5 m away from the main fuel area, and the fire could be reduced to below 30 MW.

While plenty of fire tests in tunnels can be found, full-scale experiments with high-pressure water mist systems are still rare. Due to the different physics in suppressing fire, a different behaviour may be found from the sprinkler system tested in the Runehamar Test Tunnel in 2013 and 2016 [1,15], and the performance of such systems needs to be verified before installation in an actual tunnel.

In the present work, full-scale experiments were conducted in the Runehamar Test Tunnel in 2021 with high-pressure water mist systems installed. A class A fire representing a realistic severe fire scenario is investigated. A Class A fire is the most common fire involving solid materials normally of an organic nature, and the most effective fire suppression agent is generally water in the form of a jet or spray [16]. While plenty of fire tests in tunnels can be found in literature, few discussions are given about the implementation of the tests. SOLIT$^2$ Research Consortium [17,18] presented guidelines for the evaluation of FFFS (Fixed Fire Fighting System) based on tests conducted in the test tunnel in Asturias, Spain. The tunnel is 600 m long with a width at the base of 9.5 m and a maximum height of 8.1 m. The guidelines provide detailed guidance in performing the tests. For example, it suggests that the fire source should be placed eccentrically rather than on the centre line, which may result in a higher HRR. The test conducted in this study is based on the guidelines in SOLIT$^2$, but with adjustments to give more accurate and correct measurements to fit the conditions in a real tunnel, such as the Runehamar Test Tunnel. The SOLIT$^2$ guidelines are discussed, and recommendations are provided.

**EXPERIMENTAL SETUP**

**Description of the test setup**

The Runehamar Test Tunnel belongs to the Norwegian Public Roads Administration (NPRA), and it was previously a part of the road infrastructure. It is located outside Åndalsnes, Norway, and is a two-way asphalted road tunnel with an approximate length of 1520 m, a width of 9 m and a height of 6 m. The Runehamar Test Tunnel is equipped with electricity and facilities for personnel outside the tunnel and is continuously maintained by the owner, NPRA. To provide a site for fire tests, an 80 m long section of the tunnel is protected by fire-resistant concrete. The fire zone in this study is about 500 m away from the east portal. Prior to the main test, calibration tests were conducted to calibrate the HRR and the measuring equipment with 5 MW and 30 MW diesel pool fires.
In the test setup, a total of 408 Euro wood pallet stacks were used as fuel, stacked in the height of 17 pallets, 2 pallets in width and 12 pallets in length. This fire source was built following SOLIT² [18] to simulate a severe Heavy Goods Vehicle (HGV) trailer fire. According to SOLIT² guidelines, a minimum of 400 pallets corresponds to a minimum fire size of approximately 110-140 GJ with a potential HRR of 150 MW. A fire target with 34 pallets was located 5 m downstream from the mock-up to evaluate the risk of fire spread. The fire target had the same width, height, and fuel (Euro wood pallets) as the mock-up but was only 1 pallet in length. The moisture content was estimated by randomly checking the pallets. With the measurement of nine spruce-based pallets and nine pine-based pallets, the average moisture content was 15.3% and 13.8%, respectively.

The mock-up of the fire load and the target is shown in Figure 1. The geometry of the mock-up corresponded to a typical HGV of 10 m long, 2.4 m wide and 4 m high. The Euro wood pallets were fastened together to prevent them from falling apart and were stacked on a concrete platform covered with non-combustible fibre cement plates. The platform was on top of concrete elements with a total height of 1.5 m. The back and front of the mock-up were covered with a steel plate, representing the truck or trailer doors, and blocking the air access straight inside the mock-up. In the class A fire test in this report, a PVC tarpaulin was used to cover the fire load. The tarpaulin was not fire retardant and was fixed to the Euro wood pallets with staples. The ignition source was two small pans of size 0.6 m × 0.15 m × 0.05 m filled with 2 litres of heptane. The pans were placed inside the first pallets on the side of the mock-up (the second stack of pallets on the upstream front). During the test, the pallets were secured against collapsing to the floor by a steel framework (not shown in Figure 1).

![Figure 1. Fire load and target consisted of EUR wood pallets.](image)

The position of the fire mock-up was eccentric relative to the centre line in the test tunnel, and the distance from the tunnel side wall to the mock-up was less than 1.5 m. Seen from upstream towards downstream, the mock-up was positioned on the left side of the Runehamar Test tunnel. Based on measurement tests performed at SP Technical Research Institute of Sweden [19], the theoretical value of heat of combustion for wood was 16.7 MJ/kg. The number of pallets used (408) and the average weight of pallets used in this test series (22.43 kg) gave a theoretical design fire load of 153 GJ. The higher content of total available energy in these tests, compared to that in the SOLIT² tests, might be caused by the lower moisture content of the wood pallets in the environment of the Runehamar Test Tunnel. Including the target pallets, the entire fire load gave an energy content of 165 GJ. In designing the fire load, a low value of heat of combustion was used, which gave potential energy content in a conservative way. Using a higher heat of combustion of 17.9 MJ/kg [20], the fire load was 164 GJ, and the entire fire load, including the target pallets, was 177 GJ.
To generate the ventilation flow, 5 fans were placed at 550 m, 450 m, and 385 m upstream of the center of the main fire source (mock-up), which gave approximately 3 m/s air flow without causing too much turbulence near the mock-up.

The nozzles were installed at the height of 4.9 m above the tunnel floor. The water was pressurised with a pump system. On the left side of the tunnel, nozzles were installed from 25 m upstream to 20.5 m downstream, with 14 nozzles in total. On the right side of the tunnel, there were also 14 nozzles, but the position was from 23.25 m upstream to 22.25 m downstream. Figure 2 shows the fire suppression by high-pressure water mist in the test. For each nozzle, there were ten smaller holes to distribute the water mist towards various directions.

Figure 2. Water mist system after activation. The fire mock-up was eccentric relative to the centre line of the tunnel.

**Instrumentation**

Gas temperature, gas concentration, air velocity, visibility, radiation, humidity, and pressure of the water mist system were measured at different locations inside the tunnel along the centre line. Nominating the middle of mock-up as virtual zero point 0, measurements upstream were marked with U× and downstream were marked with D×. The heat release rate (HRR) was determined by measuring the gas and air flows at a measuring station located 855 m downstream of the fire source (D855).

The thermocouples (Type K 1.5mm) were located at U100, U50, U25, U15, U5, U3, D3, D5, D10, D15, D25, D50, D100, D145 and D855. For each location, gas temperatures were measured at 0.6 m, 1.6 m, 2.6 m, 3.6 m, and 4.6 m above the tunnel floor. The gas temperature measurements close to the fire source (U5, U3, D3, D5) were adjusted due to the existence of the wood pallets by moving thermocouples to the two sides of the tunnel or the front and rear of the fire source. Bidirectional probes were located at U50 and D855, at the same five heights as the thermocouples. Gas concentrations (CO, CO₂, O₂) were measured at U50, D145 and D855, with four gas analysers placed at 1m, 2 m, 2.5 m, and 3 m above the floor. Plate thermometers (PT) were placed at U15, D15 and D35 at the height of 1.8 m to estimate the incident heat flux that may expose to the face of a person. The incident heat flux measured at D15 was towards the fire, while it was towards the ceiling at D35. The humidity at 2.5 m above the floor was measured at U50, D145 and D855. Four cameras placed at 1.8 m height, located at U50, U35, D145 and D855, were used for visual recordings. Pressure transducers were placed at U25 and D10 to measure the pressure of the water mist system.

**Test procedure**

The test procedure is provided in Table 1. The ventilation fans were started 30 min before ignition to establish the airflow. Thermocouples were used to mimic a fire detection system. The detection was based on the gas temperature measurement above the mock-up to reach 60 °C. After detection, a three-minute delay was established before the system was activated. This delay is designed to allow the first responders to have time for verification. The actual time of activation was approximately 5
min after ignition. The system was kept running for 30 min after the water mist discharge, and only pure water was used. After the test, the target was inspected for damages to evaluate the fire spread.

Table 1. Time sequence for activities during the fire testing.

<table>
<thead>
<tr>
<th>Time [mm : ss]</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>-32:00</td>
<td>Data logging is started.</td>
</tr>
<tr>
<td>-30:00</td>
<td>Ventilation fans are started.</td>
</tr>
<tr>
<td>-05:00</td>
<td>Test tunnel is ensured ready for fire testing, i.e., only person present who shall conduct the tests.</td>
</tr>
<tr>
<td>00:00</td>
<td>Fire is ignited manually by igniting the two steel pans placed in the pallets with a torch.</td>
</tr>
<tr>
<td>( t_{\text{detection}} )</td>
<td>Fire detection is based on the gas temperature above mock-up reaches 60 °C.</td>
</tr>
<tr>
<td>( t_{\text{activation}} = t_{\text{detection}} + 3:00 )</td>
<td>Manual activation of water mist pump unit (03:00 min delay of water mist after temperature above mock-up reaches 60 °C).</td>
</tr>
<tr>
<td>( t_{\text{end}} = t_{\text{activation}} + 30:00 )</td>
<td>Controlled fuel burnout. Note the travelling time during which air (gasses and smoke inclusive) moves from the fire towards the measuring location of 855 m downstream is included in the estimation of ( t_{\text{end}} ).</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

As the information from the fire test is substantial, only the information relevant to the acceptance criteria in SOLIT\(^2\) is discussed. Only data from the first 30 min is analysed as per the performance objective in SOLIT\(^2\) is set to be 30 minutes duration of water mist discharge. The total water flow rate during the test was 847.6 L/min. The main results from the test are shown in Table 2, and the water mist system is found to meet the acceptance criteria.
Table 2. Test information and selected test results based on acceptance criteria in SOLIT².

<table>
<thead>
<tr>
<th>Description of performance criteria</th>
<th>Unit</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control and suppress fire from a Class A Fire load built according to the guideline.</td>
<td>[MW]</td>
<td>Max measured: 43.88</td>
</tr>
<tr>
<td>The fire shall be suppressed so that the gas temperature from 0 m to 2.6 m above ground level should be a maximum of 60 °C no later than 2 minutes after system activation, and hereafter the gas temperature should be kept below 60 °C for a duration of minimum 10 min. Measured in cross sections between D50 and D145.</td>
<td>[°C]</td>
<td>The gas temperature was kept below 60 °C for the required period of 10 minutes.</td>
</tr>
<tr>
<td>The heat flux 15 m from the fire at 1.8 m height above the floor shall not exceed 5.0 kW/m².</td>
<td>[kW/m²]</td>
<td>Max measured: 0.52</td>
</tr>
<tr>
<td>The heat flux from the gas layer 35 m from the fire at 1.8 m height shall not exceed 2.5 kW/m².</td>
<td>[kW/m²]</td>
<td>Max measured: 0.62</td>
</tr>
<tr>
<td>Visibility to light-emitting objects 35 m upstream from the centre of the fire at 1.8 m height above the floor must have a minimum length of 15 m.</td>
<td>[-]</td>
<td>&gt;15 m</td>
</tr>
<tr>
<td>Fractional effective dose (FED) at D145, 1.8 m height above the floor, must be below 0.3 for 10 minutes after system activation.</td>
<td>[-]</td>
<td>Max measured: 0.04</td>
</tr>
<tr>
<td>Carbon monoxide concentration at D145 should be below 2000 ppm for 10 min after system activation.</td>
<td>[ppm]</td>
<td>Max measured: 180</td>
</tr>
<tr>
<td>The target pallets shall remain intact during the test from ignition until after the water mist discharge duration has ended, i.e. the target pallets cannot be ignited or show signs of charring which indicates the pallets have been ignited during the test.</td>
<td>[-]</td>
<td>No fire damage or charring on the target pallets was found. The target was intact.</td>
</tr>
</tbody>
</table>

* the visibility is determined by a LED strip with a camera recording the scenario

**Gas temperature**

The gas temperature downstream at D50 (a), D100 (b), D145 (c) and D855 (d) is shown in Figure 3, which is measured at 2.6 m, 1.6 m and 0.6 m above the floor (i.e., the lower part of the tunnel). To aid the HRR discussion in the following section, the temperatures at 3.6 m and 4.6 m for D100, D145 and D855 are also shown. According to SOLIT², the temperature from 0 m to 2.6 m above ground level between D50 and D145 should be a maximum of 60 °C no later than 2 minutes after system activation, and hereafter the temperature should be kept below 60 °C for a duration of minimum 10 min. In this test, the temperature in the lower part of the tunnel is at the ambient before system activation. Upon activation, a temperature rise of about 10 °C is observed due to the mixing between the upper layer and the lower layer caused by the water mist. Note that the water mist system is only installed from U23 to D22, and it takes time for the mixed smoke to be transported downstream. The temperature rise is, therefore, not at the same time at different measuring positions. The temperature rise in the following 10 min is about 7 °C at D50 and 5 °C at D145. The temperature is kept below 30 °C for the duration of 10 min and below 60 °C during the whole test. Unlike the temperature at the lower layer, the temperature at the upper layer drops after system activation, as shown in the measurement at D100 and D145. Afterwards, the temperature curves at the upper layer almost coincide with the curves in the lower part of the tunnel, indicating a well mixing of the smoke in the tunnel cross-section. One finding from the gas temperature measurement is that the water mist interrupts smoke stratification, but the temperature rise in the lower part of the tunnel caused by the mixing is not high.
Figure 3. Gas temperature measurements at D50 (a), D100 (b), D145 (c) and D855 (d). Time = 0 represents ignition. Temperature measurements after the test stop are included to show the decrease in temperature.

Gas concentrations
Gas concentrations of CO$_2$ and O$_2$ measured at 2 m above the tunnel floor at D145 are shown in Figure 4. The change of gas concentrations is found at about 7 min. Due to the large ventilation flow, few combustion products are detectable at the initial stage of fire development. During the test, oxygen remains at a high level while the CO$_2$ concentration is low. With the gas concentrations, the fractional effective dose (FED) at this position can be obtained, and a maximum of 0.04 is found at 10 min, which is much lower than the acceptance criteria of 0.3.
Figure 4. Gas concentrations of CO$_2$ and O$_2$ at D145.

Heat release rate

The heat release rate (HRR) was estimated using oxygen consumption calorimetry, based on the fact that a constant net amount of heat is released per unit mass of oxygen consumed in the combustion, i.e. 13.1 MJ/kg O$_2$ [15,20]. The gas concentrations were measured 855 m downstream of the fire source. As a result, the HRR at the fire source must be corrected by a transportation time from the fire source to the measuring station [20]. In SOLIT$^2$ [18], HRR is used as the triggering point for activation of FFFS, and the maximum delay is 60 s in order to get timely activation. In the experiment, the activation was based on the gas temperature measurement close to the fire, and a delay of 3 min was given. With the suppression system, the designed HGV fire was reduced to 44 MW.

For an estimation of the transportation time from the fire source to the measuring station, the case without fire can be first assumed. The transportation time is 855 m / 3 m/s = 4.75 min for pure air flow without smoke. Due to an increased gas temperature and thus an increased flow velocity, the actual transportation time would be shorter. Nevertheless, the ventilation flow is quite large, and the gas temperature downstream is not high due to the cooling of the water mist system. In addition, the temperature rises at D855 shown in Figure 3(d), also suggests that it takes about 5 min for the well-mixed smoke to reach D855. The transportation time is therefore estimated to be close to 4.75 min. A further discussion on the transportation time can be found in Ingason and Li [15] by taking into account the increased gas temperature downstream of the fire.

In SOLIT$^2$ [18], HRR was recommended to be measured at D45, which was different from the study in Ingason et al. [1], where it was measured at 1000 m downstream of the fire source. The combustion process may be incomplete at D45 due to the chemical reaction processes that are not ended, as the gasses still contain combustible products and oxygen together with temperature to continue, especially for a large fire with large flames. For a complete combustion process, all oxygen that can be consumed is used for transforming carbon and oxygen molecules into carbon dioxide. In an incomplete combustion process, carbon monoxide, the most ubiquitous product of incomplete combustion, will reside in the gasses [21]. Figure 5 shows the difference in the heat of formation between complete and incomplete combustion of a reaction between carbon (C) and oxygen (O$_2$). As long as there is carbon monoxide present in the smoke gasses, the combustion has not yet been fully completed. When the temperature has been reduced sufficiently, it is no longer possible to continue the combustion process, and it is therefore not possible to reduce the amount of CO to zero.
Besides incomplete combustion, another aspect related to HRR measurement is smoke stratification. As shown in Figures 3 (b) and (c), the gas temperature measurement at different heights suggests large thermal stratification even at D145 before system activation. At D855 (Figure 3 d), the temperature gradient at different heights (0-4.6 m) is small, which indicates good mixing. In oxygen consumption calorimetry, HRR is calculated by the summation of HRR for each segment where the flow is well-established [20]. When the flow is not well mixed, it is possible to give false readings by relying too much on the precise positioning of the gas sample probes. For instance, measuring very close to the fire can give falsely low readings if the gas sample probes are not in direct line with the smoke and gases released from the fire. On the other hand, placing the measurement further downstream means an increase in the transportation time from the fire source to the measuring station. This delay is directly related to wind speed and can be taken into account by the correlation proposed by Ingason and Li [15]. Nevertheless, the ventilation flow in the experiment has fluctuations, and the HRR measured far downstream cannot immediately reflect the HRR development at the fire source. Large delay time can cause significant errors in the HRR calculations, and the delayed data of O\textsubscript{2}, CO\textsubscript{2} and CO concentrations must be shifted to synchronise with other data of temperatures and velocities [23]. The flow velocity measured downstream is not exactly the same as the flow velocity at the fire source, where the smoke was transported downstream at an earlier time. The position where the HRR should be measured is a topic worth further investigation. The desired position would be that with complete combustion and good mixing of the flow but not too far away from the fire.

**Heat flux**

In SOLIT\textsuperscript{2} [18], heat radiation is recommended to be measured by heat flux sensors of type Gordon. Thermo plates are not recommended due to slow reaction to fast changes during a fire test and the possibility of failure when water droplets hit the measurement surface. However, heat flux measurement is mainly conducted to evaluate tenability conditions for people and the exposure of the tunnel structure. The large surface of the thermo plates can better simulate the radiation received by the human body, including the period after the water mist system activation. Moreover, the water mist droplet size is tiny in this study and is not expected to cause failure to the thermo plates.

Figure 6 shows the heat flux measured at D15 and D35, 1.8 m above the tunnel floor. The heat flux experiences a slight increase after water mist activation but is still small compared to the criteria of 5.0 kW/m\textsuperscript{2} at D15 and 2.5 kW/m\textsuperscript{2} at D35.
Deviations from SOLIT²
The SOLIT² guidelines are based on the test conditions at the Applus+ TST technological centre in Asturias (Spain). Although the Runehamar Test Tunnel fulfils the criteria and specifications described in SOLIT², some deviations in the fire source mock-up and instrumentations were made to fit the test conditions. All deviations were performed to get higher accuracy, better measurements and, in some cases, due to logistical or practical reasons. In the cases where logistical or practical adaptions were done, it was evaluated to give equal or more accurate readings of the measurements.

The class A fire scenario in “SOLIT² Engineering Guidance, Annex 7: Fire tests and Fire Scenarios for Evaluation of FFFS” describes:

“Euro wood pallets shall be stacked with steel frames preventing them falling and so having larger surface and improved effect of FFFS. Steel frames shall survive the test without collapsing, but they should not cover more than 10% of the sides or top of fuel.”

The mock-up used in the class A fire scenario in this report used a steel reinforcement set, 5 mm in diameter covering 2 m height on half of the mock-up (from upstream, U5, to the centre of the mock-up, U0/D0), preventing the pallets from falling and getting a larger surface. The reinforcement covered much less than 10% of the side or top area. In addition, all pallets were individually fixed to each other with two nails, with each nail at least 50 mm long. The images from the side of the mock-up during the tests show that there is no fallout from the mock-up during the duration of the tests. The parts of the mock-up not covered by the steel grating were not considerably involved in the fire before the test ended, and the deviation is acceptable.

SOLIT² describes gas temperature and air velocity measurements at U340. There are no related criteria on these measurements, and the reason for this position is likely the layout of the test tunnel in which the specifications were written. It is useful to measure the temperature and velocity at the beginning of the tunnel and the temperature and velocity impacting the fire. This was handled by measuring both temperature and air velocity at U100. This gives a more accurate and stable air velocity entering the fire zone.

SOLIT² describes gas temperature, air velocity, gas measurements, visibility, and humidity at U45. All these measurements were moved to U50 for logistical reasons, and in addition, visibility was measured at U35 since this was the only measurement with criteria that could benefit from being moved further away than 45 m.

SOLIT² describes gas temperature, gas measurements, visibility and humidity at D45. The heat flux in this study was measured at D35, as well as visibility. Temperatures were measured at D50 mostly for logistical reasons but also to avoid turbulent conditions to reach more stable readings. The gas
measurements, humidity, air velocity and additional visibility and temperature measurements were moved to D145. This was to get more precise measurements since the smoke and gas will be better mixed and less reliant on the precise positioning of the gas sample probes. In addition to these measurements, a similar measurement setup was placed closer to the end of the tunnel at D855, giving even more precise gas readings.

To show that the difference in measuring locations did not affect the gas temperature in measuring points with approval criteria, a summary of temperatures in the various locations at 4.9 min and 24.2 min is shown in Figure 7. According to Hu et al. [24], the dimensionless temperature decay follows an exponential form and a large temperature drop is only expected close to the fire source. The temperature difference between the measurements at different locations is limited. After system activation, the smoke stratification is interrupted, and the temperature difference along the longitudinal direction becomes small.

Figure 7. Gas temperatures at different locations at 4.9 min (a) and 24.2 min (b) after ignition. 4.9 min is the time just before the water mist system activation, and 24.2 min is the time at first measurement exceeding 60 °C.

SOLIT² describes gas temperature and visibility at D215. There are no related criteria on these measurements, and the reason for this position is likely the layout of the test tunnel in which the specification was written. This was covered by measuring the same and additional measurements at D145 and D855.

The only downside to location D855 is the time delay from the air and smoke leaving the fire until it arrives at the measurement location 855 m downstream. This delay varies with the wind speed in the tunnel and should be considered where necessary.

SOLIT² describes that heat radiation measurements should be at a height of 1.5 m. The heat radiation measurements performed in these tests were placed at a height of 1.8 m to better represent a worst-case scenario regarding heat radiation exposure to the face of a person.

CONCLUSIONS

A full-scale fire test was conducted to study the performance of a high-pressure water mist system in a road tunnel. The test was carried out according to guidelines in SOLIT², but with deviations to better fit the test tunnel. The HRR was estimated with the oxygen consumption method measured at 855 m downstream of the fire source. It is found that the high-pressure water mist system can suppress the designed HGV fire down to 44 MW, and the fire spread to a nearby target is prevented. Gas temperatures measured at different heights suggest a strong stratification close to the fire source before system activation. After activation, the temperature in the lower layer has a rise of 10 °C from
the ambient between D50 and D145, due to mixing with the hot smoke layer caused by the water mist. Measuring HRR too close to the fire source can cause errors since the combustion may be incomplete. In addition, the strong stratification means the measurement relies too much on the precise positioning of the gas sample probes. On the other hand, measuring HRR too far downstream increases the transportation time and may not accurately reflect the HRR development at the fire source. The position where the HRR should be measured is a topic worth further investigation. SOLIT² guidelines are proposed based on fire tests in a tunnel 600 m long, 9.5 m wide, and 8.1 m high. Some measurements can be adjusted to give equal or more accurate readings in performing tunnel fire tests.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support from Mr. Henrik Bygbjerg, Mr. Lars Wrang Jensen, and Mr. Jonas Ertmann Hansen from Danfoss Fire Safety A/S.

REFERENCES


Design fire heat release rate of flammable liquid fires under water mist suppression in a tunnel

Yunlong Liu, Sean Cassady, Petr Pospisil & Eric Jones
HNTB Corporation, USA

ABSTRACT

Tunnel fire which involves flammable liquid cargo (FLC) fuel can result in a heat release rate (HRR) as high as 200 to 300 MW, and its growth rate can be faster than that of a heavy goods vehicle (HGV) or other type of vehicles. Fire suppression is one of the approaches to control the fire spread, however, sprinkler systems are not effective for FLC fire because the water density is higher than the flammable liquid and the liquid fuel tends to float on top of the water. Foam is a better solution since it can generate a bubble blanket on top of the fuel isolating the oxygen from the fuel, however this would result in environmental issues. This paper discusses a water mist suppression approach which would be an alternative for controlling the FLC fires in tunnels, and eliminate the environmental concerns caused by foam discharge in the local area. With the aid of computational fluid dynamics (CFD) modelling, the fire HRR growth curve has been developed based on the experiment recorded temperature and the portal oxygen concentration, and it has been confirmed that water mist is effective for controlling FLC fires in a tunnel environment, where ventilation airflow exists.

KEYWORDS: Water mist, fire suppression, flammable liquid cargo (FLC), fire heat release rate, tunnels, design fire

INTRODUCTION

Water mist fire suppression systems have been successfully applied in industrial application and several European road tunnels, but until recently not in US tunnels. This paper will discuss and review the effectiveness of water mist fire suppression systems to control flammable liquid cargo (FLC) fires in a tunnel environment.

In regions throughout the United States, some road tunnels which accommodate FLC’s rely on foam suppression systems for fire events, which generate a foam ‘blanket’ on a fuel spill surface. The foam agent’s lower density allows the foam to cover the fuel surface and isolate the fuel from the oxygen; hindering the combustion process. However, environmental and personal health concerns are becoming more prevalent for tunnel owners, operators, and first responders using traditional foam suppression systems.

The application of water mist systems should be explored for its ability to alleviate environmental concerns associated with traditionally used roadway tunnel foam suppression systems. When water mist reaches the surface of a FLC fuel fire, it can easily evaporate and the latent heat from its phase change absorbs a substantial portion of energy and decreases the temperature of the fuel surface. The gas phase water, i.e., water vapor, will also reduce oxygen concentration, further slowing fire growth. Because gas phase water has lower density than the air (as the density of water vapor is 0.804g/litre, which is significantly less than that of dry air at 1.27g/litre at STP), it tends to flow upward; displacing and diluting the oxygen concentration in the tunnel feeding the combustion process.
Computational Fluid Dynamics (CFD) modeling with the software Fire Dynamics Simulator (FDS) has been performed for FLC pool fire under water mist application in a tunnel environment. Gas temperature and oxygen concentration has been recorded to understand the mechanism of the water mist fire suppression on flammable liquid fuel fires. Heat release rate (HRR) growth curve for pool fire with applied water mist suppression has been developed with the computer modelling approach.

This paper will also review the existing tests that have been conducted to understand the efficiency of water mist to extinguish FLC pool fires. The existing tunnels that have been designed with water mist system and these under design and construction are also presented as secondary reference.

EXISTING FIRE TESTS

Though fire tests comprising small droplets nozzles were carried out at factory Mutual since 1940s, it was not until 1990s that this technology started to draw attention\(^{[1]}\). NFPA 502 – 2020 Appendix E compiled some existing tests with fixed water-based systems in road tunnels\(^{[2]}\). There are seven reported water mist tests on class B (flammable liquid) fires referenced in NFPA 502.

Car fire tests in a tunnel mockup with mist suppression were completed in Switzerland in 2003, and full-scale HGV fire tests at San Pedro de Anes (Spain)\(^{[3]}\) and the Runehamar tunnels (Norway)\(^{[4-7]}\) are among the most widely referenced ones.

According to Fernandez \(^{[3]}\), the tests at the Center of Experimentation "San Pedro of Anes" which is a 600 m tunnel with a removable false ceiling for reproducing different ceiling heights and ventilation conditions, has recorded a ceiling gas temperature decrease from 720 °C to 70 °C in test #2. Analysis has shown that the fire HRR can be controlled to no more than 30 MW.

Cesmat et al \(^{[8]}\) reported in a paper at the ISTSS conference 2008 that the model tests have shown the water mist can effectively control the class A and class B fire, with the peak HRR decreased by 70% within 30 seconds upon activation of the water mist Fixed Fire Fighting Systems (FFFS).

In 2008 Kristen Opstad and Thai Trung Mai of SINTEF reported water mist tests in Runehamar Tunnel in Norway\(^{[9]}\), where heavy goods vehicle and 100 m² pool fires filled with diesel oil on top of water were used as fuel for a potential fire HRR of 200 - 250MW. These tests have shown that water mist can control class A and class B fires effectively.

Lakkonen M, Feltmann A and Sprakel D \(^{[10-11]}\) reported water mist fire suppression on pool fire and compared the performance of low-pressure deluge system and the high-pressure water mist system.

This paper will reference SINTEF test report, to back calculate the pool fire heat release (HRR) development curve based on its test case#6, to confirm the effectiveness of the pure water mist system\(^{[12]}\) for controlling the FLC pool fires, so that the fire suppression system can eliminate the Aqueous Film Forming Foam (AFFF) additives and avoid the environmental concerns.

FDS FIRE MODEL

CFD simulation has been performed to understand the gas temperature with water mist suppression for the other project, where the highway is trenched and covered with a lid which results in a short tunnel. CFD model was setup using the Fire Dynamics Simulator\(^{[13]}\). The prevailing wind and traffic developed airflow, which is represented by a 4 m/s velocity, was considered at the portal.

As shown in Figure 1, the tunnel has a cross section area 8.5m wide x 5.4m high and 245m long. For the portion of the tunnel considered for the CFD model, total number of mesh is 570 x 34 x 27 along the length, width, and height direction, respectively. Total required CPU time is approximately 72 hours with 4 processors running in parallel to complete 300 seconds fire time.
Water mist fire suppression employed a high-pressure system, detailed mist parameters of Test #6 detail in SINTEF report[5] are shown below in Figure 1.

To modelling the test #6 and back calculate the HRR growth, the pool fire was simulated with a 25m long and 4m wide uniform heat source, which generate of maximum heat release rate of 2500 kW/m², which represent a FLC pool fire of 100 m² with a bi-linear growth rate of 5 MW/minute during the first 30 seconds, then grows at 165 MW/min to 250 MW for unsuppressed free burning condition. When water mist is applied at 166 seconds as shown in Figure 2, the pool fire can be effectively controlled and its HRR will decrease to approximately 25 MW within 20 seconds. The fire HRR will further decrease to 0 at 240 seconds, and the fire has completely extinguished.

Water application rate: 4.0 mm/min.
liquid pool area: 100 m²
pure water mist, 0 AFFF
spacing of nozzles: 3.0m x 3.5m
Rows of nozzle: 3 rows along the tunnel
flowrate per nozzle: 42 L/min
pressure at the nozzle: 30 bar = 435 psi
droplet size: Dv0,9= 200 microns
mist droplet discharge velocity: 60 m/s

Figure 1: Cross section of the Runehamar Tunnel

Figure 2: FLC Fire HRR curves with water mist suppression of Test #6 of SINTEF report[5]

Transient gas temperatures recorded at CFD model test locations are shown in Figure 3A and compared to the experiment tested temperature curves in Figure 3B (only curve 18 which recorded the highest temperature in Figure 3B, has been used here for comparison). The CFD model obtained gas temperature agrees well with the tested temperature of 1100 °C which is recorded at 4.5m above the fire. This has not only validated the CFD model, but also back calculated the HRR growth curve, which can be used as a reference design fire HRR curve for the FLC pool fire with water mist fire suppression. The CFD model has demonstrated that high pressure water mist can serve as an effective tool to control the FLC fire and without the need of any addition of AFFF.
Figure 4A and 4B compare the FDS modelling Oxygen concentration at 142m downstream of the fire and 0.4m below the tunnel ceiling with measurements from the SINEFF test. The oxygen concentration decreased to approximately 10% when peak HRR is reached during 120 sec – 180 sec. The CFD model agrees with Runehamar test result well. Red curve in Figure 4A for O$_2$ represents the Oxygen concentration measured in the tunnel test at 142m downstream of the fire, which agrees well with the modelling results as shown in Figure 4B. The oxygen concentration is reduced to 10% at the time of the peak heat release rate.
Figure 4B: CFD modelling oxygen (O2) concentration +142m downstream of the fire

**FIRE HRR AND TUNNEL GAS TEMPERATURE**

It is apparent that FLC pool fire growth rate is extremely fast in the Runehamar test. After the initial incipient stage, fire HRR grows at 165 MW/min since the flammable liquid pool has already spread out in the test case #6. The flammable liquid pool should be spread out gradually if there is a leakage from FLC vehicle. However, this test has established the worst fire growth rate and should be referenced when nominating a design fire for FLC fire case. The FLC fire peak HRR will heavily rely on the surface area of the flammable liquid pool and the tunnel fire/smoke detector’s settings and performance, and these parameters will determine the activation time of high-pressure water mist system.

In order to understand the influence of specific tunnel on the fire detection time and its HRR, additional CFD modelling have been performed for Runehamar tunnel and an example tunnel project named NHHIP, to understand the influence of tunnel geometry on peak heat release rate and the maximum gas temperature under an ideally developed 100 m² pool fire. Table 1 shows the cases and parameters that have been used in the two example tunnels, the resulting peak HRR is also given in the table. The difference between these two CFD cases and the test case #6 is that detection time is based on the heat detector’s triggering time in these two CFD cases listed in Table-1. Both CFD case #1 and #2 consider a 4m/s longitudinal ventilation and with water mist suppression activated with a 60 sec delay after the fire is detected.

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Tunnel Name</th>
<th>Tunnel Width</th>
<th>Tunnel Height</th>
<th>Detector height</th>
<th>Detection time</th>
<th>Water mist discharge</th>
<th>Peak HRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case #1</td>
<td>Runehamar</td>
<td>8.5m</td>
<td>5.4m</td>
<td>5.2m</td>
<td>30 sec</td>
<td>90 sec</td>
<td>190 MW</td>
</tr>
<tr>
<td>Case #2</td>
<td>NHHIP</td>
<td>25.0m</td>
<td>6.8m</td>
<td>6.6m</td>
<td>32 sec</td>
<td>92 sec</td>
<td>200 MW</td>
</tr>
</tbody>
</table>

Figure 5 shows the HRR curve of a 100m² pool fire for Runehamar and NHHIP tunnel under water mist suppression which is activated with heat detectors. Since the tunnel width and ceiling height of the two tunnels are different, the fire detection time for NHHIP tunnel is longer, resulting in a higher peak HRR since the water mist application is a few seconds later than for Runehamar tunnel.

Figure 6 shows the recorded gas temperature at location #18 as indicated in the SINTEF test [5], which is 4.3m above the tunnel base, Runehamar recoded a maximum gas temperature of around 1000 °C and the NHHIP recorded 600-700 °C for the same pool size, though the peak HRR of the NHHIP tunnel is higher than that for Runehamar tunnel. This can be explained by the fact the NHHIP tunnel cross section area is approximately 4 times that of the Runehamar tunnel, especially NHHIP tunnel height differs by 1.4 m, which also can reduce the ceiling temperature, as it needs more energy to heat
up the air-smoke mixture in the tunnel. This also explains why each tunnel would require performance-based design for fire and life safety and structural fire durability solutions.

Figure 5: HRR curve of pool fire with water mist suppression in Runehamar and NHHIP

![HRR in Runehamar](image1)

![HRR in NHHIP](image2)

Figure 6: Gas temperature curve of pool fire with water mist suppression in Runehamar and NHHIP

![Location #18 for Runehamar](image3)

![Location #18 for NHHIP](image4)

DISCUSSION

With a heat detector setting of 68°C, a FLC fire should be detected at 40 seconds after fire starts (assuming a linear fire growth rate 20 MW/Min.), if a delayed operation of water mist by 60 seconds
is assumed, the FLC fire can develop a 250 MW fire at 120 seconds for a well-established flammable liquid pool. However, a more realistic condition is a case that its growth rate would be slower because the fully developed liquid pool in the mockup test is ideally setup which resulted in a maximum growth rate. In an actual situation, if the road surface is sloped or the drainage are available, some of the liquid may have been drained away leaving a limited size of the liquid pool. However, in the test situation the pan filled with flammable liquid itself make it easier to extinguish the fire, and in real cases it may worsen it due to interaction of the unforeseen boundary conditions, and its initial HRR development is slower as discussed in the FDS fire model section of this paper. A fire growth rate of 20MW/minute has been proposed for the NHHIP project. Figure 5 shows a design fire growth curve used in NHHIP project, if assuming the water mist can start operation 60 seconds after fire detection which happens at 15 seconds of the FLC pool fire starts, the water mist discharge can operate at full capacity at 105 seconds, and its peak HRR is capped at 35 MW at 105 seconds after fire starts.

Figure 5: Design fire used in NHHIP Project

Water mist systems which utilize pure water can eliminate environmental issues associated with foam suppression systems. Furthermore, it has been shown to be as effective as deluge systems where large water droplets are involved \[5\]. However, for shielded HGV fires, e.g. under a tarpaulin if it not burned away, its fire cannot always be effectively controlled by deluge systems. Water has a high density forcing the water to penetrate through the flammable liquid fuel, allowing the fuel to layer on top of the deluge water where it can remain as part of the combustion process. Deluge water droplets also have larger diameters, taking longer to evaporate, making them not as effective as water mist to cool the tunnel structure and airborne combustibles.

On the other hand, water mist can be a promising solution for controlling FLC fires in roadway tunnels if properly designed. Most importantly, the amount of water required for fire suppression can significantly be reduced.

Water mist is effective in interrupting the oxygen supply, resulting in a reduced combustion process, and therefore reducing the convective heat transfer and decreasing the associated temperatures of adjacent fuel materials with reduction in pyrolysis. The mist can also absorb or block radiative heat transfer to adjacent fuel materials therefore resulting in reduction in pyrolysis, slowing down the combustion. Mist is also effective at reducing fire hazards in the vicinity, and the temperature reductions improving tenability and may coalescing smoke particles out of the air.
Based on the existing tests and CFD results shown in Figures 2, 3A, 4B, the heat release rate has been back-calculated based on the test measured temperature curve in test case#6, CFD modeling of the test results have demonstrated that water mist exhibits satisfactory performance on FLC fires in the test environment. The design fire peak HRR of FLC relies on detection which determines the time when water mist is to be applied on the fire. Furthermore, development and formation of flammable liquid pool needs time when a FLC leakage happens, and the road slope as well as the availability of drainage system will also significantly impact the size of the flammable liquid pool, compared to an ideally developed pool fire, which may have a decisive impact on peak HRR. Therefore, in a field scenario, FLC fire may not always be able to develop into a 100 m² liquid pool and result in a fire as high as 250 MW.

CONCLUSION

Water mist is effective in controlling FLC pool fires, its HRR growth rate can be as fast as 165 MW/min after the incipient stage. However, peak HRR of FLC fire with water mist operation is highly dependent on the fire detection time, size of the existing flammable liquid pool when the fire started. Currently, application of water has been proposed for some new projects, such as Hugh L. Carey Tunnel Manhattan in New York, and Houston Highway lid project in Texas. An incomplete list of the tunnels in the world has been listed below for reference.

EXISTING WATER MIST APPLICATION IN TUNNELS

As of 2022, The following tunnels uses the water mist system:

- Mona Lisa tunnel (775 m, Austria, installed in 2004)
- Felbertauern tunnel (at an altitude of 1632-1650m, exposed to temperatures of -30°C at cold winter in Austria, 5034m long, high wind speeds up to 1968 fpm, i.e. 10m/s, system installed in 2006)
  (Note: the Felbertauern tunnel and the Mona Lisa Tunnel have both been existing tunnels which have been retrofitted with water mist systems.)
- Roermond tunnel, NL, and Tunnel Swalmen, NL (A73, Roermond tunnel is 2.45 km long, longest road tunnel in Netherlands; a sister tunnel, Tunnel Swalmen, 400 m long; both are new tunnels and installed mist system in 2008)
  (Note: both tunnels are equipped with mist systems to allow dangerous goods passing through)
- Tunnel A73 Swalmen, Netherlands, 0.4km, new twin bore tunnel, 3-lane each bore
- Öresund Tunnel DK-SE (service gallery only)
- Virgolo tunnel (887m, dual lane, main link through the Alps from Italy through Austria to Germany, especially for cargo transport, 30% traffic is Heavy Vehicles, Italy)
- Critical sections of M30 Tunnels, Madrid (2006, Spain)
- Silver Forest Tunnel (Moscow, Russia, 2.1km, 2006)
  (The tunnel design comprises two parallel tubes, each measuring 2.1km long with a diameter of 14.2m and double-deck construction)
- New Tyne Crossing (Newcastle, UK, 2009)
  (Two under-river tunnels are the vital part of the Tyne and Wear Road network)
- Dartford crossing (M25, London K, 2 tunnels, 1.43 km, 2010)
- Train tunnel projects (metro Budapest, Hungary)
- Eurotunnel (channel tunnel), France/UK
- Cable tunnels in various countries
- A86 Duplex Tunnel in Paris (road tunnels) 2005-2009
- 2 x NDIA Taxiway tunnels (road tunnels, 2x340m), 2009-2010, Qatar
- Helsinki Service Tunnel (road tunnels, 850m; 2000m) 2009-2010 Finland
- City Tunnel A14 Bregenz, Austria, 1.4km, refurbished in 2014
- Arlberg tunnel, St. Jakob, Austria, 14km, refurbished in 2017
Tenth International Symposium on Tunnel Safety and Security, Stavanger, Norway, April 26-28, 2023

- Tunnel A1 Liefering, Salzburg, Austria, 0.55km, refurbished in 2017
- Main Tunnel Heathrow Airport, UK, 0.65km, refurbished in 2021
- Thu Thiem Tunnel, Hoo Chi Minh City, Vietnam, refurbished in 2022
- Koralm Tunnel, Austria, 0.9km, new tunnel under construction (expected to complete soon).
- Hugh L. Carey Tunnel Manhattan, NY, USA (expected to complete soon)

ACKNOWLEDGEMENT

The authors would like to acknowledge that the paper has included the input from the conversation with Helmut Kern of Aquasys. Discussion with HNTB colleague Ralph Trapani on reference projects and a final review of the paper by Dave Parker of HNTB are kindly acknowledged.

REFERENCES

2. NFPA 502 - 2020, Standard for Road Tunnels, Bridges, and other limited access highways.
13. FDS Users Guide, National Institute of Standards and Technology, NIST.
Sprinkler system design using CFD tools for assessing tenability impact and total hydraulic demand

Miguel Ángel Fuentes Llanos, Panos Iliadis & Sohail Alizadeh
Mott MacDonald House, 8-10 Sydenham Rd, Croydon CR0 2EE, UK

ABSTRACT

Water sprinklers are often installed at underground train stations to control or suppress a fire. A sprinkler system can assist the intervention of fire brigade services and protect the asset. This paper reports the Computational Fluid Dynamics (CFD) modelling of a fire and the deployment of sprinklers in a train station to demonstrate the coordination of tunnel ventilation system response and sprinkler design. Spray atomization at sprinkler heads is a strongly stochastic process and its modelling is complex. A methodology is presented to set initial sprinkler spray characteristics based on different physical modelling approaches and experimental data available in the literature. CFD simulation results presented in the form of visibility and temperature contours show the cooling effect of the sprinkler deployment with no significant impact on smoke visibility. Total hydraulic demand is similar for the two head activation temperatures studied: 68°C and 93°C. However, the higher temperature rating assures that earliest activation occurs after passenger egress is completed.

KEYWORD: CFD, sprinkler system design, sprinkler modelling, train fire, station tenability, fire life safety, fire suppression, tunnel ventilation.

INTRODUCTION

The installation of a sprinkler system at underground stations is a consideration to improve the platform environment for intervention of the fire brigade services. CFD techniques have the potential to demonstrate the coordination of tunnel ventilation system response and sprinkler design during emergency incident scenarios of a train fire at an underground station. Results of CFD models also serve to backcheck against initial mechanical system flows and pressures and water supply capability of the system.

Sprinkler activation is one of the key events for sizing the hydraulic demand of the system. A common approach for defining the number of sprinklers is by means of prescriptive codes that specify exactly what steps need to be taken depending on the hazard classification. However, there is an increasing demand for performance-based design strategies. Given experiences of station tenability assessments in large framework design projects, the aim of this work is to provide a practical three-dimensional detailed analysis, that can be used by Tunnel Ventilation engineers to assist Fire Suppression System (FSS) designers in the assessment and design of a sprinkler system.

The deployment of a sprinkler system at platform level is simulated by CFD modelling to assess the performance of the system with respect to sprinkler head activation. The impact of the water spray on airflow, absorption of thermal energy by water droplets and the disruption of smoke stratification is also of interest, thereby impacting Fire Life Safety tenability assessments for station spaces during intervention. In the present implementation, it was assumed that the water spray had no impact on the heat release of the fire and production of soot, representing a simplified yet conservative representation of the FSS.
Modelling spray atomization at the sprinkler head is a challenging task due to the stochastic nature of impinging water jets. The present methodology sets the initial sprinkler spray characteristics through different physics-based modelling approaches and experimental data available in literature. D. T. Sheppard [1] presented experimental measurements of spray characteristics for an extensive range of fire sprinklers. The findings of this thesis are used in the methodology presented here to define unknown parameters of a sprinkler spray that are usually not provided in manufacturers’ data sheets.

**SCENARIO**

**Station and Train Geometry**

This study details the CFD study carried out on a mock-up station to simulate an emergency incident scenario of a train fire in the station. The model included the station spaces and running tunnel extents to assess the tenability for the required time of egress. Geometry dimensions are 130m long, 15m wide and 6m height. The station model has ventilation shafts at the east and west ends of the station. The evacuation route for all scenarios is towards two escalators/stairs. The location of shafts and ventilation adits as well as the egress routes off the platform (escalators/stairs and emergency exit) are shown in Figure 1 below.

**Figure 1: Station geometry. Location of shafts and egress routes.**

The train geometry is shown in Figure 2. It is 70m long, 2.6m wide and 3m height (2.4m internal height). The train’s internal space consists of the volume between the floor and internal ceiling and no other internal features were included. Equipment below the train car floor were modelled in the computational domain by using solid blockages. The incident train was setup as stationary and comprised of several car units, connected together in open wide gangways. All train doors facing platform side are assumed to be open and all windows in the vicinity of the fire origin (i.e., about 7m distance) assumed to have failed.

**Figure 2: Train geometry. Location of doors and windows.**

**Fire Definition**

Ingason H. et al. [2] compile heat release rates from large-scale experimental data on rolling stock fires. The Peak Heat Release Rate (HRR) range is large depending on the type of vehicle and ventilation rate. Time to reach the peak HRR varies from 5min to 30min. The equivalent t-squared fire growth parameter for those tests ranges from 0.001 kW/s² (slow) to 0.389 kW/s² (ultra-fast). For this study, the fire was assumed to be represented as a medium-fast growth (0.02 kW/s²) t-squared fire with a peak HRR of 9.0 MW, which is similar to the limit of 8.8MW stablished for London Underground and Transport for London projects [3].

The incident car is the middle car of the train and is located at the midpoint of the platform. The CFD analysis starts at the point when the incident train has just arrived at the station and the train doors
have opened. The fire starts at time = -2 minutes prior to the start of simulations. At time = 0 when the simulation starts and train doors open, the fire is at 288kW and there is a smoke volume inside the train that represents the smoke accumulation from the design fire after it has been growing for 2 minutes. The analysis duration is 15 minutes, in order to assess steady state conditions.

**Emergency Ventilation and Fire Life Safety**
The Tunnel Ventilation System (TVS) follows a pull-pull approach and extracts smoke from both ends (east and west) of the incident track to preserve tenability along the egress route, and to minimise smoke propagation to the non-incident platform and track. At the start of the simulations, the ventilation shaft fans turn on and ramp up to full capacity over the course of one minute. Platform tenability for evacuation is required at 240s (i.e., 4 minutes), as per NFPA 130 standard [4].

**SPRINKLER SYSTEM**

**System Layout**
The total number of sprinkler heads is 96. Head location and coding is provided in Figure 3. Sprinklers are located 3.7m height above the platform floor. They are spaced 3.5m in the X direction and 2.5m in the Y direction.

![Figure 3: Sprinkler layout.](image)

**Coverage and Hydraulic Demand**
The discharge pattern is representative of water transported to each location below the sprinkler. Figure 4 shows the assumed spray discharge pattern of sprinkler heads. It is based on a generic industrial head from reference [5]. Sprinkler flow rate is 57 l/min. Water pressure is 0.5 bar. The sprinkler orifice diameter is 13mm.

![Figure 4: Selected sprinkler spray discharge pattern.](image)

**Head Activation**
A wet fire sprinkler system is considered. Platform sprinkler head activation is dynamic, dependent on the temperature at each head location. Sprinkler heads activate after their temperature sensitive bulb
reach a predetermined fixed temperature (also called the activation temperature) and break. The configurable head temperatures in this study are 68°C and 93°C.

**CFD METHODOLOGY**

**Software**
A three-dimensional CFD model of the mock-up station was developed. The CFD study was performed using ANSYS software suite with Fluent 2022 R2 as the CFD Solver.

**Computational Mesh**
The computational domain was divided into 766,588 cells. The mesh resolution for the CFD model was tailored to resolve important physical features and where locally high spatial gradients of flow properties are anticipated – i.e., in the vicinity of fires, train doors & windows and TVS adits. Mesh inflation layers were used at solid surfaces (i.e., station walls and train shell) such that high gradients in flow field parameters could be represented appropriately. The general cell size was of the order of 0.2m. In the environment of the fire car the mesh size was more refined whereas in the region away from the fire, the mesh was coarser in order to reduce computational time and maintain simulations efficiency. Mesh size expansion ratios were generally specified as 1.2, from higher to lower resolution regions. An example of the mesh structure and density is shown in Figure 5.

![Figure 5: Section mesh of the station and incident carriage.](image)

**Fire Representation**
An Eddy Dissipation combustion model was used to represent the fire. A single step chemical reaction is used in the consumption of the fuel leading to a 9MW fire (cf., Fire Definition above) with no decay. A medium-fast (0.02 kW/s²) t-squared growth is used so that the fire reaches the peak HRR after approximately 670 seconds. The fire ignites two minutes before the start of the simulation. The heat of combustion resulting from the fuel burn is 19,770 kJ/kg [6]. The CFD calculation actively controls the fire area parameter to maintain realistic fire conditions throughout the full duration of a simulation: the train fire will grow from the centre of the floor area and spread to the ends. Average fire temperature is maintained within reasonable lower and upper bounds. Transport of smoke, as one of the by-products of combustion, is simulated by solving an additional species transport equation. Soot yield was assumed 0.094 kg/kg [6]. The convection fraction of the heat release rate is 0.65 [6]. The radiative portion is not modelled in the calculations as radiative effects are considered limited to the immediate vicinity of the fire. Radiative effects follow an inverse-square law, varying with distance from the source. Therefore, smoke, and hot gases are found to move primarily due to the convective component of the heat release from the fire.

**Turbulence Model**
The Reynolds-Averaged Navier-Stokes (RANS) approach was adopted for the solution of the flow field conservation equations. The standard k-ε turbulence model was used in conjunction with the Wall Function treatment for near-wall boundary layer calculations. The buoyancy body force was incorporated into the fluid flow equations and in the turbulence model, based on localised differences in temperature and hence flow density.
Boundary Conditions
The no-slip boundary condition is applied to station and tunnel walls. All walls are set to adiabatic. Adiabatic walls retain more heat energy within the CFD domain, and this is consequently a more conservative assumption than the assumption of isothermal walls. Water droplets are reported as having escaped when they vanish from the model after encountering any boundary in the domain. The flow boundary conditions for the running tunnels and platform exits at the station consist of pressure loss coefficients. The ventilation fans and ductwork have not been modelled explicitly. Instead, the fans have been assumed to operate at a design fan capacity of 250m$^3$/s. The volumetric flowrate was specified at ventilation adits, represented by a uniform flow velocity prescription.

Initial Conditions
It was assumed that the initial air temperature inside the station and tunnel bores is 25°C. Initial temperature of water droplets was also set to 25°C. This is representative of a high ambient temperature for the station and tunnels and a more onerous scenario, which was not dissimilar to projects encountered in practice. The flow solution was initialized with still air conditions. Smoke accumulation inside the train was modelled to represent the volume of smoke that would develop in the two minutes from ignition $t = -2$ minutes to $t = 0$ minutes, when the doors open. At this time the fire has reached a HRR = 288kW.

Air-droplet Interaction
The fire suppression zones at the platform are represented via explicit representation of the individual sprinklers. The Discrete Phase Model (DPM) available in Ansys Fluent was used to model water droplets trajectories through the domain. This solution uses a two-phase approach consisting of a fluid phase (air) and a discrete particle phase (sprinkler water droplets). Air as the fluid phase is treated as a continuum and is governed by the continuity and Navier-Stokes equations. Water droplets as the discrete phase consist of a definite number of particles that move through the continuous fluid flow, and which are tracked in a Lagrangian frame. The effect of water droplets or particles on the turbulence of the airflow is an important feature. The turbulence level affects not only the effective viscosity of the air and the air–droplet transfer coefficients (e.g., drag and heat transfer) but also the particle dispersion. A practical way of determining whether one–way, two–way, or four–way coupling should be adopted is through the proposed map of particle–turbulence modulation suggested by Elghobashi [7], which is shown in Figure 6.

The vertical axis measures the ratio between the particle response time ($\tau_p$) and the turnover time of large eddy ($\tau_e$). For particle volume fractions $\alpha_p$ between $10^{-6}$ and $10^{-3}$, the particles can affect the turbulence of air and a two–way coupling is required. The effect of the droplet trajectories on the air is undertaken by feeding appropriate DPM sources back into the balance equations of the continuous phase. Average water volume fractions of commercially available sprinkler heads range from $10^{-4}$ to $10^{-3}$ [1]. Consequently, a two-way coupling approach was followed for the CFD model of sprinklers and the collision between particles was assumed negligible.

![Figure 6: Map of different regimes of interaction between particles and turbulence.](image-url)
Secondary breakup of water droplets following atomization was also modelled. The droplet oscillation and distortion at any given time was determined using the Breakup-TAB model equation. If droplet oscillations grew to a critical value, the parent droplet broke up into a few smaller child droplets. Aerodynamic drag of particles was modelled as perfect spheres. Trajectories of droplets was predicted using the mean and the instantaneous value of the fluctuating air flow velocity. The random effects of turbulence on the droplet dispersion were included using the Discrete Random Walk Model. The Random Walk Model is a stochastic method to determine the instantaneous air velocity. The fluctuating velocity components are discrete piecewise constant functions whose random value is kept constant over an interval of time given by a characteristic eddy lifetime [8][9].

The CFD model will present the cooling of smoke (i.e., destratification) resulting from sprinkler activation, as has been described below. However, it is assumed that the sprinkler system will not impact the fire source, in terms of heat release rate and production of Soot and CO. This is a conservative representation, in that the amount of fuel burned with time, together with the accompanying combustion reaction, is not affected by the fire suppression system. While this does not represent the physical reality of sprinkler usage on a fire, this approach has been used for a conservative representation of the FSS. Modelling fire suppression requires the consideration of two additional phenomena: tracking water along walls and other surfaces and calculating the reduction of the burning rate. When water droplets hit a surface, they create a thin film that should be modelled. Moreover, water run-off at edges should be also evaluated. These fundamental physics are well understood but increase the computational cost of simulation. On the other hand, the analysis of the impact of water droplets on the fuel burning rate requires detailed chemical kinetic models instead of the mixed-controlled combustion model applied in this study. Given that the size of a fire is rather uncertain, and most analyses consider a design fire curve set by local standards or authorities, the benefit of applying a more complex pyrolysis model is uncertain. An alternative approach is to freeze or reduce the heat release rate of the fuel after the activation of a first set of sprinklers.

It should be noted that whilst a system-wide validation for the whole station emergency scenario presented in this paper is not available, there exists validation and verification studies for component parts of the modelling. This includes key physics such as smoke plumes (turbulent buoyant flows), fire modelling (Eddy Dissipation combustion model) and sprinkler representation (Lagrangian two-phase flow models), that has been a subject of wide scale research over the past few decades.

### Spray Modelling

The initial sprinkler spray has been characterized in terms of the following main parameters: sprinkler flow rate, droplet size distribution, initial droplet velocity and spray angle, and number of injected parcels per second.

**Sprinkler Flow Rate:**
A sprinkler flow rate of 57 l/min was considered in this study. Water pressure is 0.5 bar.

**Droplet Size Distribution:**
It was assumed that the water jet is already atomised at the nozzle exit and the distribution of droplet sizes follows a Rosin-Rammler-Lognormal distribution as shown in experimental tests carried by Chan [10] and some of the sprinklers tested by Shepard [1]. It was also assumed that the droplet size distribution does not change with azimuthal or elevation angles, for example due to deflector geometry. The Cumulative Volume Fraction (CVF) function of the size distribution is:

$$CVF(D) = \begin{cases} \frac{1}{\sqrt{2\pi}} \int_0^D \frac{1}{\sigma_D} e^{-\frac{\left[\ln(D/D_{v,0.5})\right]^2}{2\sigma_D^2}} dD & (D \leq D_{v,0.5}) \\ 1 - e^{-\left[\frac{D}{D_{v,0.5}}\right]^\gamma} & (D \leq D_{v,0.5}) \end{cases}$$

(1)
Where $D_{V0.5}$ is the volume median diameter such that half of a given volume of water is contained in droplets greater than this diameter. $\sigma$, $\beta$ and $\gamma$ are empirical parameters. $\sigma$ is calculated to ensure that the two functions are smoothly joined at $D = D_{V0.5}$. $\beta$ and $\gamma$ are assumed 0.693 and 2.3 based on average values from experimental data provided in [10]. These values are similar to the ones used in the Fire Dynamics Simulator software (FDS) [11]. Experiments in [1] ranged from 0.64 to 0.75 for $\beta$ and from 1.85 to 2.57 for $\gamma$. The minimum and maximum diameter for the numerical representation of the distribution was set to 20$\mu$m and 5000$\mu$m based the smallest and largest droplets measured in the experiments undertaken by Sheppard [1]. $D_{V0.5}$ was set to 1100$\mu$m based on a sensitivity analysis presented later in this paper. The minimum and maximum droplet sizes define the minimum and maximum bounds of the CVF distribution. Nevertheless, the impact of their exact value on the overall performance of the sprinkler is not significant as the CVF curves are asymptotic at both ends. The Rosin-Rammler-Lognormal distribution was discretized into ten different diameters or bins.

Initial Droplet Velocity and Spray Angle:
The experimental analysis carried by Sheppard [1] concluded that sprinklers spray could be treated as nearly radial flow with the origin located at the sprinkler. Therefore, water droplets were introduced in the CFD model using point-cone injectors with a prescribed radial velocity. As the velocity distribution of droplets after atomization is unknown, a constant initial velocity of droplets was assumed. Initial droplet velocity was iterated to best fit the discharge pattern of the generic industrial sprinkler shown in Figure 4. Specifically, the initial droplet velocity was iterated until the spray pattern of a single sprinkler head in still air conditions complied with the 70% Flow Inside / 30% Flow Outside configuration. The volume fraction of droplets inside and outside the region limited by the 70% Flow Inside line was checked at three different heights below the sprinkler: -0.5m, -1.5m and -2.5m.

![Figure 7: Monitoring surfaces used for matching the discharge pattern.](image)

The spray pattern was assumed axisymmetric. A cone angle of 76.5°C was estimated from the angle described in the near region of the sprinkler by the 100% Flow Inside line and the vertical axis of the sprinkler. A droplet initial velocity of 4.7 m/s performed the closest match to the required pattern providing a volume flow rate ratio of 64% at 0.5m below the sprinkler, 71% at 1.5m, 76% at 2.5m and 70% on average in all three monitored surfaces. This result shows a good agreement with the relationship estimated by Sheppard [1]:

$$\bar{U}_{avg} \approx 0.6\sqrt{P/\rho} = 4.2 \text{ m/s}$$

Where $P$ is the water pressure, which is 0.5 bar in this study, and $\rho$ is the water density which equals to 998.2kg/m$^3$ as per Fluent Material Database.

Number of parcels per second:
The number of parcels injected per second at each sprinkler head was set to 2000 parcels/s. Sensitivity analysis were carried to confirm that a good solution similarity was achieved above this value. The number of streams at each injector was set to 50 and parcels were injected every 0.25s, which is the flow time step size.
Head Activation Modelling

Most common fire sprinklers contain a glass bulb with a glycerine-based solution that stops the water flow in normal conditions. This solution expands when its temperature rises until it breaks the glass bulb and releases the water coming from the pipes. General-purpose CFD software such as ANSYS Fluent does not include any calculation tool for the heat transfer phenomena leading to sprinkler bulb breakup and activation unless its geometry is modelled explicitly, which is not a cost-effective solution. Nevertheless, the software is highly customized and additional features can be introduced through external coding. For this study, a sprinkler activation model was implemented in Fluent through coding of User Defined Functions (UDFs).

The Response Time Index (RTI) model assumes that the link acts as a thermally thin body that is heated by the hot gases coming from the fire plume. Upon reaching the activation temperature, the sprinkler bulb breaks and triggers the release of water in the sprinklers. The RTI model is the industry standard for the determination of sprinkler response. It was introduced by Heskestad et al. in 1976 [12] and modified by Heskestad and Bill in 1988 [13]:

\[
\frac{dT_e}{dt} = \sqrt{\frac{|u|}{RTI}} (T_g - T_e) - \frac{C_F}{RTI} (T_g - T_0)
\]  

(3)

Where \( u \) is the velocity of the hot gases; \( T_g \) and \( T_e \) are gas phase (air) and the thermal element (bulb) temperatures, respectively; \( C_F \) is a parameter related to conductive transport to the sprinkler fitting; \( T_0 \) is the temperature of the sprinkler mount (assumed ambient in this study); and the RTI is a constant which depends on the thermal properties of the sprinkler link, and it provided by sprinkler manufacturers. Equation (3) was further modified by P. Rufino et. al. in [14] to account for the evaporative cooling of the heads by water droplets flowing in the air from previously activated sprinklers. This phenomenon is not considered in the current methodology and the RTI model based on Equation (3) was implemented in ANSYS Fluent. This equation was solved numerically during the CFD simulation using the transient temperature and velocity conditions of the air surrounding each sprinkler head. For that purpose, a UDF tracks the temperature of each sprinkler bulb located in given cells in every time step of the fire analysis. A User Defined Memory (UDM) slot was used to store an activation switch variable. If the link temperature reaches the activation temperature in a given time step, the sprinkler is flagged as activated in the UDM and an additional UDF initialize water injection in the activated head. Finally, User-defined Report Definitions record the bulb temperature and activation switch values of each sprinkler at every time step. The activation of a sprinkler stops further calculations of its link temperature.

Volume Median Diameter Analysis

The volume median diameter \( D_{v0.5} \) refers to the median droplet size where half of the volume of spray is in smaller droplets, and half of the volume is in droplets larger than this median. Experiments carried by Sheppard [1] measured \( D_{v0.5} \) values between 700µm and 1500µm depending on the elevation angle for a sprinkler with similar orifice diameter and working pressure (13mm and 0.57bar) to the one used in this study. Three \( D_{v0.5} \) values for Rosin-Rammler-Lognormal distribution prescribed at sprinkler head were carried for a sensitivity analysis: with 700µm, 1500µm and 1100µm as the average value. The simulations were undertaken on the assumption that all sprinklers were simultaneously activated at \( t = 600s \). The flow time step was 0.25s and parcels were injected four times per second. Figure 8 shows the total DPM Sensible Enthalpy Source of all water droplets for the duration of the simulation and the three \( D_{v0.5} \) considered. The DPM Sensible Enthalpy Source is the exchange of sensible enthalpy from the discrete phase (water droplets) to the continuous phase (air). The source is negative when the particles absorb heat from the continuous phase.
Figure 8: DPM Sensible Enthalpy Source vs. Volume Median Diameter Dv50.

Results show that the smallest median diameter (700 µm) absorbed approximately 18% more heat than the average value (1100 µm). On the other hand, the largest median diameter (1500 µm) absorbed about 15% less heat. As expected, smaller water droplets have a higher total surface-to-volume ratio which increases heat transfer from air. Figure 9 shows the total water evaporated mass from sprinklers for the duration of the simulation and the three Dv0.5 considered. Results show that the evaporated mass of water for the 700 µm case is 12% higher than the 1000 µm case at the end of the simulation. On the other hand, the evaporated mass for the 1500 µm case is 12% lower once steady state conditions are reached at time = 660s.

Figure 9: DPM Evaporated Mass vs. Volume Median Diameter Dv50.

These results show that using the average value of 1100µm for the sprinkler spray provides a simplified solution for representing the experimental values which vary depending on the elevation angle of the spray as shown in the experiments undertaken by Sheppard [1]. Consequently, this is the value used in this study. Nevertheless, the designer might use the largest measure for a more onerous solution if desired.

RESULTS

The results of the CFD simulations for each case scenario are presented in the form of visibility and temperature contours. Results are plotted at a plane 2.0m above the platform floor to show the impact on tenability with the activation of the sprinkler system. Visibility of reflective surfaces through smoke (i.e., station walls, doors) is calculated using the equation:

\[ S = \frac{C}{K_m \rho Y_s} \]  

Where \( C \) is the visibility factor, and it is equal to 3 for a light-reflecting sign [14]. \( K_m \) is the soot extinction coefficient, and it is assumed 8700 m²/kg [15]. \( \rho \) is the density of the mixture and \( Y_s \) is the mass fraction of soot.
Tenability conditions are assessed along the evacuation routes, including the stairs, and associated bottom landings, for the duration of platform egress. The black colour in contour plots illustrates a condition not meeting tenability criteria. For temperature there exist two thresholds – the radiant heat threshold of 200°C for the smoke layer overhead (colour black in temperature scale) and an additional threshold of 60°C (dark grey in temperature scale) associated with the peak air temperature along evacuation pathways. For visibility, a threshold of 10m was considered. Figure 13 and Figure 14 show visibility contours from 0 to 10m. Additionally, Figure 15 shows visibility contours from 0 to 60m at 4 and 6 minutes (evacuation time requirements as per NFPA 130 standard [4]), and at 15 minutes (steady state flow conditions). Tenability of egress routes is maintained for the required time of egress in all scenarios. The extent of head activation is also provided for each simulation to confirm hydraulic demand. Figure 10 shows the number of heads activated through time for the two head temperatures. Headline results are tabulated in Table 1.

![Figure 10: Number of heads activated vs. time.](image)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Activation Temperature (°C)</th>
<th>Number Heads Activated</th>
<th>Hydraulic Demand (l/s)</th>
<th>Earliest Activation Time (s)</th>
<th>Final Deployment Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68</td>
<td>12</td>
<td>11.4</td>
<td>206.25</td>
<td>607.25</td>
</tr>
<tr>
<td>2</td>
<td>93</td>
<td>11</td>
<td>10.4</td>
<td>264.50</td>
<td>658.50</td>
</tr>
</tbody>
</table>
Figure 11: Air temperature at platform level – from $t = 60s$ to $t = 360s$. 
Figure 12: Air temperature at platform level – from $t = 480s$ to $t = 900s$. 
Figure 13: Walls and doors visibility at platform level – from $t = 60s$ to $t = 360s$. 
Figure 14: Walls and doors visibility at platform level – from $t = 480s$ to $t = 900s$. 
CONCLUSIONS

CFD analyses have been performed to assess system performance and tenability for a train fire emergency incident at a train station. Temperature and visibility contours plotted at a plane 2m above the platform floor show that a tenable egress route to exits/escalators is maintained up to 240s in all three scenarios: without sprinklers, 68°C and 93°C sprinkler heads. Earliest activation occurs approximately 200s after the start of the simulation if 68°C sprinkler head are considered. This is less than the required for platform egress time which was considered 240s. Therefore, water deployment will be triggered during passenger evacuation, which is something not desirable and would likely need to be overcome in an actual design case, via a time delay in the control system. Total number of head activated, and maximum hydraulic demand was higher for the lower activation temperature rating. In all cases, the cooling effect of the sprinkler deployment is evident in the temperature plots. It is also evident that sprinklers do not have a significant effect on visibility in these analyses. Visibility level decreases to 1m in the region behind the eastern escalator due to smoke destratification from the activation of sprinklers. Both activation temperature settings helped to maintain the platform.
temperature below 40°C to assist with the intervention of fire brigade services. However, a lower activation temperature has higher probabilities of false alarms due to faster activation and a higher risk of system failure due to higher numbers of sprinklers being activated. Therefore, an activation temperature of 93°C is recommended for the system in this study.

The methodology presented in this paper can be used to confirm the water supply capability of the system estimated by Fire Engineers. It also serves as a procedure to adjust the earliest activation of sprinkler and avoid water deployment during passenger evacuation. The UDF code implemented into ANSYS Fluent could be highly customized. For example, a water fill-up time could be added for cases where a wet sprinkler system is evaluated. Additional delays could be also included in the activation logic. The impact of the individual flowrate of sprinklers on the activation timeline could be another variable to study.

The present study requires further verification by means of testing. In the CFD simulations, the main sources of uncertainty in the activation of sprinklers, arise from accuracy of heat transfer prediction at the heads. This in turn is largely governed by the localised flow field velocity and temperature predictions in the vicinity of the heads, as well as water flow rates through individual sprinklers. It is interesting to note that Ingason et. al. [17] in their fire tests in an intermediate tunnel, also express bulk parameters such as ventilation rate and water density as important factors impacting head activation. Further complexity to solutions could arise in the aesthetic design of concealed sprinklers. In such cases, accurate solution of the local flow field surrounding the link element might require the explicit modelling of its geometry with high grid resolution in near-wall regions. Further areas of uncertainty in the modelling could arise from key model setups, associated with the fire definition and TVS parameters and could pose additional areas for verification.

REFERENCES
Experimental Report on a System for Maintaining the Evacuation Environment by Early Detection of Tunnel Fire and Control of Longitudinal Wind Speed

Masahiro Yokota, Ken-Ichiro Yamazaki, Taku Nakayama, Takumi Ota
Central Nippon Highway Engineering Tokyo Co., Ltd.

ABSTRACT

In Japanese expressway tunnels, the longitudinal ventilation method using a jet fan is mainly used for exhausting smoke during a fire. Usually, when there are no stopped vehicles downstream of the fire source in the tunnel, the smoke is exhausted downstream to maintain the evacuation environment on the windward side. However, when there is a stopped vehicle on the leeward side of the tunnel, it is necessary to suppress the movement of smoke to maintain the environment until evacuees complete their evacuation. At this time, there is a concern that the fire disaster will spread if there is a mistake in the smoke exhaust. For this reason, it is desirable for the control to be automatic, without the intervention of an operator.

To solve these problems, a new smoke control system method was proposed from the viewpoint of early detection of fire, and its superiority was confirmed via computational fluid dynamics (CFD) evaluation of smoke behavior during a fire. Based on these findings, this paper reports the results of an evaluation experiment in a full-scale tunnel.

KEYWORDS: evacuation environment, early detection, longitudinal ventilation, smoke propagation section, smoke sensor, inverter-driven jet fan system

SYSTEM PLANNING

Flame detectors are used for fire detection in expressway tunnels in Japan. Tunnel emergency equipment design is based on the concept of completing evacuation within 10 minutes while maintaining the evacuation environment (smoke concentration $C_s < 0.4 \text{ [m}^3\text{]}$ at a height of 1.5 [m] from the road surface) by activating various emergency equipment after fire detection. The smoke exhausting system uses a longitudinal ventilation method. Usually, when there are no stopped vehicles downstream of the fire source in the tunnel, the smoke is exhausted downstream to maintain the evacuation environment on the windward side. However, when there is a stopped vehicle on the leeward side of the tunnel, it is necessary to suppress the movement of smoke to maintain the environment until evacuees complete their evacuation, and there is a concern that the fire disaster will spread if there is a mistake in the smoke exhaust operation (Figure 1).

![Figure-1 Example of current smoke exhausting system operation in Japan](image)
In addition, it is expected that traffic will be heavy on an urban expressway that is currently under construction, and if a fire has broken out in a congested section of a tunnel, there is a concern that the fire source would be in a blind spot and the flame detection would be delayed. In addition, delays in fire detection include risks that lead to delays in instructing following vehicles to stop, diffusion of smoke into tunnels, deterioration of the evacuation environment, and ultimately expansion of secondary disasters. To reduce these risks, methods for early fire detection, understanding constantly changing smoke diffusion conditions, control of traffic flow, accurate information provision, maintenance of tunnel environments, and quick evacuation are considered to be the first measures to be established [1].

To realize these goals, this system uses smoke detectors instead of conventional flame detectors as shown in Figure 2, and we are working on the development of a system (SSCS: Smoke Sensing & Control System) with the aim of controlling the movement of smoke and maintaining the evacuation environment by controlling the longitudinal wind velocity according to traffic conditions.

**Figure 2. Early detection method of tunnel fire**

**CFD ANALYSIS**

To realize this system concept, we set up a fire scenario (fire scale 5 to 30 MW, $\alpha t^2$ model) and compared the detection functions and installation positions of the smoke sensor and the flame sensor by three-dimensional computational fluid dynamics (3D CFD) for the target tunnel. For details, refer to [2].

The 3D CFD code uses the large eddy simulation (LES) turbulence model FIRELES [3]. In addition, the calculation uses an orthogonal grid, with $dx = 0.4$ m, $dy = 0.3$ m, and $dz = 0.3$ m, based on past examination results. An overview of the CFD analysis is shown in Figure-3 to Figure-5.

**Figure 3. Model tunnel section area**

**Figure 4. Model tunnel longitudinal section**
Vehicles stopped in the tunnel were lined up with an average headway of 10 m, and the number of large vehicles was set at 25% of the total. Furthermore, there were no stopped vehicles in the area 50 m before and after the fire source and 50 m from the entrance/exit (Figure-6).

The $a_t^2$ heat release rate curve for a passenger car-sized 5 MW fire shows that a detectable fire size for a standard flame detector is reached after 180 to 210 seconds. On the other hand, for smoke detectors, detectability was evaluated based on the installation height from the fire CFD results. The detection criterion was based on a comparison of the time when the smoke concentration reached a mean value of $C_s > 0.1 \text{ m}^{-1}$ over 10 seconds at heights of 1.5 m, 3 m, 4.5 m, and 6.9 m at 50 m on the leeward side of the fire outbreak (Table-1), confirming that fire can be detected earlier by installing smoke detectors at heights of 4.5 m or higher.

A previous study on smoke concentration and evacuation environment [4] found that when the $C_s$ concentration exceeds 0.4 m$^{-1}$ at a height of 1.5 m above the road surface, smoke obstructs visibility and makes evacuation difficult. For this reason, we set the smoke detection criteria of this CFD evaluation to 0.1 m$^{-1}$ or more in order to detect fires quickly.

For a downhill ramp 5 MW fire, the results of the smoke descent characteristics evaluation during the fire are shown in Figure-7 and Figure-8. When the wind speed is low on the windward side of the fire source, the upwind smoke descends faster due to the gradient and buoyancy. On the other hand, on the leeward side of the fire source, the smoke descends faster at higher wind speeds, and the flow turbulence caused by stopped vehicles accelerated smoke descent, such that the descent proceeds from the side closer to the fire source. However, controlling the wind speed below 1 m/s can delay the smoke descent, which maintains the evacuation environment for a longer time.
We evaluate the evacuation risk if a fire occurs under conditions of a wind speed in the tunnel of 2.5 m/s, fire detection by flame detectors and smoke detectors, and subsequent wind speed suppression (0.5 m/s). The conditions for starting evacuation are (1) smoke reaching overhead, (2) seeing people evacuating, and (3) hearing an evacuation announcement (90, 120, and 240 seconds after fire outbreak). Furthermore, evacuation walking speed was set to 1 m/s for \(0 < C_s \leq 0.3 \text{ m}^{-1}\), 0.5 m/s for \(0.3 < C_s \leq 0.4 \text{ m}^{-1}\), and 0.1 m/s for \(C_s < 0.4 \text{ m}^{-1}\). If there are foot lights, the setting is evacuation at 1 m/s even if \(0.3 < C_s \leq 1.0 \text{ m}^{-1}\). These conditions were combined with emergency exits and coupled with the smoke behavior determined by CFD results for each wind speed in the tunnel to identify the residual persons who were unable to evacuate (risk) during the first 600 seconds from fire outbreak. When the start time of control of the wind speed in the tunnel is 210 seconds, dense smoke (\(C_s \approx 0.3 \text{ m}^{-1}\)) descends to a height of 1.5 m on the leeward side, as shown in Figure-9. However, when the time was set to 60 seconds, there was almost no smoke descent, as shown in Figure-10. This shows that risk can be reduced by delaying the degradation of the tunnel environment through early reduction of wind speed.
The following findings were obtained from the model tunnel fire CFD evaluation.  
• Smoke detectors should be installed at a height of 4.5 m or higher for early detection of fires.  
• When there are stopped vehicles, smoke descent can be delayed by controlling the wind speed below 1 m/s.  
• Under limited conditions, coupling evaluation of fire and evacuation simulation was used to evaluate the relative merits of different evacuation measures.  
• Risk can be reduced by delaying the degradation of the tunnel environment through early reduction of wind speed.

With regard to these results, we decided to conduct a comprehensive experiment and evaluation, including smoke movement control, in a full-scale tunnel.

**FIRE TESTS**

For the experiment, we borrowed a full-scale tunnel (Length = 700 m, Area = 57 m²) owned by a national agency. The full-scale tunnel test site is located close to a residential area and was planned with a limited fire source.

In a previous experiment [1], a 1 m² fire pan (n-Heptane) was used to investigate the possibility of early fire detection, but the sensors were installed in a limited area up to 110 m downstream of the fire point, and under conditions of 0 m/s and 2 m/s (constant) longitudinal wind speed.

In other experiments conducted on fixed and moving smoke sources for the purpose of setting out requirements for automatic smoke detection for rapid fire detection, and smoke source identification was discussed [5].

In this study, a situation in which smoke is generated by a fire in the interior of a vehicle is considered, assuming that the vehicle has stopped due to a breakdown. To detect smoke, activate the smoke exhausting system at an early stage, and secure the evacuation environment, the following items were verified with the aim of capturing the constantly changing smoke tip and concentration changes.

1. Early detectability of fire by smoke detection
2. Smoke controllability by wind speed control
3. Superiority over existing systems

For the simulated fire scenario, a smoke candle was used as a substitute for smoke emission. An n-heptane fire pan was used to reproduce the appearance of flames blowing out as the fire progressed. With regard to the detectability of these fires, we compared the characteristics of flame detectors and
smoke detectors. In addition, smoke detectors were placed at intervals of 50 m in the tunnel, and the constantly changing range and concentration of smoke were observed together with wind speed control. The arrangement of the experimental equipment is shown in Figure-11, and the test cases are shown in Table-2.

Figure-11_Full-scale tunnel experiment equipment layout

Table-2_List of test cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Smoke source</th>
<th>Heat source</th>
<th>Wind speed control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Smoke candle</td>
<td>n-Heptane 0.5 m²</td>
<td>1 m/s to -0.5 m/s</td>
</tr>
<tr>
<td>Case 2</td>
<td>Smoke candle</td>
<td>n-Heptane 0.5 m²</td>
<td>1 m/s to -0.5 m/s</td>
</tr>
<tr>
<td>Case 3</td>
<td>Smoke candle</td>
<td>n-Heptane 0.5 m²</td>
<td>1 m/s to -0.5 m/s</td>
</tr>
</tbody>
</table>

The test procedure consisted of four smoke candles (five-minute smoke) each emitting smoke three times, and a 0.5 m² fire pan was used, set to ignite six minutes after the smoke was emitted (Figure-12).

Figure-12_Time series chart of the test cases
In this test, we used a prototype of the SSCS controller under development. Jet fan 1 uses a wireless device to tell the operator the initial wind speed in each experimental tunnel to set the output of the inverter. The prototype SSCS controller is connected to smoke sensors, a cross-sectional anemometer, and jet fan 2 to monitor smoke concentration and longitudinal wind velocity at various locations in the tunnel (Figure-13). When a smoke sensor installed in the tunnel detects smoke, the jet fan 2 have a function of operation and automatic control to a preset longitudinal wind velocity. To quickly control the wind speed in the tunnel to a low speed in the event of a fire, inverter power supply panels for jet fans [6] were used in combination to improve the controllability of the wind speed.

![Connection diagram of prototype SSCS and each device](image)

For the selection of smoke sensors, we decided to increase the system’s availability by using existing products, and selected a model capable of measuring smoke concentration in the tunnel. Furthermore, at present, the main objective is to detect smoke in the early stages of a fire and to capture the smoke tip and concentration changes, and the behavior of smoke and toxic gases is assumed to be similar. Fire detectors used in existing systems are also installed near the fire point to confirm the superiority of smoke detection in this experimental scenario. A list of the equipment used in this experiment is shown in Table-3. An overview of the main equipment is shown in Figure-14 to Figure-21 and Table-4 to Table-10.

Moreover, a photodiode sensor was also installed as a means of smoke detection, but it is treated as a reference and is omitted from the evaluation in this report.

### Table-3 List of equipment used

<table>
<thead>
<tr>
<th>Product name</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSCS controller</td>
<td>1</td>
</tr>
<tr>
<td>Generators (150 kVA)</td>
<td>2</td>
</tr>
<tr>
<td>INV panels (for 50 kW)</td>
<td>2</td>
</tr>
<tr>
<td>Cross-sectional anemometer</td>
<td>1</td>
</tr>
<tr>
<td>Jet fans(Φ1250mm)</td>
<td>2</td>
</tr>
<tr>
<td>Fire detector</td>
<td>1</td>
</tr>
<tr>
<td>Photoelectric separate smoke sensors</td>
<td>13</td>
</tr>
<tr>
<td>Scattered light smoke sensors</td>
<td>5</td>
</tr>
<tr>
<td>Photodiode sensors</td>
<td>3</td>
</tr>
<tr>
<td>Data logger</td>
<td>1</td>
</tr>
<tr>
<td>Temporary scaffolding</td>
<td>13</td>
</tr>
<tr>
<td>Fire pan (0.5 m²)</td>
<td>1</td>
</tr>
<tr>
<td>n-heptane</td>
<td>240 L</td>
</tr>
</tbody>
</table>
Figure-14_Appearance and measurement principle (scattered light smoke sensor) [7]

Table-4 Specifications of smoke sensor (scattered light smoke sensor)

<table>
<thead>
<tr>
<th>Measurement principle</th>
<th>120° scattered light measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement wavelength</td>
<td>670 mm</td>
</tr>
<tr>
<td>Nominal range</td>
<td>0 to 3 E/m</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.001 E/m</td>
</tr>
<tr>
<td>Reaction time</td>
<td>5 s (Wind Speed of 1.5 m/s)</td>
</tr>
<tr>
<td>Flow cell material</td>
<td>PC/ABS</td>
</tr>
<tr>
<td>Housing material</td>
<td>Stainless steel 316Ti</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>-30 °C to 55 °C</td>
</tr>
<tr>
<td>Ambient humidity</td>
<td>0 to 100 %</td>
</tr>
<tr>
<td>Protection class</td>
<td>IP66</td>
</tr>
<tr>
<td>Voltage</td>
<td>DC 24 V</td>
</tr>
<tr>
<td>Input power</td>
<td>4 W</td>
</tr>
<tr>
<td>Weight</td>
<td>0.9 kg</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Ø107 mm × 283 mm</td>
</tr>
</tbody>
</table>

Figure-15_Appearance and measurement principle (photoelectric separate smoke sensor)

Table-5 Specifications of smoke sensor (photoelectric separate smoke sensor)

<table>
<thead>
<tr>
<th>Detection principle</th>
<th>Measurement of change in amount of light received between optical axes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring distance</td>
<td>5 m to 100 m</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>30% to 70%</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>DC 24 V</td>
</tr>
<tr>
<td>Rated current</td>
<td>75 mA</td>
</tr>
<tr>
<td>Maximum number of connections</td>
<td>2 units/line</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>-10 °C to 50 °C (no condensation)</td>
</tr>
<tr>
<td>Optical axis adjustment range</td>
<td>20° up/down, 20° left/right</td>
</tr>
<tr>
<td>Material</td>
<td>Polycarbonate resin</td>
</tr>
<tr>
<td>External dimensions</td>
<td>142.5 mm × 107.2 mm × 95 mm</td>
</tr>
<tr>
<td>Mass</td>
<td>Light receiving part: approx. 750 g</td>
</tr>
<tr>
<td></td>
<td>Light sending part: approx. 750 g</td>
</tr>
</tbody>
</table>
Table 6. Specifications of fire detector [8]

<table>
<thead>
<tr>
<th>Name</th>
<th>Fire detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection method</td>
<td>Two wavelength-band type</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>DC 48V -20% , +10</td>
</tr>
<tr>
<td>Temperature</td>
<td>-20 °C to +50 °C</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>85% or less</td>
</tr>
<tr>
<td>Allowable damage rate</td>
<td>85% (optical attenuation rate)</td>
</tr>
<tr>
<td>Installation interval</td>
<td>25 m type and 50 m type</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Gasoline (2 liters) in 0.5m² pan, detected within 30 seconds after ignition Wind speed inside the tunnel: 0 to 12 m/s</td>
</tr>
</tbody>
</table>

Table 7. Specifications of inverter-type power feeder for jet fan

<table>
<thead>
<tr>
<th>Inverter capacity</th>
<th>37 kW, 55 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>3Φ 380 to 480V ± 10%</td>
</tr>
<tr>
<td>Output voltage</td>
<td>3Φ 380 to 480V</td>
</tr>
<tr>
<td>Output frequency</td>
<td>0 to 50/60 Hz</td>
</tr>
<tr>
<td>Control method</td>
<td>Two-level PWM control method</td>
</tr>
<tr>
<td>Surge voltage noise measures</td>
<td>DFSA (feedback-type sinusoidal waveform filter)</td>
</tr>
<tr>
<td>Axial current measures</td>
<td></td>
</tr>
<tr>
<td>Harmonics measures</td>
<td>Three-phase bridge (capacitor smoothing) with ACL+DCL 12-pulse converter device Self-excitation three-phase bridge (PWM converter)</td>
</tr>
<tr>
<td>Input and output signals</td>
<td>No-voltage contact, Ethernet communication, PLC general-purpose network</td>
</tr>
<tr>
<td>Power cable</td>
<td>Up to 2000 m possible</td>
</tr>
<tr>
<td>Applicable jet fan</td>
<td>30,33 kW × 1, 50 kW × 1</td>
</tr>
<tr>
<td>Applicable jet fan motor</td>
<td>General-purpose motor can be used</td>
</tr>
<tr>
<td>Panel size</td>
<td>W 1,000 × H 2,300 × D 1,000 mm</td>
</tr>
</tbody>
</table>
Table 8. Specifications of jet fan

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>1250 mm</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>50/60</td>
</tr>
<tr>
<td>Jet wind speed</td>
<td>35</td>
</tr>
<tr>
<td>Noise</td>
<td>Less than 95 dB(a)</td>
</tr>
<tr>
<td>Overall length</td>
<td>3500 mm</td>
</tr>
<tr>
<td>External form</td>
<td>1450 mm</td>
</tr>
<tr>
<td>Wind volume</td>
<td>43 m³/s</td>
</tr>
<tr>
<td>Effective discharge area</td>
<td>1.23 m²</td>
</tr>
<tr>
<td>Voltage</td>
<td>400/440</td>
</tr>
<tr>
<td>Output</td>
<td>50 kW</td>
</tr>
<tr>
<td>Starting current</td>
<td>400/380 A</td>
</tr>
<tr>
<td>Rated current</td>
<td>91/82 A</td>
</tr>
<tr>
<td>Mass</td>
<td>1,700 kg</td>
</tr>
</tbody>
</table>

Table 9. Specifications of cross-sectional anemometer

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement principle</td>
<td>Determination of direction-dependent differential transition times of ultrasonic pulses</td>
</tr>
<tr>
<td>Measured values</td>
<td>Air velocity</td>
</tr>
<tr>
<td></td>
<td>Volume flow</td>
</tr>
<tr>
<td></td>
<td>Direction of air flow</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
</tr>
<tr>
<td>Measuring range</td>
<td>-40 to 40 m/s</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1 m/s, accuracy dependent upon measuring distance</td>
</tr>
<tr>
<td>IP rating</td>
<td>IP 67</td>
</tr>
<tr>
<td>Dimensions</td>
<td>270 x 130 x 95 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>Sensor approx. 2.2 kg</td>
</tr>
<tr>
<td>Material</td>
<td>Stainless steel 1.4571 (AISI 316Ti)</td>
</tr>
<tr>
<td></td>
<td>Polyamide RAL5017; Flammability rating: B1 (UL 94 V0)</td>
</tr>
</tbody>
</table>
Table-10 Specifications of generator

<table>
<thead>
<tr>
<th>Phase</th>
<th>3Φ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>125/150 kVA</td>
</tr>
<tr>
<td>Frequency</td>
<td>50/60 Hz</td>
</tr>
<tr>
<td>Voltage</td>
<td>200, 400/220, 440</td>
</tr>
<tr>
<td>Current</td>
<td>361, 180/394, 197A</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.8 (LAG)</td>
</tr>
<tr>
<td>Engine Output</td>
<td>135.2/166.5 kW</td>
</tr>
<tr>
<td>Engine Speed</td>
<td>1500/1800 rpm</td>
</tr>
<tr>
<td>Fuel</td>
<td>ASTM Diesel Fuel Oil No. 2D</td>
</tr>
<tr>
<td>Fuel Tank Cap</td>
<td>250 L</td>
</tr>
<tr>
<td>Weight</td>
<td>2,990 kg</td>
</tr>
</tbody>
</table>

Table-11 Smoke detection time of each sensor (sec.)

<table>
<thead>
<tr>
<th>PSS detection time</th>
<th>SS detection time</th>
<th>Flame detection time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Case 2</td>
<td>Case 3</td>
</tr>
<tr>
<td>D 1</td>
<td>51</td>
<td>53</td>
</tr>
<tr>
<td>D 2</td>
<td>—</td>
<td>96</td>
</tr>
<tr>
<td>D 3</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

(1) Early detection of fire by smoke detection
Smoke detection by each sensor (D1, D2, D3) installed at a height of h = 4.5 m and the criteria set were Cs ≥ 0.1 m⁻¹, the same as in CFD. Table 11 shows the time from the start of the experiment until PSS and SS detected smoke, and the time at which the flame detector detected fire 300 seconds later. In all cases, the D1 smoke detector closest to the fire was found to respond the fastest, detecting smoke in 30-50 seconds. In addition, of course, in the simulated fire scenario set up this time, it was confirmed that the smoke detection method detects fire (initial fire due to smoke) earlier than the flame detector.

(2) Smoke movement and wind speed control
The purpose of this experiment is to confirm the controllability of the wind speed in the tunnel from the initial condition wind speed to the specified wind speed. The results for each case are shown in Table-12. As a result of analyzing each case, the fluctuation of the instantaneous value was confirmed, but the
difference between the target wind speed and the control wind speed was very small even in the low wind speed region of less than 1m/s. The establishment time of the control target wind speed almost agreed with the preliminary wind speed simulation results (Figure 22). On checking the median value of the control wind speed, it was confirmed that it approached the target wind speed with good accuracy (Figure 23).

Note that the preliminary wind speed simulation is based on a stepwise calculation of the pressure balance in the tunnel to calculate the longitudinal wind speed per second. For details, refer to [9].

**Table-12 Results of control of wind speed in tunnel**

<table>
<thead>
<tr>
<th>No.</th>
<th>Control of wind speed in tunnel</th>
<th>Wind speed control time</th>
<th>Deviation from 110 sec. expected value</th>
<th>Median wind speed after completion of control</th>
<th>Maximum/Minimum wind speed after completion of control</th>
<th>Difference from target wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1 m/s To -0.5 m/s</td>
<td>72 sec.</td>
<td>-8 sec.</td>
<td>-0.5 m/s</td>
<td>Max: -0.4 m/s, Min: -0.7 m/s</td>
<td>+19%, -12%</td>
</tr>
<tr>
<td>Case 2</td>
<td>69 sec.</td>
<td>-11 sec.</td>
<td>-0.5 m/s</td>
<td>Max: -0.2 m/s, Min: -0.7 m/s</td>
<td>+23%, -17%</td>
<td></td>
</tr>
<tr>
<td>Case 3</td>
<td>92 sec.</td>
<td>12 sec.</td>
<td>-0.5 m/s</td>
<td>Max: -0.3 m/s, Min: -0.8 m/s</td>
<td>+19%, -16%</td>
<td></td>
</tr>
</tbody>
</table>

**Figure-22 Comparison of preliminary wind speed simulation results and experimental results**

**Figure-23 Box-and-whisker diagram of results of control of wind speed in tunnel**

(3) Superiority over existing systems
With (1) and (2) above, when low wind speed control was implemented, even if the wind direction was reversed, the smoke stratification was not disturbed, and the evacuation environment on the upstream and downstream sides was maintained. In addition, we were able to confirm in real time the smoke distribution in the longitudinal direction and the constantly changing smoke density (that is, the changes in the evacuation environment) (Figure 25). The smoke concentrations measured at a height of 4.5 m at various locations were organized in chronological order and the results compared with the results of
the CFD analysis. Although the diffusion range of smoke that can be confirmed in the experiment is limited and there is a time delay, it was found that it shows a similar tendency. (Figure-26).

![State of fire experiment](image1)

**Figure-24** State of fire experiment(Around the fire source)

![Smoke stratification in fire experiment](image2)

**Figure-25** Smoke stratification in fire experiment (wind speed in tunnel 1 m/s to -0.5 m/s)

![Comparison of smoke behavior between wind speed control experiment and CFD](image3)

**Figure-26** Comparison of smoke behavior between wind speed control experiment and CFD
DISCUSSION

Smoke detector height and installation interval are set based on the environment in the tunnel confirmed by preliminary CFD, and the characteristics of this system, which were confirmed through a full-scale tunnel experiment under limited fire source conditions, are shown below.

(1) Early detection of fire by smoke detection: In the simulated fire scenario set up in this experiment, smoke was detected earlier than with the flame detector.

(2) Smoke movement and wind speed control: The establishment time of the control target wind speed almost agreed with the preliminary simulation results, and the difference between the target wind speed and the control wind speed was very small even in the low wind speed range of less than 1 m/s.

(3) Superiority over existing systems: With (1) and (2) above, when low wind speed control was implemented, even if the wind direction was reversed, the smoke stratification was not disturbed, and the evacuation environment on the upstream and downstream sides was maintained. In addition, we were able to confirm in real time the smoke distribution in the longitudinal direction and the constantly changing smoke density (that is, the changes in the evacuation environment).

However, the experimental environment was relatively conducive to a decrease in smoke buoyancy due to the increase in ambient temperature caused by solar radiation heat received by the lining (Figure-27). About 10% of the ventilation air leaked out through openings and the like. Therefore, further verification in a test field closer to an actual environment is necessary.

- Verification of factors that cause divergence from CFD results (smoke source with hot air flow, experiments in mountain tunnels)
- Selection of an optimal installation height for the amounts of heat and smoke generated by an actual fire
- Fire source capacity, and smoke source review (with plume, gasoline/actual vehicle fire)
- Verification of optimal control wind speed and sensor location in a real tunnel environment
- Confirmation of detailed upstream conditions (due to the number of units available in the present research, upstream sensors are omitted)
- Confirmation of applicability of existing anemometers (a cross-sectional anemometer was used in the present research)

![Figure-27](image)

**Figure-27** Appearance of the full-scale experimental tunnel and temperature of the ceiling

CONCLUSIONS

Under limited conditions, we were able to confirm the expected performance of this system from the results of full-scale tunnel experiments. However, in an actual expressway tunnel, it is necessary to confirm the functions of this system by confirming the detection control characteristics of gasoline fire pan fires, which are the evaluation criteria of current fire detectors, or hot air currents and smoke caused...
by actual vehicle fires. It will also be necessary to confirm the fire characteristics of other types of fires that will become more prevalent in the future, such as next-generation automobile fires.

ACKNOWLEDGEMENTS

We would like to express our sincere appreciation to everyone involved in the development of this system, as we were able to safely and efficiently complete the full-scale tunnel experiments and gain significant knowledge toward completing the system development, thanks to the cooperation of various people both in Japan and overseas.

REFERENCES


Progressive Evacuation Approach in a High-Security Hazardous Tunnel

Sandeep Upadhya, Jonathan Tang, Mukesh Tomar, James Fletcher & Rares Zupu
Jacobs UK, London, United Kingdom

ABSTRACT

This paper describes the use of smoke management techniques and an evacuation strategy which was implemented in a High-Security Single Bore Tunnel with multiple hazardous underground stores (adits) along its length. There are numerous standards and guidance documents available for the design of Road, Rail, and Cable or Utility Tunnels, yet guidance is lacking when it comes to the tunnels for special purposes. Naturally, due to the passage of vehicles in this tunnel requiring access to the underground stores, a road tunnel standard (NFPA 502) was explored [1]. NFPA 502 requires tunnel exits or cross-passages at a maximum distance of 300 m where the exact intervals depend on engineering analysis. However, due to the inherent security risk of this hazardous tunnel, the design team at the request of the Client studied ways to mitigate the requirement of multiple exits along the length of the tunnel. This was implemented through an innovative solution that compartmented the tunnel at defined intervals using walk-through full-height drop-down smoke curtains. While this solution mitigated the security risks, the danger to occupants from the effects of a tunnel fire was increased. The performance of the proposed solution was examined by an Available Safe Evacuation Time (ASET) vs Required Safe Evacuation Time (RSET) study using Computational Fluid Dynamics (CFD) simulations. Results demonstrated that the smoke curtain can reduce the smoke propagation speed to adjacent areas and keep tenable conditions for evacuation in non-fire zones. The smoke curtain spacing along the tunnel is a function of tunnel geometry (i.e., gradient, area), evacuees walking speed, and fire size.

KEYWORDS: Progressive Evacuation, Performance Based Design, Computational Fluid Dynamics, High-Security Tunnels

INTRODUCTION

This study examines the use of automatic walk-through full-height drop-down smoke curtains to assist in evacuating occupants from a high-security tunnel with hazardous stores (adits of 20-50m in length) located at regular intervals within the tunnel. The tunnel is a single bore with over 1000 m in length, and a vehicle entry is planned from one portal and exit from another portal. There are niches built within this tunnel for parking and turnarounds as needed. The tunnel is approximately 6 m wide and has a single lane for vehicle movement with walkways on either side. It has a steep gradient at the portals of 9.1 %, followed by lengths with gradients of 6 %, 3 %, and 0.5%, respectively. For confidentiality reasons, actual tunnel plans and sections cannot be shared at any public forum; hence the same was not included in this study.

Unlike a highway road tunnel, the usage of this tunnel is very infrequent and a maximum of 5 vehicles are expected to be in the tunnel at a single time. The type of vehicles using the tunnel varies from forklift trucks to heavy-duty goods vehicles. Occupancy of the tunnel would vary between a maximum of 30 to 50 persons at a time, either on foot or by vehicle. The occupancy consists of a mix of authorized personnel, trained drivers, operators, and maintainers. The general public, elderly or People of Reduced Mobility (PRM) are not expected to use the tunnel and all those entering are operationally trained on emergency procedures.
Relevant road tunnel fire safety standards and local building codes for special hazardous occupancy were consulted for guidance on egress provisions. In the case of the road tunnels using NFPA 502, the maximum distance between the exits would be 300 m, while other building code suggested exit provisions at less than 100 m intervals. Due to the inherent security risk of this confidential tunnel, multiple exits from the tunnel were not favourable. Hence, no intermediate exits were considered in this tunnel and evacuation relied only on entry and exit portals. This strategy requires occupants to travel along the tunnel for evacuation. However, during a fire, the tenability of the tunnel will be compromised very quickly, making it unsafe for the occupant’s evacuation. To ensure the same level of safety as it would be with the required number of intermediate exits prescribed by the standards, walk-through full-height drop-down smoke curtains are proposed at defined intervals along the length of the tunnel [1].

This study uses a performance-based solution for egress design rather than following prescriptive design recommendations. This approach is justified as an equivalency method supported by various international fire safety standards, including National Fire Protection Association (NFPA) [1]. The equivalency method is described in NFPA 502 as an alternative means of providing an equal or greater level of safety afforded by strict conformance to prescribed codes and standards [1].

In the spirit of meeting fire safety “equivalency”, smoke curtains are proposed to replace the emergency exits in this tunnel. The main objective of using the smoke curtain is to significantly decrease the speed at which the smoke spreads through the tunnel, thereby allowing occupants sufficient time to escape. These curtains will impede the propagation of smoke and will allow for a longer ASET for occupants to escape. The spacings of the curtains would be more frequent in steeper grades and less frequent in flatter tunnel grades, as smoke travels faster in the steeper grades. Fire Dynamic Simulator (FDS) was conducted to compare RSET vs ASET evacuation analysis to ensure the safe passage of all the occupants, while protected by the full-height drop-down smoke curtains.

SMOKE CURTAIN

Smoke curtains are generally categorized based on their enclosing arrangement and their smoke-resistant properties. Commonly used smoke curtain types are partial and full-closure smoke curtains.

A permeable smoke curtain is a special type that allows evacuees and vehicles to pass through the curtain in an emergency. On the other hand, a partial closure smoke curtain usually covers only a few meters from the top and restricts smoke at a high level. It may allow occupants to escape but cannot allow vehicle access. Full closure smoke curtain uses a single big curtain covering the whole area and restricts the smoke movement throughout the height of the tunnel. Figure 1 illustrates different types of smoke curtains.

During a literature review it was found that most studies have been done using partial closure and full closure smoke curtains. Halawa [3] did extensive research using FDS on partial smoke curtains in the road tunnel. Their research highlighted that the smoke curtain can contain smoke within a certain region. Bettelini et al. [2] also performed a numerical simulation analysis on partial closure smoke curtains and fully closure smoke curtains. The research concluded that the different kinds of smoke curtains could
limit the longitudinal smoke flow rate and improve the smoke control strategy utilising natural or longitudinal ventilation.

Very limited information is available in the current literature on the usage of the permeable smoke curtain in a tunnel environment. Although a permeable smoke curtain system allowing occupants and vehicles to continue their evacuation in a fire is understood to have been used in the A12 Roppener Tunnel in Austria [4], no design documents are available to understand its benefit in the tunnel.

The smoke curtains adopted in the high-security tunnel are made up of multiple smoke-resistant strips. The selected product is a unique patented bi-roller system which has interweaving, overlapped panels as narrow as 600 mm wide. Each panel overlaps the other and has its own self-leveling bottom ballast system. Evacuees can simply ‘walk through the panels, which then fall back into place, helped by the anti-tangle overlap retention system. Active Smoke Barriers comprise technologically advanced fire-resistant fabric barriers encased in a compact steel housing. Barriers remain invisibly retracted until activated by an alarm or detector signal, at which time they descend safely to their fire operational position. The total mass of the curtain is 27 kg for every meter run of the assembled curtain. The product has been successfully implemented in several underground rail systems (in escape passages) and has been validated for use with appropriate aerodynamics and fire resistance characteristics as provided below.

This smoke curtain is a hybrid between a full closure and a permeable smoke curtain. The smoke curtain enables smoke to be contained within a zone and allows occupants and vehicles to continue to move through, as necessary. The permeable feature is introduced for this study due to the potential of crossing occupants and assuming for porosity through general airtightness issues. In this study, only evacuees evacuating on foot are considered, although the possibility of vehicles driving through the curtains and out of the tunnel is also possible. The curtain also provides 2 hours of fire resistance against the standard time-temperature curve. Validation reports and experiments from the manufacturer demonstrate compliance with the required project specifications.

In this tunnel, the compartments using smoke curtains are not required to have any fire separation. However, smoke curtains will also provide 2 hours of integrity against the standard time temperature curve. The smoke curtain will also meet the following requirements:

- Tested in accordance with BS EN ISO 1716:2010 standard to achieve non-combustible classification.
- Linked with Linear Heat Detector system for automatic operation
- Total gravity failsafe (TGFS) operation to ensure safe rates of descent even following total power loss, wiring, short circuit, or system corruption.
- Self-leveling bottom ballast system to overcome uneven floors
- Strip retraction for safe, consistent rewinding when ascending
- Provision of a mechanical over-ride system for emergency Services

The figure below illustrates a typical arrangement of smoke curtains in the tunnel for evacuation purposes.

![Figure 2 - Smoke curtain with evacuation provisions](image-url)
Evacuation Strategy

Figure 3 shows the current evacuation strategy for tunnel users.

![Figure 3 - Current evacuation strategy for the tunnel](image)

The proposed strategy involves creating multiple horizontal evacuation zones in the tunnel made up of permeable smoke curtains (with evacuation features). This arrangement allows occupants to migrate from the fire-affected zone to the nearest zone which would be a place of relative safety once the evacuation is initiated. The smoke curtains are fixed from the ceiling and are proposed generally at an interval of 300 m or less to comply with the equivalency approach. The steeper gradient location requires closer spacings, whilst flatter tunnel sections have greater spacings between curtains. A false ceiling (down stand) with the necessary smoke compartmentation (using sealants) is provided where tunnel MEP services are located along the length of the tunnel, such that fire-affected zones do not allow smoke to infiltrate between other zones, as shown in Figure 4. All services hung from the tunnel ceiling penetrate the fire-rated false ceiling. A small amount of smoke infiltration may still occur at the lower levels and through the permeability feature of these curtains, but this was not sufficient to prevent human egress from the tunnel.

![Figure 4 – False ceiling and drop-down smoke curtain cross-section](image)

Emergency System Interfaces

Other than the proposed smoke curtain, several other critical emergency systems shall also be installed inside the tunnel, including CCTV, emergency lighting and a hand-held communication device will be held by all occupants of the tunnel.
Linear Heat Detection is the primary detection system proposed for the current tunnel. Two linear heat detection cables are proposed to be installed below the soffit and one cable on each side with an activation temperature of 70 °C.

A longitudinal smoke clearance strategy is proposed for this tunnel and is intended to activate once all occupants have escaped the tunnel. The longitudinal strategy comprises an axial fan located at one end of the portal which depressurises the tunnel and extracts smoke from the tunnel. Make-up air is provided via openable tunnel dampers located at the other portal. Depressurising the tunnel ensures that smoke does not leak into the hazardous stores; there are no pressurisation units proposed in the stores, however, HVAC fans serving the stores could serve this purpose if modified. The axial fans are sized for smoke clearance only and unsuitable for smoke control which would have necessitated significantly larger fans.

**Smoke Clearing Strategy/ Emergency Procedures**

In case of a fire, unless any occupants discover the fire and report to the control room using a two-way hand-held mobile device, the fire would be detected automatically by the Linear Heat Detection system. Once activated, the system would be interfaced with the Fire and Life Safety (FLS) and alarm system which would start alerting occupants to evacuate and automatically deploy the smoke curtains. A fail-safe drop-down mechanism is also available should the electric circuit connecting the smoke curtain would fail.

The smoke curtains are intended to create smoke zones and to contain the smoke as it builds up within a designated zone. Evacuees can walk through the curtains specially engineered to prevent smoke spread but allow occupants to escape through. The curtains can also be traversed by vehicle if needed.

Once all the occupants are safely evacuated, the smoke curtain can be automatically retracted to its original position and the ventilation system would be activated manually to clear the smoke.

**DESIGN FIRE LOAD**

The anticipated vehicles within the tunnel are industrial electrical forklifts with rubber tyres and heavy-duty goods vehicle. As the fire load of the goods vehicle is greater than the forklift, this has been assumed to be the worst-case fire load for the design of the FLS systems in the tunnel. The peak design Heat Release Rate (HRR) for the truck is considered to be 50 MW maximum [6] [7]. Hence a 50 MW peak HRR fire load is adopted in all the simulations of this study. A Fixed Fire Fighting System (FFFS) is proposed for this tunnel; however, all studies included in this paper do not consider the effect of the FFFS; hence the same is not discussed. It should also be noted that the current solution is independent of the inclusion of an FFFS.

Cheong et al. [8] have done various experiments on the HGV fully loaded with pallets and presented their fire growth rates. The fire HRR showed an ultra-fast fire growth rate. A similar fire growth rate is also used for this tunnel fire.

![Figure 5 – HGV experimental fire curve [9]](image-url)
RSET VS ASET ANALYSIS

An engineering analysis is carried out to demonstrate that the ASET is greater than the RSET and is used as a basis to assess whether the provisions for escape are adequate for the worst-case fire scenario. A simplified schematic of processes involved in an ASET vs RSET calculation is shown in Figure 6, taken from BS 7974 - Part 6 [10] as the standard approach used for evacuation.

![Figure 6 – ASET vs RSET principle described in BS 7974 Part 6 [10]](image)

The evacuation calculations in this section describe processes and time taken for an occupant to escape from a fire in the tunnel. The various evacuation scenarios presented in this section are described from the moment the fire is ignited.

RSET

RSET is built up from the following components.

- Detection time: The time required by the detection system to detect the presence of fire or smoke.
- Alarm time: The time spent since the fire is detected until an alarm is given to the users/staff.
- Pre-movement time: The time required by people to be aware of what is happening and to start moving.
- Travel time: The time spent by all evacuees to reach a place of relative or ultimate safety.

Detection and Alarm Time

Linear Heat Detection system is in place to detect fire along the whole tunnel. The detection time was examined by using FDS and was found that the detectors will be activated at a maximum of 72 s for a 50 MW ultrafast fire. This is only applicable to occupants far away from the incident, any occupant in the vicinity of the fire is assumed to start the evacuation after pre-movement time only.

Pre-movement time

A value of 60 s is adopted for the pre-movement time based on suggestions from Society of Fire Protection Engineers (SFPE) handbook [11] and BS 7974 - Part 6 [10]. In the Chapter dedicated to calculations for evacuation time, it is recommended for built environments where the occupants are awake and there is a fire alarm system with evacuation procedures in place, a pre-movement time of between 60 s and 120 s should be used. In support of this number, staff will be well-trained, and the facility will have regular evacuation drills. Also, a two-way hand-held mobile device is used in the tunnel, which will assist in managing the evacuation progress. Staff is trained to raise the alarm and initiate evacuation once a fire has been confirmed. This level of staff training and awareness is sufficient to achieve less than 60 s of pre-movement time. In addition to this, it should be noted that occupants closer to the fire will react much sooner than those further away. The scenarios modelled in this study
consider a lower occupancy level and with the use of radio communication between each other, pre-movement time of 60 s is considered appropriate.

**Travel Time**
For evacuation, a hand calculation method is used as the number of occupants in this tunnel is low, and minimal interaction between the occupants is expected. The evacuation time for this scenario depends upon the walking time of the final occupants who were at the most remote part of the tunnel at the end of the pre-movement time. Typically for the travel time calculations, the longest escape time in the tunnel is considered as the actual time to escape.

Previous studies conducted by various researchers have reported varying speeds of travel for evacuation ranging from 0.9 m/s to 1.6 m/s [12]. To be conservative, a value of 0.9 m/s is adopted for the purposes of evacuation. Past researchers also showed that for a gradient of more than 12 %, people would walk 5 % slower than their average speed [13], hence, no additional walking speed is considered at section of the tunnel with 9.1 %.

**ASET**
For the estimation of ASET, CFD modelling has been carried out using the FDS version 6.7.9. FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow with an emphasis on smoke and heat transport from fires [9].

FDS uses an explicit predictor-corrector scheme, second-order accurate in space and time. Turbulence is treated by means of Large Eddy Simulation (LES).

Convergence of each timestep in FDS has managed automatically within the software using a physical timestep which varies based on a simple relationship between cell size and characteristic velocity through the cell; this is bounded by a fixed maximum Courant-Friedrichs-Levy (CFL) number which must be satisfied to ensure the flow anywhere in the domain does not traverse more than a single mesh cell in a single time step.

**Tunnel Geometry and Boundary Conditions**
Figure 7 shows the schematic and cross-sectional of the base tunnel model, respectively.

![Figure 7 - General FDS model schematic](image)

In the presented domain, four smoke curtains with a spacing of 300 m are modelled and the fire is in the middle of the domain, as shown in Figure 7. With a 30 s of mechanical delay, the smoke curtains are fully deployed at 102 s accounting for detection time (72 s) and mechanical activation time. A base case model was developed for a tunnel grade of 9.1%; further models were also developed with 0% tunnel grades.

In FDS, an open boundary has been applied at both ends of the tunnel. As the tunnel is supposed to be permanently closed to the atmosphere via sealed doors, a wall with a small opening in the lower part was modelled as shown in Figure 8. This opening assures there is enough oxygen in the tunnel to sustain the fire, meanwhile limiting the airflow into the tunnel to replicate the sealed feature.
To capture the permeable feature due to the crossing of occupants and accounting for general airtightness, the smoke curtains were modelled with a slot in the middle instead of a solid wall. In this study, two leakage area values have been studied which are 5% and 10%. Note that the slot area represents the percentage of leakage in the smoke curtain.

Figure 8 – Boundary Conditions

Figure 9 – Representing 5% leakage smoke curtain
Figure 10 – Representing 10% leakage smoke curtain

Figure 11, shows the design fire curve; the fire reaches a peak HRR of 50 MW at 517 s.

Figure 11 – Designed fire curve
Assessment Criteria

The performance of the smoke control measures using curtains is examined based on the tenability of the evacuation routes from the evacuee’s place of origin. For the smoke control measures to be deemed sufficient, the evacuation routes should remain tenable until all evacuees have reached and escaped to a relatively safe point.

In line with standard practice, the tenability criteria for visibility and temperature are defined as follows.

- A visibility of 10 m is used to denote the boundary of visibility required for escape.
- A height clear of the smoke of at least 2.5 m from floor level is required above any point on the evacuation path and, a height of 2.5 m is considered here to account for modelling uncertainty.
- The maximum air temperature along the egress routes for tenable conditions is 60 °C. A temperature of 60 °C can be considered a tenable environment for approximately 10 min without incapacitation.

CASES

The following Table 1 summarises all FDS simulations that have been carried out as part of this study.

<table>
<thead>
<tr>
<th>CASES</th>
<th>Smoke Curtains</th>
<th>Spacing</th>
<th>Leakage Potential</th>
<th>Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>No</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
<td>9.1 %</td>
</tr>
<tr>
<td>1</td>
<td>Yes</td>
<td>300 m</td>
<td>10 %</td>
<td>9.1 %</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>300 m</td>
<td>5 %</td>
<td>9.1 %</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>150 m</td>
<td>10 %</td>
<td>9.1 %</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>300 m</td>
<td>10 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>

Table 1 – Simulation List

RESULT AND DISCUSSION

Base Case

The results for the base case are shown graphically in Figure 12 (comparison of RSET vs ASET). RSET line indicates the location of the occupant along the tunnel chainage at various times. The time estimate for RSET (solid line) includes the assumed pre-movement, detection, alarm, and movement time as discussed in the above section. ASET line (dashed) indicates the time and distance at which the visibility at 2.5 m above the road surface reduces to below 10 m.

The comparison between ASET and RSET shows that for the base case, when there are no smoke curtains, the conditions in the tunnel become untenable near the fire rapidly after ignition. The steep gradient of 9.1 % means that in the uphill direction, the buoyancy force is dominant and accelerates the propagation of smoke. The visibility in the tunnel drops to below 10 m before the occupants can clear the tunnel. As tenability is compromised during the escape, mitigating measure needs to be introduced for occupants to safely evacuate the tunnel via portals.
Implementation of Smoke Curtains

Smoke curtains are introduced at 300 m intervals as a mitigating measure from the base case. The graph in Figure 13 shows the comparison between the Base Case and Case 1 together with the RSET. The location of the smoke curtain is also illustrated in the figure by the label.

The benefit of having a smoke curtain can be clearly observed from the results. Before the smoke layer reaches the curtains (i.e., first 150 m from the incident), the smoke behaviour between the two cases is the same. However, once smoke reaches the smoke curtain, the results show a significant decrease in the propagation rate. This demonstrates that the smoke curtain not only traps the smoke within a zone but also helps in reduce the propagation rate to the adjacent zones by reducing its inertia upon impact.

While the introduction of the curtain improves the results from the base case, the smoke curtain spacing proposed in Case 1 can still not provide a tenable escape for occupants as required. This can be observed from the results presented in Figure 13.
Leakage of Smoke Curtain
In addition to the 10% leakage (Case 1), a smoke curtain with 5% of leakage (Case 2) was also examined to assess the difference in performance between the two cases. The permeable feature of the smoke curtain is mainly caused by,

1) While occupants move through the curtain during the escape.
2) General airtightness due to stripe geometry.

As shown in Figure 14, both cases have similar results, and both fail to provide a tenable escape for the occupants. This indicates minimal difference between 5% and 10% leakage. Therefore, the 10% leakage has been adopted for further studies based on the conservatism it provides.
Spacing Between Smoke Curtains

The smoke curtain spacing is reduced to 150 m and CFD calculations have been carried out for this case. Results are analysed for a 300 m spacing (Case 1) and a 150 m spacing (Case 3). The smoke plume results are shown in Figures 16 & 17, and the graph in Figure 15 shows the comparison between the two cases.

Comparing both cases, the initial smoke propagation is the same prior to reaching the curtain. However, for case 3 with a shorter spacing, the smoke propagation speed along the tunnel in the uphill direction is reduced as the smoke front impedes with the smoke curtain sooner. Thus, the smoke curtains not only allow a large smoke volume to be contained behind it but also help reduce the smoke propagation rates for smoke volume that permeates through the curtain. The results clearly demonstrate the benefit afforded by smoke curtains at closer intervals.

For Case 3, the smoke curtain can reduce the smoke propagation speed just when the smoke is about to catch up with the evacuees. If no smoke curtain is installed, an intermediate emergency exit is needed at that location to provide a tenable escape for evacuees. This shows how a smoke curtain in this case can provide a similar level of safety as an intermediate emergency exit would have provided it.

For Case 1, the smoke curtain fails to provide a tenable escape as the curtain cannot lower the smoke propagation speed quickly enough. The main purpose of keeping smoke curtains at regular intervals is to reduce the speed of the smoke as soon as possible. Therefore, each design should examine the optimised spacing to achieve a tenable escape in any circumstance. This can be done by analysing the worst case.

Figure 15 – RSET vs ASET - Case 1 & Case 3
Gradient Effect

As mentioned earlier, the tunnel has a gradient varying from 0 % to 9.1 %. A study of the 0 % gradients is investigated to examine the curtain spacing required for the 0 % gradient section. Figure 18 shows the RSET vs ASET for Case 4.

![Figure 18 – RSET vs ASET - Case 4](image)
For a 0% gradient (Case 4), the smoke propagates in both directions equally but at a slower pace compared to the 9.1% gradient (Case 1). In this case, instead of a 150 m spacing, a 300 m spacing smoke curtain is adequate to provide tenable escape conditions for evacuation.

**DISCUSSION**

The above five cases investigated through CFD analysis suggest that for this tunnel, a smoke curtain spacing of 150 m is required for the 9% gradient region, whilst 300 m spacing is adequate in the 0% gradient section of the tunnel. For tunnel grades in between, the spacing would range from 150 m to 300 m and to be established by appropriate simulations.

A curtain redundancy similar to jet fans is considered in the tunnel. If a fire starts in the immediate vicinity or under a curtain, despite the curtain being flame resistant, it could be compromised by the fire. Similarly, there may be issues surrounding maintenance and operability with respect to the environment in the tunnel (i.e., gathering of dust) and other mechanical issues all of which may mean that a particular curtain is not available in demand.

For this reason, a Minimum Operating Safety Requirement study was considered, and mitigations were implemented, such as temporary closure of the tunnel and restrictions on vehicle parking locations. Sufficient power redundancy is considered, and a preventative maintenance strategy has also been developed and embedded with the Supervisory Control and Data Acquisition (SCADA) and controls. In order to ensure a robust design, the spacings of 300 m and 150 m were reduced by half to account for unavailability due to maintenance and loss from fire. Despite the additional curtains being required, the fire curtains’ cost, security and carbon benefit far outweigh the cost of introducing exits at regular intervals.

**CONCLUSION**

Unlike a typical road tunnel, the tunnel in this study is a high-security hazardous tunnel with the entry/exit portals being permanently closed to the atmosphere via sealed doors and with no intermediate emergency exits. Currently, international standards are lacking in the design guidance for such special purpose tunnels. To adopt an equivalent safe design, it is proposed to use smoke curtains to replace the regular interval emergency exits which are generally required for occupant evacuation in regular tunnels.

The adopted smoke curtain is automatic, full height and permeable, which is made up of multiple smoke-resistant strips and has a leakage feature. It works like a full-closure smoke curtain when the pressure difference across is lower than the designed threshold and becomes permeable when higher than it.

The key findings of this study are as follows.

- The concept of the smoke curtain is not only to trap smoke in a single compartment but also to reduce the smoke propagation speed to adjacent areas and to keep tenable conditions for evacuation in non-fire zones.
- The design of the smoke curtain spacing is a function of tunnel geometry (i.e., gradient, area), evacuees walking speed, and fire size.
- This study suggests that for a steep gradient such as 9.1%, a curtain would be required at every 75 m while for the 0% gradient, a spacing of 150 m was adequate.
- The cost and security benefits of implementing such curtains far outweigh the cost of introducing intermediate exits from the tunnel.
REFERENCES


Application and Interpretation of Visibility in Smoke Laden Environments in Performance-Based Design

Andrew Coles, Mathilde Girault, Peter Senez & Jordan Brown
Senez Consulting Ltd
202-1777 56th St, Delta, British Columbia, V4L 0A6, Canada

ABSTRACT

There has been a significant body of work related to understanding human behavior in fire which includes experimental and human field trials. This work is used in fire engineering designs as inputs into fire and evacuation models and the built environment to provide fire safe solutions. The application and interpretation of these parameters are particularly common in performance-based design for occupant evacuation and smoke control systems in all buildings, specifically in rapid transit and tunnel (road and rail) systems.

Inconsistencies between modelling inputs, such as visibility constants, visibility criteria, and the interpretation of results have been observed to cause confusion amongst modelers and stakeholders. Occupant tenability is comprised of both visibility and irritant species. One objective of this paper is a consolidated approach to engineering calculations for determining visibility through smoke. The review evaluates the application of K factors with respect to illuminated signs or reflective surfaces, the relationship to mass extinction coefficients and acceptance criteria in various global jurisdictions. A recommendation on the method of analysis and acceptance criteria is provided.

A second objective is the use of visibility outputs in engineering design and methods to interpret results to design solutions. Interpretation of visibility is a three-dimensional problem which is influenced by other external factors such as ambient lighting and other objects and surfaces. General practice is an evaluation of smoke obscuration in a discrete point. Wayfinding capability requires consideration of exit sign characteristics (luminance, location, design), ambient lighting and smoke obscuration to understand the ability for occupants to see an exit. A review of past work and recommendations is provided.

KEYWORD: visibility, mass extinction, light extinction, mass extinction, fire modelling

INTRODUCTION

Tenability is defined as the effects a fire has on occupants and can be characterized by:

- Visibility in fire smoke,
- Convective heat,
- Radiant heat,
- Concentration of narcotic gases,
- Concentration of irritant gases.

While the last four phenomena listed above can be evaluated by a single value at a given location, visibility in fire smoke varies based on the line of sight considered and the characteristics of the object to be viewed, making the interpretation of model results more challenging. Visibility is generally the
most restrictive tenability criterion and the results can also inform the design of the means of egress and associated wayfinding measures.

**CONCEPT AND DETERMINATION OF VISIBILITY IN FIRE SMOKE**

Visibility in fire smoke can be defined as the maximum distance at which an object of a given size, brightness and contrast can be seen and recognized [1]. Visibility is a function of the optical density of the smoke, the type of smoke and the characteristics of the target object. The visibility of an object through smoke is expressed in Eqn (1) [2] where \( V \) is the visibility (m), \( C_s \) is the extinction coefficient (1/m) and \( K \) is the visibility constant (-):

\[
V = \frac{K}{C_s}
\]  

(1)

Values of \( K \) have been determined experimentally by Jin [3] and found to be in the range of 5 to 10 for illuminated signs with an experimental mean of 8. Jin also recommended the values for reflecting signs for other reflective surfaces such as walls, floors, doors, stairways, or obstacles with a range of range of 2 to 4. Figure 1 shows the linear relationship for self-illuminated signs [3] and Table 1 summarizes the experimental means.

\[ C_s = \alpha_s m_s \]  

(2)

K and \( \alpha_s \) are parameters that are defined and soot is determined through calculation as a ratio of the fuel mass loss rate and the soot yield. The soot yield is a product of the constituent material(s) and the stoichiometry of the combustion process [4]. Further, \( C_s \) can also be expressed in relation to the light intensity in Eqn (3) where \( D \) is the light path length (m), \( I \) is the intensity of light through smoke (cd) and \( I_0 \) is the intensity of light.
\[ C_s = \frac{1}{D} \log e \left( \frac{I}{I_0} \right) \]  

\( \alpha_s \) is also determined experimentally. In 1977, Seider and Einhorn [5] suggested a value of 7.6 m²/g for overventilated (flaming) fires and this value was widely used for visibility calculations [6]. Mulholland and Croarkin [7] compared the experimental results obtained from seven studies carried out on fuels of various types and scales that led to the recommendation of a value of 8.7 m²/g with an expanded (95% confidence interval or 2 standard deviations) uncertainty of 1.1 m²/g for overventilated (flaming) fires for generic fuels made of wood and plastics as typically found in buildings [Figure 2].

Mulholland noted that “between-laboratory differences” were the major source of variability. Because of its high confidence level and its representation of a wide range of fuel types, Mulholland concluded that the value of 8.7 m²/g is adequate for most designs. However, the use of lower or higher values can be substantiated for specific applications such as studies where the type of fuel is known and well defined or for studies involving smoldering fires or pyrolysis generated smoke.

Figure 3 illustrates a comparison of overall visibility results (from the analysis below) between the specific extinction coefficients. While the results are subtle, there are obvious differences where smoke is not as dense which can have a cumulative impact.

\( \alpha_s = 7.6 \text{ m}^2/\text{g} \)  
\( \alpha_s = 8.7 \text{ m}^2/\text{g} \)  
\( \alpha_s = 9.8 \text{ m}^2/\text{g} \)
Table 2 compares different values of $K$, ($K=8$ for illuminated or $K=3$ for reflective), a universal value of $\alpha_s = 8.7 \text{m}^2/\text{g}$, and $C_s$ by substituting values into Eqn (1) and Eqn (2). A value of $C_s = 0.3 \text{l/m}$ for $V= 10 \text{ m}$ and $K=3$; applying the same extinction coefficient with $K=8$ provides $V=26.67 \text{ m}$. Compared to a value of 30 m, this is within reasonable uncertainty. Alternatively, this would equate to $K=9$ for a consistent soot mass for a reflective sign, which is within the experimental bounds noted by Jin.

### Table 2: Visibility ($V$), extinction coefficient ($C_s$) and soot mass ($m_s$) calculations for variations in variables (underlined values are calculated variables)

<table>
<thead>
<tr>
<th>$V (\text{m})$</th>
<th>$K (-)$</th>
<th>$C_s (\text{l/m})$</th>
<th>$m_s (\text{g/m}^3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3</td>
<td>0.3</td>
<td>0.689</td>
</tr>
<tr>
<td>26.67</td>
<td>8</td>
<td>0.3</td>
<td>0.689</td>
</tr>
<tr>
<td>30</td>
<td>9</td>
<td>0.3</td>
<td>0.689</td>
</tr>
<tr>
<td>30</td>
<td>8</td>
<td>0.26</td>
<td>0.613</td>
</tr>
<tr>
<td>11.25</td>
<td>3</td>
<td>0.26</td>
<td>0.613</td>
</tr>
</tbody>
</table>

Evaluation of both values of $K$ to obtain visibility results for both illuminated and reflective objects can be conducted, but this process can be impractical and costly in terms of computing or post processing time when using computational fluid dynamic (CFD) tools. The general practice is to select one or the other, which then requires that the visibility slices of the CFD model be interpreted differently, with modelers and other stakeholders having different preferences as to which criterion is used. Some software requires prescription of $K$, whereas others apply as a scalar to during post processing.

The comparison of the two is of limited apparent benefit as the output provides a similar baseline extinction coefficient for visibility as shown in Table 2. Eqn (4) provides a relationship of translating between outputs for illuminated signs and reflective signs:

$$V_{ill} = \frac{8}{3} V_{refl}$$

(4)

An illuminated sign ($K = 8$) and visibility criteria of 30m is equivalent to a reflective sign ($K=3$) with visibility of 11.25m. While there is variation in the parameters (such as variations to $K$ to achieve similar mass of soot) these are within the experimental values. Reference [11] shows the initial development of a standard on this issue.

### ACCEPTANCE CRITERIA

A literature review identified a wide variety of the deemed-to-satisfy or acceptance criteria, ranging from 3 m to 30 m, generally measured at 2 m above the walking surface. The values are derived from experimental studies where people were asked to walk in spaces filled with various levels of smoke density. Examples are provided below:

- 3 m to 4 m in homes [13],
- 3.75 m for reflective surfaces in narrow egress routes where people are committed to an exit [8],
- 5 m in rooms less than 100 m$^2$ [13, 14],
- 7.6 m to 9.1 m in a university building consisting of classrooms and corridors with an atrium at the main entrance [15],
- 10 m for reflective surfaces in spaces where the egress route configuration is complex [16, 17, 8],
- 10 m for an 80 lux illuminated sign in narrow egress routes where people are committed to an exit [16, 17, 8],
- 12.8 m to 14 m in a five-storey high museum with a complex design [15],
• 30 m for an 80 lux illuminated sign in spaces where the egress route configuration is complex [16, 17, 8].

The factors to be considered when choosing the visibility acceptance criteria are:
• The familiarity with the building’s egress routes [15],
• The size of the rooms [15],
• The size and complexity of the building [15],
• The occupants’ ability to walk through smoke.

A review of the applicable building code in various countries/jurisdiction reveals that visibility performance is either:
• Prescribed at regulation level (such as in New Zealand [13]) and therefore cannot be deviated from,
• Prescribed through deemed-to-satisfy solutions (such as in Canada [18]) or a verification method (such as in Australia [14]), or
• Adopted based on engineering practice (such as in the United States [16, 17, 8] and the United Kingdom [19]).

VISIBILITY THRESHOLDS

The ability to see through smoke can affect walking speed [3] as shown in Figure 4. Walking speeds reduce by 50% at an extinction coefficient of ~0.95 for non-irritant smoke and ~0.5 for irritant smoke. These correlate to a visibility of ~3.1 and 6 m for a reflective sign (K=3). Note that lower visibility in non-irritant smoke can be maintained before a 50% decline in walking speed. The visibility will also affect their ability to find their way to the exits [7]. Fridolf et al [8] notes that movement speed ranges are marginally narrower at 0.2 – 0.8 m/s for tunnel environments for similar extinction coefficients. Fridolf et al [9] summarizes data sets on people movement in smoke and suggest variations on travel speeds in tunnels for when visibility is less than 3 m; above this, walking speeds are considered equivalent to unobstructed or smoke free environments. Nilsson et al [10] notes the walking speed reduction curves proposed and incorporated into ISO/TS 21602:2022 [11].

![Figure 4](image-url)  
Walking speed in fire smoke (reproduced from [2]) and annotated with corresponding values of Cs for visibility values (V) and visibility constants (K)
There is therefore a need to define a criterion for visibility through smoke under which a design will be considered to have failed. In respect to occupant egress there are two components, wayfinding to the exit and queuing at the exit. Figure 5 illustrates the concept of acceptance criteria in different evacuation stages.

![Figure 5](image)

**Figure 5** Application of visibility criteria ($K=8$ for illuminated signs) with respect to different components of evacuation of 1) queuing at an exit, 2) wayfinding in a narrow corridor or 3) wayfinding in an open floor space.

As noted by Jin [3] there is a rapid reduction of visual acuity ($S$) when $C_s > 0.25$ l/m [Figure 6].

![Figure 6](image)

**Figure 6** Relationship of Relative Visual Acuity ($S$) vs Extinction coefficient ($C_s$) [3]
For an occupant navigating a space (either familiar or unfamiliar) to locate an exit, a minimum level of visibility is necessary when not proximal to the exit. Such as, in an open floor area, visibility along a path should be maintained to permit wayfinding and navigation. Conversely, if occupants are waiting, the need for a higher degree of visibility is not as necessary as they are already queuing for the exit. For the latter, a lower acceptance criterion may be adopted for purposes of visibility where occupants are queuing given safe proximity to the exit, and within the context of other smoke parameters being in tolerable limits.

The methodology above would be a typical performance-based approach where time-based comparisons of tenability and evacuation would occur. The cited research highlights the potential reduced levels of visibility depending on the configuration of the space been evaluated. However, at a minimum, 10 m visibility in open areas and 4 m when proximal to an exit for K=3 are recommended baseline values (refer to Yamada et al [2] for other guidance).

ASSESSING VISIBILITY IN FIRE SMOKE

Spreadsheets and zone models consider a homogeneous smoke layer and provide a single value applicable to each zone; CFD models provide a value of visibility for each cell within the domain.

The zone model output shows that the visibility level deteriorates with time, however the variations of visibility within the zone are not captured because the model considers a uniform homogenous smoke layer. The CFD outputs are in the form of numerical values at a given location in a defined plane (slice); from a likely non-homogenous smoke plume. Examples of the outputs from zone and CFD models are provided in Figure 7(a) and Figure 7(b) respectively.

\[ V_{av} = \frac{1}{L} \sum_{i=1}^{n} V_i \Delta x_i \]  

\( (5) \)

If \( V_{av} \) is greater or equal to the length of the path \( L \), an object can be seen over the path.
Method 2: Determining the percent obscuration along a path: An illuminated sign is visible if the percent obscuration is not more than 99.966% and a reflective surface is visible if the percent obscuration is not more than 95.02% along a path of length L as determined in Eqn (6).

\[ V = \frac{KL}{\ln\left(1 - \frac{1}{100}\right)} \]  

(6)

Figure 8 shows a generic representation for a room developed to evaluate the two Klote methods. A 3 MW fire was used which allowed for development of a non-homogenous smoke layer throughout the space in earlier time periods.

Figure 9 shows the results where both methods along each path are compared with the different visibility constants with tenability slices showing smoke optical density at two time increments.

The results show that Method 1 is a representation of visibility deterioration over time where one specific location along the path may be below the acceptable limit, but over the entire path length the object may still be visible. Method 2 is more sensitive than Method 1. That is, only in the Path 1 analysis was there agreement with Method 1; all other cases it underestimated (early) or overestimated (late). For this case study Path 2 is close for both methods and values of K; which is likely attributed to a localized area of turbulent mixing. Path 3 shows a wider, expected, variation in the results where the chosen path is through an unstable area of the plume causing fluctuations in visibility. Method 2 shows earlier onset of untenable conditions.

A similar approach was undertaken for a generic tunnel with a 3 MW fire, forced ventilation to maintain the required critical velocity, and three visibility paths downstream in the contaminated air flow. An obstruction (intended to represent a train or vehicle) was located up stream of the fire to represent local air flow increases and turbulence downstream of the obstruction [Figure 10]. While the safety objective of a push pull system is to evacuate in fresh air upstream of the fire, the objective of the study is to compare visibility in a smoke ladened environment in a turbulent environment.
Figure 9 Comparative results of the three path locations for a room with corridor.

Figure 10 Geometry of generic tunnel.

Similar results to the room example were observed where Method 2 was sensitive to local optical density and either over or under predicted compared to Method 1. Because the paths evaluated were immersed in smoke at an earlier stage and remained so, less post processing was necessary for; but similar challenges were evident.

Method 2 requires additional post processing of data which resulted from fluctuating outputs specifically in turbulent zones where optical density oscillates between values. In summary, Method 1 was found to provide a more representative and less sensitive approach.
A PRIORI POST PROCESSING

Observations by Jin [3] and Ouellette [20] note that i) the decrease in visibility of illuminated signs through smoke is attributed to a reduction of intensity of the sign and background due to the obscuration and scattering of light off the smoke particles [3], and ii) ambient lighting reducing sign readability as the ambient illumination increases and luminous veil scattered from the smoke particles [20].

The concept of ambient illumination and the effect on visibility through smoke has been studied by Rubini and Zhang [21, 22, 23] that incorporated rendering packages (such as Physically Based Rendering Toolkit [24] common in computer graphics and gaming) to evaluate the effects of smoke on visibility a priori. The work evaluated visibility results from a computational fluid dynamics (cfd) model in a space with illuminated exit signs and different ambient lighting configurations. Figure 13 shows photorealistic renderings from Rubini [21] illustrating the effect of ambient light on visibility of objects of a 100 kW fire in a corridor at 1 minute.
Figure 12  Photorealistic renderings [22] showing visibility in a corridor at 1 minute for a 100 kW fire for a) ceiling lights and b) hand touch at the observer

As noted by Zhang [22, 23] CFD model visibility outputs (with tools such as Smokeview [25] or Paraview) provide an opacity of smoke in the cell. As shown in the prior examples, visibility along the line of sight requires significant instrumentation in the models prior to simulation for visibility assessments along a specific path. Zhang and Rubini’s work extend this capability to consider environmental factors (such as ambient light, object reflectiveness, distance and sign features). The concepts and the work by Zhang [23] in developing the floor map of visibility (FMV) approach considered visibility at a plane with smoke obscuration and probability of wayfinding.

Figure 13  Comparison of floor map of visibility (FMV) in (a) and smoke concentration in (b) from Zhang [23]

Figure 13 is an excerpt from [23] showing smoke concentration in the form of soot volume fraction (red = 2.5e-8, blue = 1e-8) and the FMV model of wayfinding visibility. The results from the FMV model show good visibility around the perimeter been closer to the exits (blue regions) and poorer visibility located closer to the fire (red zone). From the smoke concentration maps, conditions are poorer around the perimeter due to smoke dispersion and higher concentrations of smoke. The contrary observations are attributed to larger distances to an exit sign from the specific locations.

Work by Seike [26] and Fridolf [8] both note from the respective experimental data that occupants are likely, in a tunnel environment, to use the walls to assist with evacuation. As such, strategic considerations of emergency wayfinding and signage placement. Using the prior example, more frequent exit signage around the perimeter may be a more effective means of improving the wayfinding probability due to exit proximity. In stations or tunnels, signage at or below the handrails may have greater effectiveness elevated signs above 2 m that could be obstructed by smoke and affected by ambient lighting.

SUMMARY AND RECOMMENDATIONS

The literature review in this paper summarizes concepts of the wide body of work related to visibility in smoke. The industry would benefit from adopting a consistent approach to the input and acceptance criteria where visibility is a performance measure in numerical fire safety evaluations. Based on the above review, for most general cases the following criterion are used.

- **K = 3**, for reflective signs. If **K=8** is alternatively used (such as may be required by the local code or standard) adjust the Deem-to-Satisfy criteria.
- **αs = 8.7 m²/g** no additional variation necessary.
- Acceptance/Deem-to-Satisfy criteria:
  - 10 m for areas in spaces where the egress route configuration is complex and wayfinding is challenging, and
  - 4 m in narrow spaces (such as corridors), near exits for queuing.
  - Adjust the prior values accordingly for the K value used based on Equation 4.
The broader concept is that visibility should not be solely evaluated on a pass/fail basis of a localized loss of tenability. Applying a broader approach has potential if there is a localized loss of visibility. Opportunities for a fire engineering design could be to augment with emergency lighting and signage (directional or other). While more comprehensive tools are not currently available, additional practical and research opportunities could include the following:

- Methods to augment code-required emergency signage in areas determined to have low levels of visibility from CFD models. Figure 14b illustrates signs in a road tunnel that would be considered to exceed code-minimum requirements.
- Increasing opportunities for use of additional signage and operational information in more complex occupancies. For example, static emergency signage could be supplemented with dynamic components that interface with the operating environment, additional ambient lighting. Figure 14a illustrates use of train message boards to supplement the fire alarm visual notification.
- Appropriate installation height (i.e. at shoulder height or an elevation that is not so quickly immersed in a smoke layer)
- Research into the above could facilitate the development of post processing tools to evaluate actual visibility in smoke laden environments.

In summary, this paper proposes a methodology to provide consistency for performance-based assessments of visibility through smoke. Additional work and tools are necessary to consolidate the human behavior factors with the built environment analysis such as post processing tools that evaluate smoke laden environments in concert with building or facility lighting and signage systems. Concepts have been presented with possible solutions for the interim with the current gap in modelling capabilities.

REFERENCES


20. Ouellette, M.J., “Exit Signs in Smoke: design parameter for greater visibility” NRCC


Enhancement of the safety management for the three main passenger rail tunnels in Antwerp

Lieven Schoonbaert, Sven Spelmans, Stefaan Vernieuwe, Olivier Bivort & Christof De Backere, Infrabel / Belgian Railway Infrastructure Manager – divisions ICT, BCE & Tuc Rail (Engineering) Various offices, Brussels, Belgium

ABSTRACT

The three passenger tunnels in Antwerp will be further equipped with the necessary safety systems this and next year. A risk analysis and European regulations show that this is indeed necessary. Their implementation also follows the logic of an enhanced integrity level of the linked equipment. This is emphasised by imposing minimum operating conditions: in the absence of a pre-imposed cover of the safety level, the tunnels are closed to traffic, or at least an extra surveillance at crucial points. More attention is also given to intrusion protection, an integrated visualisation system (SCADA), accurate action by operators in the control room in the event of an incident and specific instructions to the fire brigade in the event of an intervention.

KEYWORDS: Risk Analysis, Safety Integrity Level, Decision and Action Timing, more Focus on Intrusion Prevention, Minimum Conditions for Exploitation, Building Operations Handbook

INTRODUCTION

Three existing train tunnels in Antwerp are currently undergoing a serious upgrade of their safety systems in a so-called migration project: an old tunnel ("Kennedy" - under the river Scheldt - (1969)) and the recent underground tunnels north and south of the Antwerp Central Station (2007). This concerns both hardware (e.g. new ventilators and fire detection) but also new operating software (IT-based) and improved insight into the handling of initiated alarms. The experience of more recent projects (Brussels International Airport [1] & Antwerp Port Freight Tunnel [2] & Brussels North-South Junction [3]) provided good knowledge for an increased safety level. The risk analyses carried out, including the expected operational reliability of the equipment, provide a system with improved integrity. The appropriate signalling in case of evacuation has been greatly increased and an incident such as intrusion by unauthorised persons have been added to the list of possible scenarios.

Figure 1  localization of the 3 tunnels, in the city of Antwerp
CURRENT SITUATION OF THE TUNNELS

The Kennedy railway tunnel is an existing railway tunnel of which construction dates back to the sixties of the previous century. It is a common civil construction with the Kennedy road tunnel which was officially opened 31 May 1969. The railway tunnel itself opened a few months later when on the 1st of February 1970 the first train passed through the tunnel.

As knowledge and awareness of tunnel safety was at a different level during the years of initial construction, both the passive and active safety measures taken in the initial Kennedy rail tunnel were limited. Below is an overall descriptive view of the tunnel and the particular areas of improvement which are being executed as part of the upgrade works on the tunnel.

<table>
<thead>
<tr>
<th>Tunnelsections</th>
<th>A single tunnel tube with a combination of round, then rectangular (sunken construction), and again a round cross section. The tunnel section below the Schelde river consists of sunken prefabricated caissons with a rectangular section. The two other round segments at both end were constructed in situ.</th>
</tr>
</thead>
</table>
| Other locations | Besides the installation of technical safety equipment in the tunnel itself, various other locations and interfaces of the tunnel are subject to improvement and upgrade activities:  
(1) Access roads for fire fighters on Left Bank + additional evacuation path  
(2) Interface with the Kennedy road tunnel: upgrade of the 5 evacuation points  
(3) Technical building Right Bank  
(4) New evacuation point Right Bank  
(5) Technical building Left Bank  
(6) Open trench acces  
(7) Various Technical rooms  
(8) ACR/ABCR (not on figure 2): tunnel controlrooms with operators in Berchem and Antwerp (backup) |

The Antwerp North South junction tunnel (ANS) was built in the early 2000s. The system was commissioned in 2007. As its name suggests, it connects the northern and southern parts of the city of Antwerp and serves the central station. As shown in the figure 3, the complex is divided into 3 parts  
- Part “Toegangshellings” = Junction South : single tunnel with 4 tracks;  
  - two of these tracks connect the -1 level of the station
the other two cross the station at level -2 to reach the “geboorde kokers”
- Part “Central Station” : platforms on 2 levels (management by NMBS/SNCB, not Infrabel !)
- Part “Geboorde kokers” = Junction North : two drilled tubes, each with one track

Figure 3 Synoptic representation of the ANS tunnel

The following table provides the main characteristics of the ANS system:

<table>
<thead>
<tr>
<th>Traffic</th>
<th>Passenger traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Number of individual journeys per year: 4,368;</td>
</tr>
<tr>
<td></td>
<td>- Number of trains per year: 65,832;</td>
</tr>
<tr>
<td></td>
<td>- Total number of movements per year: 70,200</td>
</tr>
<tr>
<td></td>
<td>No RID or freight transports allowed in the ANZ rail tunnel.</td>
</tr>
<tr>
<td></td>
<td>There are no restrictions regarding the simultaneous presence of multiple passenger trains in the tunnel.</td>
</tr>
</tbody>
</table>

| Design speed(s) | 90 km/h |
| Lengte          | ~3.4 km |
| Number of tracks | Toegangshelling: 4 |
|                 | Station -2: 4 |
|                 | Station -1: 4 |
|                 | Geboorde kokers: 2x 1 track |

FROM SCOPE TO REQUIREMENTS: RISK ANALYSES AT VARIOUS DETAIL LEVELS

The common denominator during the whole process, running over more than 10 years, of identification of the opportunity to upgrade the Kennedy tunnel till the final execution of the upgrade works is the risk based approach.
Indeed, over the years, a series of risk analysis has driven the definition, analysis, design and execution process, at various levels of details.
The First and highest level risk analysis was a Infrabel network level risk analysis. This Business Continuity analysis aimed at identifying the weak spots in the Infrabel network from a business continuity point of view: with incidents and what location would hurt us most in terms of being able to provide the obligations we have as a public service provider to the community. One result of this analysis was the identification of the need to upgrade the old railway tunnels to modern safety standards, in order to be better prepared for disastrous events like tunnel train fires.
This network level risk analysis resulted in the action to perform a risk based engineering approach to identify specifically for the Kennedy tunnel what were the highest risks, what mitigations were possible, and what the effectivity and cost for the various mitigations would be. The purpose of this pre-study feasibility phase was to identify a technical scope for a tunnel improvement project. The approach started with a risk analysis identifying the hazards, hazard scenarios, causes, consequences and possible mitigations. For each identified risk, an estimation was made of the current risk and the
risk achievable with the mitigations in place. The mitigations were, where possible, described in a functional way, in order not to be bound to technical choices at that level. The various functional mitigation proposal were subject to a feasibility study and cost estimation. The outcome of the pre-study was the proposal of a technical functional scope of works, which, according to the impact on the risk reduction and on the technical feasibility, would be most beneficial to the overall risk reduction at network level. All of this whilst also maximizing cross-tunnel technical consistency.

After budgetary confirmation of the functional scope, the P315 Program was put in place to start the realization of the selected functional scope. This program is to be seen as, in terms of the railway safety directive, a change of the network. For each change in the railway system, Infrabel applies it’s Safety Management System and acts in line with the Common Safety Methods, even if at the moment the program started, the legal framework was still under development.

The first step within the management of this program (or change), in line with the legal CSM framework, but also in line with EN50126, is the Preliminary Hazard Analysis (PHA). The purpose of this analysis is to update and finetune the existing hazard and risk information (from the pre study in this case), in line with the final definition of the scope of the change. The outcome of the PHA is a finetuning of the functional safety measures identified as scope, as well as the identification of a series of additional measures, needed to assure the safety of the tunnel and the rail network as a whole, when making the change on the tunnel. These mitigations are not only functional and technical. They also involve procedural changes (for instance for the control room), needs for training (for the maintenance staff), communication (with the firefighting), etc.

On top of the application of the European legal framework of the Common Safety Methods, also at that moment ‘new’ Technical Specification for Interoperability were to be applied. Specifically the TSI-Safety in Railway Tunnels was put to scrutiny in the final alignment and detailed definition of the technical and functional scope. On the one hand this TSI-SRT obliges certain technical measures to assure a minimal common level of safety in all new European tunnels. But it also imposes to apply a risk based approach both to manage the migration of existing tunnels to this common level of safety, as well a for the management and reduction of risks specific to a given tunnel. The PHA mentioned above serves these purposes.

The next steps in the realization were again risk driven: identification of the reliability and safety requirements (in terms of reliability and SIL levels) for the different functions to be realized. This is a common approach on all our project, including the ANS tunnel improvement. It is discussed further in the article.

**SCOPE AND OBJECTIVE OF THE MIGRATION**

The first aim of the migration project is to replace and modernize the architecture as well as the technology of the control system.

- The existing automation system is decentralized. The detection systems put the detection message on the LON network, and all LON nodes listen to that message. Based on the parameterized accident scenarios in the LON node, the latter will either perform actions or not. The LON system is an ageing technology, which is increasingly difficult to maintain. From a performance and monitoring point of view, the system is also limited.
- The new concept, identical to all renovations of tunnel control systems, is based on redundant central PLCs. These link all detection systems and actuators based on an accident scenario matrix.

The second objective is to split the management of the ANS complex into two parts in accordance with European regulations:

- The tunnel parts, managed by the Belgian Infrastructure Manager (Infrabel)
- The station part, managed by the Belgian Transport Company (SNCB/NMBS)
The overall migration project is divided in two parallel projects: one for the station, managed by SNCB; and one for the tunnels, managed by Infrabel. Regarding safety of exploitation, the main objective is to maintain safety at the level achieved when the project was commissioned. It is not a migration that has been decided with the objective of increasing the level of exploitation safety.

**Challenges for the safety management of the migration projects**

The ANS migration is facing some challenges, among which:

- Availability of technical documentation: even though it was first put into service some 15 years ago, the technical documentation is not fully available. Some reverse engineering is needed.

- Initial safety choices and arbitration not documented: the safety functions are well documented. However, the reasons for the safety choices are partially documented.

- Detection of the (few) modification to safety principles: changes in technology inevitably lead to changes that impact on security. Although the scenarios are not modified, often subtle changes can impact the behaviour of the automation system (e.g. priority management of the automation system, modification of the performance of the fire detection system, modification of the GUI). The exhaustive identification of these requires a continuous safety monitoring and analysis.

- The splitting of the automation system in two independent parts requires careful analysis and coordination between the two projects.

- Maintain safety an acceptable safety level during the migration process: The exploitation of the ANS system shall maintained during the migration with an acceptable safety level. This is a major constraint for the execution of the project. Moreover, these two projects do not have the same schedule, which multiplies the states of the control system.

**SAFETY MANAGEMENT**

The safety objectives of the two projects are not identical:

- Kennedy upgrade project: increase the safety toward an acceptable level
- ANS migration project: maintain the safety level achieved when first put into service

The approach to demonstrating the achievement of the objectives is different but is based on the acceptation principles defined in the European regulation (Common Safety Method Risk Analysis)

- Application of code of practice
- Similar reference system(s)
- Explicit risk estimation

For ANS migration project, the main acceptation principles will be based on a reference system, that is in its state at the time of commissioning. Other tunnels in Belgium are also used as reference systems, such as the tunnel through Brussels.

For Kennedy upgrade project, explicit risk estimation will be used more to define the RAMS target. Infrabel's process (see figure 4 below) for defining RAMS objectives consists of the following steps:

- Analysis of the hazards and the probability of their occurrence
- Functional analysis of the system and definition of the high-level system safety functions (FMEA)
By use of the risk acceptance matrix of Infrabel, identification of the risk reduction factors needed. Allocation of the risk reduction factor to the functions and identification of equivalent SIL level for the instrumented functions. Allocation of these to the sub-systems.

**Figure 4**  Infrabel Process for RAMS objective definition

**INTRUSION PREVENTION**

Previous Infrabel tunnel projects have already applied intrusion detection and handling. This proved to be a correct analysis because unwanted intrusions were reported each time during the past few years: the freight tunnel in the Port of Antwerp, Antwerp Central Station, and The airport station. In one case, this was not noticed in time, resulting in a fatal accident with a train. No automatic detection system was yet in place by then. The involved tunnel is part of current adaptation works. Several technical realisations are applicable and will be implemented depending on the location. As a back-up system, manual action can also be taken at any time, based on visual observation:

1. **Manual action**
   In a first phase of the upgrade of the tunnels, no specific detection equipment is yet present but the operator in the control room can already start a targeted intrusion scenario. This that after being assured of an unwanted intrusion by notification via a phone or visual observation via the cameras present. It is quite possible that a prior warning has been reported to the control room so that the operator can activate a targeted number of cameras (up to 16, in a 4 x 4 grid) in the vicinity of the supposed incident.

Of course, this method of a manual action depends on the alertness of the other passengers and the operator, and an undesired delay of an alert is likely. Therefore, it was also decided to automatically detect an intrusion, using the following techniques:

2. **Contact on the door**
   For regular maintenance work, it is useful to be able to enter the tunnel section concerned via the closest accesses and evacuation stairs. In doing so, the track is released (check 1), outside normal train traffic, and one can then enter the tunnel provided one uses a validated badge, immediately recognised
by the access control (check 2). Opening a door to the tracks without both security checks always triggers an alarm in the control room. Also, nearby lights are immediately switched on and the closest camera is activated. After confirmation by the operator of an intrusion by an unauthorised person, train traffic will be interrupted and the sono system will order the invader to return to the entrance: a set of pre-programmed messages is available for this purpose, which are clearly different from evacuation commands. The police services are also notified so that they can make the necessary determinations about this unauthorised action: as in the case of a fire scenario, an SMS message is automatically sent to the service, indicating the affected area in the wider tunnel complex.

3. Thermal cameras
The two previous notification systems have some limitations as they result from an unanticipated action by an unknown person. The operator has to make a quick decision without being able to double-check: he has to rely on the image of a nearby camera to act. If concerned camera is not functional, the operator will take a possibly improper action. Thermal cameras are therefore provided that can diagnose the problem independently of the daily equipment.

Figure 5  Positioning and image of thermal camera

The activation of a thermal camera is reported by the ASMS (= Automation Scenario Management System) network to the operator via the SCADA server (= visualisation). The images are also stored in a proprietary Video platform. From here, they can be viewed directly on the associated screens or at a later time for further analysis.

Figure 6  Intrusion camera visualisation system
4. Infrared barriers

Another technique, which is currently under investigation, is the use of obstacle detection through infrared delineation. The observation of several intrusions per year in the busiest tunnel in Belgium (in Brussels) gave rise to this research into additional possibilities in addition to the previously mentioned cameras. With this technique, 2 types are possible: those with unilateral emission of a radiation, with a maximum detection field in length and height. However, this makes it difficult to distinguish between passing or stationary trains and unwanted persons, due to a limited number of useful IR ‘fields’. On the other hand, there is the double-sided system using a transmitter and a receiver: in this way, a true infrared barrier is set up, with separately searchable heights and a maximum width of up to 100 m.

The current test rig follows the 2nd principle after positive feedback came from application at other international locations such as e.g. at the Eurotunnel under The Channel. A permanent scanning of an unwanted passing object or person is done in the opening of the tunnel portal. On both columns, which are 4 m high and 9 m apart, there is an alternation of 12 receivers and transmitters, which are arranged obliquely.

![Figure 7](image)

**Figure 7** functionality of infrared intrusion barriers

The first tests with it indicate that the number of unwanted alarms is low and also that the distinction between trains (with intermittent IR beams up to the top) and persons (up to 2 m) can be made clearly. This system is therefore being investigated further for the current ‘Kennedy’ and ‘Antwerp North-South’ projects.

**MINIMAL EXPLOITATION CONDITIONS**

For its tunnels, Infrabel has also defined Minimal Exploitation Conditions (MEC) within its Safety Management System. These are the minimum safety functions required to allow tunnel operation. These functions are related to fire, which is the major risk in tunnels:

1. Detecting a fire
2. Stopping rail traffic
3. Ensure evacuation (track, lighting, smoke extraction)
4. Be able to manage different scenarios
5. Provide water for the emergency services

These five high level functions needs to be tailored to each tunnel, in function of the tunnel and the architecture of safety systems. The integration of these MEC in the design requires to:

- Details the functional definition of unavailability for each safety functions
- Details the technical definition of unavailability for each sub-systems (i.e. combination of failures that leads to unavailability of function

418
One of the consequences on the design of these MEC, is that no SPOF can directly lead to a MEC to limit the impact on the exploitation.

These five functions are integrated on the main dashboard of the command system. In case an MEC is reached, a Safety Board, regrouping all the parties, has max 10 hours to assess the risk and implement measures to bring the system back to an acceptable safety state.

STANDARDISATION OF VISUALISATION SYSTEMS FOR REMOTE MANAGEMENT OF (TRAIN) TUNNELS

Infrabel's train tunnels where an automatic scenario system (ASMS) was installed are managed remotely from a Control Room, where safety operators handle the various types of alarms in the tunnels, such as safety (fire alarm, gas alarm) and security (intruders) alarms. As mentioned earlier in this paper, an operator must always acknowledge the alarm via the visualisation system to trigger the most critical actions. In addition, there is also the maintenance services' need for remote monitoring of the technical installations installed in the tunnel.

In the past, a separate visualisation system was developed each time to manage each tunnel. However, this approach presented several problems:

1. Limited lifetime of the visualisation relative to the automation system.
Each visualisation system was designed together with the scenario system and was therefore often closely linked to it technologically. The lifetime of the platform of a visualisation system, is 5 to 10 years, with the hardware (PCs and Servers) and the operating system (e.g. Microsoft Windows) being the limiting factor for the lifetime. In contrast, the automation system for managing the tunnel is designed with a technical and operational lifetime of 20 to 30 years. The limiting factor for the lifetime of the automation system is the availability of spare parts. Given the difference in lifetime between the automation and visualisation system, the visualisation system will therefore have to be upgraded and migrated several times during the period of operation of the automation system. To make this possible, the right technological choices are crucial, both for the language (source code) in which the visualisation system is written and the way the automation and visualisation system communicate with each other. This communication protocol should be based on an open, widely supported technology, which is supported by the industry throughout the life of the automation system.

In the worst case, for example if the visualisation system is no longer supported technologically, it will have to be completely redeveloped, in which case an open interface is crucial.

2. High dependence on external developers of the visualisation system.
Support for the visualisation system must be guaranteed throughout the entire lifetime of the tunnel safety system, for example because of the aforementioned problem of migrations when the Operating System is updated. This creates a dependence on the developers of this application, which is usually an external company. To obtain maximum independence, one must obtain the source code of the application, which in many cases is not possible, due to intellectual property rights that are usually held by the developer of the application.

3. The number of operators needed to operate the tunnels is higher than necessary.
Managing a tunnel requires several screens (usually 2 screens for tunnel plus 2 additional screens for camera images. As there is only space per operator station to install a limited number of screens, it is therefore not practically possible to have more than 1-2 tunnels managed per workstation/operator. In practice, only one operator is usually provided to manage one tunnel. As a result, the number of operators for managing train tunnels is higher than is in fact strictly necessary. After all, given the very limited incidence of fire alarms in tunnels, one operator is sufficient to manage several train tunnels, at least as far as safety alarms are concerned. After all, the risk of multiple alarms occurring simultaneously in several tunnels is very small. Note: the number of security alarms is much higher due to the nature of the system and the sensitivity of the intrusion detection system, e.g. for Brussels
North South tunnel with 2000 train movements per day, there are on average about 2 intrusion alarms per week.

As a result, the number of operators responsible for managing tunnels in practice is higher than it could theoretically be, leading to a higher operational cost.

4. **Availability of systems and control rooms.**

As an alarm in our tunnel safety systems must always be acknowledged by an operator before all scenario actions will start, the visualisation system in the respective control room must be available at all times (the tunnel management system is a Minimum Operating Condition for the use of the tunnel). A back-up location should therefore be provided for the entire control room (including all operator stations). This requires heavy investments in systems that are extremely rarely used; only in case of failure of the Control Room due to a severe technical breakdown or fire will the backup Control Room be used.

5. **A final problem is training the operators on the different systems.**

Since both the functioning and the graphical user interface (GUI) of each visualisation system are different for each tunnel, operators will have to be trained on multiple systems, which requires an ongoing effort. All this led to the need to standardise the visualisation system for managing the safety systems of our train tunnels, with the aim of eventually managing all train tunnels from a single (TunnelSCADA) platform.

This visualisation system should meet the **following requirements:**

- It should have a uniform look-and-feel, e.g. equipment that has a similar function should be represented by the same icon, even if it is of a different brand. The colour codes and symbols for displaying the status of an equipment (in operation, alarm, fault, etc.) should be standard, regardless of the tunnel and installation.

![Presentation of ventilation station on Tunnel SCADA system.](image)

Figure 8

- From a single operator station, it should be possible to manage several tunnel complexes simultaneously. The responsibility of who manages which tunnel must be transparent to all users and must be easily adapted dynamically. It must be possible to temporarily take over the management of tunnels in a simple manner, e.g. in the event of an alarm in one tunnel, the management of the other tunnels managed at this workstation must be automatically
transferred to other workstations/operators, possibly located in other Control Rooms. The failure of a workstation or Control Room is also handled in a similar way.

The coupling to the tunnel systems must be realised via a standard and open interface, which will be supported by the industry in the long term and thus be "future proof". Both systems must be able to evolve autonomously.

- The coupling between the field and the TunnelSCADA should be encrypted for cyber security reasons.
- It must be possible to write extensions independently, in order to avoid the risk of vendor lock-in. So we must have the source code and its intellectual property rights ourselves to be able to extend it.
- The system must be scalable, so that over time, it can be used to manage all of Infrabel’s train tunnels.
- The system should be able to be linked to a tunnel emulator so that the operation of the GUI can be tested, without using the field equipment and having to take the tunnel out of service.
- A link to various other systems must be possible, such as, for example, the camera management platform, where the aim is to display the correct camera images during an incident.
- It must be possible to use web clients to consult the GUI, in order to enable maintenance services to consult technical alarms, without having to install additional software.
- It should be possible to manage the different types of alarms on one integrated visualisation system, and thus not have a separate system for handling fire alarms and another system for intrusion alarms.

**TECHNOLOGICAL CHOICES**

- The technological solution we’ve chosen for TunnelSCADA is based on **WINCC OA** technology. The application itself was developed by an external vendor, and upon completion of the project, the source code was transferred to our own developers, who continue to manage it. For a new tunnel project, the existing source code is used as the basis for integrating the new tunnel safety system. This development is then done by our own
developers or by an external partner, but upon delivery, the modified source code is re-integrated into the standard library.

- The code is object-oriented, so equipment from other manufacturers still has a similar user interface.

- Communication with the field PLC is via an OPC UA interface. OPC UA is documented according to the IEC 62541 standard. This makes it possible to interface other systems from other vendors. The interface with the field is also standardised and documented.

- For the IT Architecture of the system, a 3-layered system was chosen, with visualisation decoupled from communication, for performance and scalability reasons.

- Each tunnel must have its own pair of servers for communication, for performance reasons and to avoid a technical problem in one tunnel having an impact on the operation of the other tunnels. The servers responsible for visualisation are installed in the data centre to guarantee high availability.

- The OPC UA servers are located in technical rooms in the field. The servers are located in our own data centres. All systems are redundant with automatic switchover in case of failure of one system.

Conclusion for the visualisation system
Standardising on a single visualisation system to manage multiple tunnels brings significant operational and financial benefits. However, the right technology choices are crucial here; among other things, it is important that these technologies are long-term and widely supported by the industry. It is also important that the operator or owner of the tunnels acquires the intellectual property rights of the source code of the visualisation software, to obtain maximum independence from 3rd parties.

Adding already existing tunnels to the common visualisation system, on the other hand, requires adapting the automation system each time, and requires long-term planning. In our case, these migrations are planned when the lifetime of the tunnel systems approaches, or when significant modifications are required.

SCENARIO SEQUENCE AND INTERACTION WITH THE CONTROL ROOM

A further upgrade to the manageability of the safety systems is the creation of a clear manual for the operators, here specifically in the Antwerp Control Room. In the implementation of the current systems, a fine As Built file of the equipment is available each time, for both detection (input) and safety equipment (output). Via an accurate description of the ASMS and corresponding programming in the PLCs and functional visualisation on the SCADA, the "Information Technology" part is perfectly finished and functional. It is obvious that the operator in the Control Room also has an important and responsible function in the handling of incident scenarios; chronologically managing the situation and acting correctly using the available tools requires experience and, first of all, proper training.

The instructions for this were further fine-tuned and formalised in the course of 2022. Also the action of a RESET after a completed scenario as the possible masking of detection elements in malfunction. This manual with procedures has been prepared generically for the improved safety management of all current and future train tunnels in Belgium. Addenda have been prepared for specific locations, containing e.g. technical details as well as telephone numbers of closest signal boxes, for direct control of train traffic.

Figure 10 below shows the flow diagram of one type scenario (fire detection in the tunnel)
EMERGENCY SERVICES IN BELGIAN RAILWAY TUNNELS

“Prepare and prevent, don’t repair and repent”

Even with all the technologies in our tunnels, aimed towards detection and automation, we still rely on humans in case of a tragedy.

In every incident, we have to communicate with the external emergency services in every part of Belgium. Therefore, we implemented a simple and uniform guideline, called the “Alarm Sheet”.

![Diagram](image-url)
Alarm Sheets
Looking at Fire Detection, we can separate our tunnels into different sections with several possible scenarios, depending on the location of the fire vs location of the train. (We push the smoke towards to shortest end of the train to minimize casualties).

Per section, we can create three alarm sheets, summarizing several scenarios:
1. Fire, but no train
2. Fire in the back of the train = ventilation pushes towards the back
3. Fire in the front of the train = ventilation pulls to the front

Figure 11  Example explaining number 2 “Fire in the back of the train”

Alarm sheet – information and use
Every alarm sheet has an unique number, contains vital information, is prepared in collaboration with the intervening services and summarizes the following information:

Internal information (Control Room & Traffic Operations) such as the location of the incident on the train line, signalling information, earthing information, meeting point with the emergency services and technical specifications towards the ventilation and evacuation.

External information (Fire brigade, medics and police) such as points of entrance, deployment upscaling information, casualty take-over point, perimeters and Command Post location.

Overall information (For everyone) with a schematic drawing of the incident, including all relevant information (Train / fire, ventilation, evacuation, CP-OPS, earthing zone,…)

Whenever the Control Room accepts and starts a specific scenario, Traffic Operations (signalling cabins) receive an automated pop-up on their screen, showing the alarm sheet. Even before the official confirmation by phone, this gives them the opportunity to react faster, take measurements on traffic and send out the proper technical teams.

The Control Room must contact the emergency services, with a standard phrase and the use of the specific number of the alarm sheet. The recipient of the alarm message sends out the emergency services as indicated on the sheet.
TRAINING OF EMERGENCY SERVICES

In close collaboration with the technical tunnel branches of our company, Infrabel also has 3 Tunnel Safety Supervisors. One supervisor per region (Flanders, Brussels and Wallony).

One of their main tasks is to liaise with, and training of the emergency services. The emergency services are educated and trained on different subjects, through different ways.

We provide the fire brigade with equipment inside of the tunnel, installed inside fire boxes and preventing them from having to carry tools and fire hoses downstairs.

Each tunnel has a different fire brigade responding to our alarm message, meaning that they have their own needs and wishes, thus resulting in an extra cost of maintenance.

Together with the different fire brigade commanders, we worked out a guideline for the tunnels. Giving us the chance of standardisation, from waterpressure to the content of the fireboxes.

Figure 12   Example of an Alarm Sheet
OVERALL CONCLUSION

Infrabel attaches great importance to the safety of train tunnels. An analysis of the existing automatic systems in other important tunnels and a list of lessons learned in the process led to an upgrade of the installations in the Antwerp passenger tunnels. A preliminary risk analysis provides the justification for installing the latest techniques in the tunnels and a reinforced connection with the operators in the control room. The visualisation system will be standardised for the whole of Belgium and the instructions for the emergency services will also be standardised. Better monitoring of incidents that occur and the temporary unavailability of crucial safety systems will minimise interrupted travel times for passing trains.

REFERENCES

1. Schoonbaert L. and Eeckhaut S. “Realisation of fire and intrusion protection at the “Diabolo” train tunnel complex at Brussels Int’l Airport”, proceedings ISTTS, Marseille, 2014


Incident management in long railway tunnels, taking the Koralm tunnel as an example

Michael Bacher¹, Helmut Steiner², Daniel Fruhwirt¹, Peter Sturm¹
¹ Graz University of Technology Austria, 8010 Graz, Austria
² ÖBB Austrian Federal Railways

ABSTRACT

Operational procedures are one of the key factors in incident management in underground transport and in long railway tunnels. The co-ordination of emergency management, the halting of trains and ventilation control must be such that smoke free zones are created which enable evacuees to move safely away from danger areas towards areas of safety and emergency services. This paper focuses on the aerodynamic problems involved in ensuring smoke free areas during the evacuation of the train. In the case of an incident, passengers escape from the train to the emergency exits (escape tunnels) and from there into the safe rescue area. Here, they then await evacuation by the emergency services. In such cases, emergency ventilation puts the unaffected tube under overpressure to prevent smoke entering the safe area. As trains in the safe tube may still be running during the activation phase of the ventilation system, the ensuing aerodynamic interactions are of particular interest. One-dimensional simulations were conducted in order to investigate the transient air flow conditions.

KEYWORD: incident management, railway tunnel, emergency station, Koralm tunnel, escape rooms, ventilation, aerodynamic simulation

INTRODUCTION

The Koralm tunnel, comprising two single-track tubes, is the prime component of the approximately 130 km long Koralm railway. Upon completion, the tunnel will be almost 33 km long. The emergency station, with a length of approximately 950 m, is located in the middle of the tunnel and between the two tracks. The emergency station includes an emergency platform per track with emergency exits leading into a large escape and rescue room between the two tracks. Figure 1 shows an overview of the Koralm tunnel with the emergency station and the overlying rock formation.

The mechanical ventilation system of the Koralm tunnel is activated both in cases of emergency, and during maintenance. During regular operation, the Koralm tunnel is ventilated by the train traffic itself. Owing to the large overlying rock formation of up to 1200 m, from a technical/economic point of view, it was not feasible to build a smoke extraction system with a shaft in the area of the emergency station.

Keeping the escape routes smoke-free during an emergency entails maintaining overpressure in the safe tube and in the emergency station. For this purpose, a total amount of 720 m³/s of outside air is brought into the safe tube via the ventilation shafts Paierdorf and Leibenfeld. This creates a positive pressure gradient between the safe tube and the event tube. One part of the air flows from the safe tube into the emergency station. The other part goes through a separate ventilation tunnel from the safe tube to the event tube directly. These separate ventilation tunnels are located outside the emergency station. When the emergency exit doors are opened by passengers, the air flows from the rescue room into the event tube and the escape routes can thus be kept smoke-free. Figure 2 shows a
schematic figure of the emergency station using the example of evacuation following an incident in tube 2. The passenger train stops in the emergency station near the escape routes. At the beginning of the evacuation phase, the passengers escape from the train to the platform. They then take the escape routes to the rescue area and remain there until the rescue train arrives for their further evacuation to the outside of the tunnel to the “final place of safety”. The escape route lengths vary from 50 to 500 meters. There are a total of 9 emergency exits per tube leading into the safe area.

Figure 1: Overview Koralmtunnel (ÖBB Infra): The Paierdorf shaft can be seen on the left and the Leibenfeld shaft on the right. The shafts have a height of 120 m and 50 m, respectively. Both shafts are located about 3.5 km from the portals. The exhaust and fresh air exchange takes place via connecting tunnels between the base of the ventilation shaft and the corresponding tube. By means of dampers, these junctions can be opened or closed independently of each other, in order to provide for targeted air intake.

Figure 2: Emergency ventilation during escape process: Air flows from the safe tube via the open dampers into the rescue and escape area of the emergency station and from there via the open emergency exit doors into the emergency tube.

When the escape process has been completed, and no emergency exit door has been opened for a certain period of time, the ventilation bypass, which is further away, is opened. The air then flows directly into the event tube via the open ventilation bypass. This is important in order to generate an air flow in the event tube so as to blow out the smoke. Figure 3 shows the situation after completion of the escape process. All escape doors are designed as sliding doors in order to keep the opening forces low.
Figure 3: Emergency ventilation after completed escape process: When the escape process is complete the ventilation bypass is opened. The air then flows directly into the event tube via the open ventilation bypass. The rescue and escape areas of the emergency station are kept at overpressure. The passengers wait in the rescue area for the arrival of the rescue train.

A comprehensive tunnel safety plan [1] for the Koral tunnel already exists. This defines the specific protection measures needed (i.e., for passengers, train crews, emergency services, maintenance and repair work). The following safety measure is particularly relevant with respect to the dimensioning of the emergency ventilation:

'Emergency ventilation must have an impact no later than 5 minutes after emergency begin. This requires a minimum flow speed of 1.0 m/s when the emergency exit doors are open. The target value should be 2m/s.'

The tunnel safety and rescue plan defines the procedures to be followed in the event of an incident. This entails the recognition and reporting of the emergency, initiation of the emergency program and self-rescue, and then safe evacuation of those affected, from the tubes to the emergency station, and then via rescue train to the outside. The timing and co-ordination of the required safety and operational measures present a major challenge for the ventilation system as several parameters have to be taken into consideration simultaneously, e.g., the flow rate of the axial fans, the speed of the passenger and freight trains, and the possible failure of individual axial fans.

**MOTIVATION**

Among all the incidents that may occur, the possibility of a passenger train fire is regarded as a crucial event when assessing passenger safety and risk scenarios. As the impact of terrorist acts cannot be quantified in advance, they are not taken into account in such considerations. Nonetheless, as up to 1,000 passengers can be involved in an incident, in order to avoid a possible catastrophe, safety requirements have to be quite extensive. Among the various safety measures needed, keeping escape routes free of smoke is one of the most important for successful evacuation during an emergency. The time component, in particular, plays a major role in this context.

Changes in air column conditions are of particular interest. In the present paper, therefore, selected questions relating to aerodynamics are examined in detail. The first challenge is related to the train traffic in the safe tube during the initial phase of the emergency, and the associated negative influence on the air flow in the escape routes when a train passes the emergency station. Thus, in order to
comply with safety requirements, the permitted train speeds need to be set in such a way that the emergency station always remains smoke-free. How much time is allowed to elapse between the onset of an emergency and the actual impact of the safety measures is also a matter of considerable interest. Here, a distinction must be made between an emergency during normal operation (with train traffic in both tubes) and an emergency occurring during maintenance work in one of the two tubes. In the latter case, one tube is closed to train traffic and the ventilation system is used to ensure the air exchange needed for maintenance work. Depending on the meteorological portal pressure, the axial fans of one ventilation building may be operated as exhaust air fans and the axial fans of the other ventilation building as fresh air fans. If an emergency occurs in the tube in operation during maintenance, the axial fans that are in exhaust air mode must be switched to fresh air mode. Naturally, this takes time as the movement of the very large air column has to be slowed down and reversed by the force of the axial fans.

AERODYNAMIC INVESTIGATIONS

The amounts of air that are fed into the tunnel via the two ventilation buildings in the event of a fire were determined in such a way that in the steady state (i.e. the state that occurs after the train-induced flows have subsided and the ventilation is fully effective), the flow velocities at the emergency exit doors of the escape tunnels to the rescue room of the emergency station are at least 1 m/s, even in the event that all 9 emergency exit doors are open at the same time. Under normal conditions, the speeds at the emergency exits of the escape routes should be between 1 m/s and 10 m/s. Short-term velocities of up to 11 m/s are accepted - in accordance with NFPA 130 [3] - since it can be assumed that over periods of less than 1 minute, this will not lead to any significant impairment of the escape process. In addition, these high air velocities only occur when one emergency exit door is open and, at the same time, a passenger train is passing through the emergency station in the safe tube. For the purposes of the present paper, a design fire of 28 MW [4] was assumed for the dimensioning of the ventilation system. The results of numerical investigations covering two possible situations are presented below. In the first case, the evacuation of the passengers of the incident train takes place without simultaneous train traffic in the safe tube. In the second case, it is assumed that a passenger or a freight train passes the emergency station during the evacuation process and thus negatively affects the flow situation throughout the whole emergency station for the duration of the passage.

The aerodynamic forces (pressure and suction load) due to moving trains usually range between +2100 N/m² and -1200 N/m² [5]. In addition, the air column in the tube is strongly influenced by the train movements. Natural, the mechanical ventilation system can only have a minor influence on these effects. In order to ensure that the protection goal of "smoke-free safe areas" can be met, the train speeds in the safe tube must be limited in the event of an emergency.

In order to unleash the potential of the emergency ventilation as quickly as possible, the axial fans must be activated immediately after the emergency is triggered. The control chain of the ventilation components is shown in figure 4. The time sequence shown is used as a boundary condition for the transient flow calculations. The two train types, InterCity (passenger train) and freight train, are taken into account by using their respective planned driving speeds in regular operation (210 km/h and 100 km/h), and the maximum speed of the passenger train is 250 km/h [6]. During planning, extensive evacuation simulations were carried out for the Koralm tunnel [7]. These showed that the evacuation of the train passengers from the event train to the safe areas behind the emergency exit doors can be completed within 5 minutes.
Figure 4: Schematic representation of the operational process in the event of an emergency involving a passenger train.

Keeping the emergency station smoke-free – the passing of a passenger train at 210 km/h

In the event of an incident, it is possible that a train is still in the safe tube. This train must then be moved out of the safe tube. If the train has to pass the emergency station during the escape process, the air flow in the escape routes will be influenced, and will depend on the speed of the train. Figure 5 shows the emergency station during the escape process and the associated air flow. In order to be able to estimate the effects of the passing train, a one-dimensional flow simulation program is used to simulate the Koralm tunnel in accordance with the operational processes shown in figure 4 and to calculate the dynamics of the transient air flow velocities at the exits in the emergency station. In the present investigation, the train in the safe tube passes the emergency station at the regular driving speed of 200 km/h.

Figure 5: A passenger train passing the emergency station during the evacuation process. All nine emergency exit doors are open.
Figure 6 shows the air velocities at the emergency exit doors nos. 1 - 9. Negative velocities represent a flow from the safe tube into the event tube. In the present case, there is a distinct backflow at all emergency exit doors. A significant smoke movement into the safe areas cannot be excluded at this train speed. The driving speed of the train must be reduced.

Figure 6: Flow velocity with nine emergency exit doors open. The train on fire arrives from the east portal (0 m) and reduces its speed so that it stops in front of the emergency exit doors in the emergency station, 12.5 minutes after the emergency is triggered. 1 minute later, all nine emergency exit doors are opened by passengers. Another minute later, a passenger train, coming from the west portal (33,000 m), passes the emergency station at 210 km/h. 5 minutes after the first opening of the emergency exit doors, the escape from the event train is completed and all emergency exit doors are closed again.

Keeping the emergency station smoke-free – the passing of a passenger train at 80 km/h
If a passenger train passes the emergency station at 200 km/h during the escape phase, compliance with the specified safety objectives cannot be guaranteed. For this reason, it was necessary to reduce the speed of the passenger trains in the safety tube. For the investigations, the driving speed was reduced in stages until compliance with the protection goals could be ensured. The final result of the investigation is presented below. The passenger train passes the emergency station at a reduced speed of 80 km/h. The two cases "nine emergency exit doors open" and "one emergency exit door open" are analysed. In terms of aerodynamics, all other situations, i.e., with more than one and less than nine open emergency exit doors, lie between these two cases. Figure 7 shows the air velocities at the emergency exit doors nos. 1 - 9. Negative velocities represent a flow from the safe tube into the event tube. In the present case, there are only brief backflow effects in the escape routes no. 8 and 9. As this is only of short duration (approximately 20 seconds), it does not appear problematic and it is assumed that this will not result in any significant smoke levels in the safe areas. The target velocity is reached at all nine emergency exit doors within one minute and does not fall below the target level at any time during the escape phase. A further reduction of the driving speed is therefore no longer necessary.
Figure 7: Flow velocity with nine emergency exit doors open. The train on fire arrives from the east portal (0 m) and reduces its speed so that it stops in front of the emergency exit doors in the emergency station, 12.5 minutes after the emergency is triggered. 1 minute later, all nine emergency exit doors are opened by passengers. Another minute later, a passenger train, coming from the west portal (33,000 m), passes the emergency station at 80 km/h. 5 minutes after the first opening of the emergency exit doors, the escape from the event train is completed and all emergency exit doors are closed again.

This case was also examined in order to ascertain whether the emergency station was kept smoke-free when only one emergency exit door was open. Figure 8 shows the velocity situation for emergency exit door no. 9. Negative velocities represent a flow from the safe tube into the event tube. The target velocity is reached very quickly, and velocity does not fall below the target level during the escape phase, nor is the upper limit of the permissible air velocities of 11 m/s exceeded.

Keeping the emergency station smoke-free – the passing of a freight train at 60 km/h

The same procedure used for the passenger train was also used for analysing the passage of a freight train. Passenger and freight trains do not only differ in terms of driving speed. Their different lengths and aerodynamics also have an impact on air flows. The longer length (up to 600m) and poorer aerodynamic design of a freight train lead to a stronger negative effect on the air velocity in the emergency station compared to that associated with passenger trains. In the following analysis, the freight train passes the emergency station at a reduced speed of 60 km/h. Figure 9 again shows the flow situation at the emergency exit doors nos. 1 - 9. Negative velocities represent a flow from the safe tube into the event tube. In the present case, a brief backflow of air from the event tube into the safe area occurs only at emergency exit door no. 9. However, as this only lasts for approx. 15 - 20 seconds, it is again assumed that this will not result in any significant increase in smoke in the safe areas. The target velocity is reached for all nine emergency exit doors within 1.5 minutes and does not fall below this level at any point during the escape phase. A further reduction of the driving speed is therefore no longer necessary.
Figure 8: Flow velocity with one emergency exit door open. The train on fire arrives from the east portal (0 m) and reduces its speed so that it stops in front of the emergency exit doors in the emergency station, 12.5 minutes after the emergency is triggered. 1 minute later, one emergency exit door is opened by passengers. Another minute later, a passenger train, coming from the west portal (33,000 m), passes the emergency station at 80 km/h. 5 minutes after the first opening of the emergency exit doors, the escape from the event train is completed and the emergency exit door is closed again.

Figure 9: Flow velocity with nine emergency exit doors open. The train on fire arrives from the east portal (0 m) and reduces its speed so that it stops in front of the emergency exit doors in the emergency station, 12.5 minutes after the emergency is triggered. 1 minute later, all nine emergency exit doors are opened by passengers. Another minute later, a freight train, coming from the west portal (33,000 m), passes the emergency station at 60 km/h. 5 minutes after the first opening of the emergency exit doors, the escape from the event train is completed and all emergency exit doors are closed again.
As with the passenger train, the case of one open emergency exit door is also investigated here. Figure 10 shows the velocity situation at emergency exit door no. 9. Negative velocities represent a flow from the safe tube into the event tube. The target velocity is reached very quickly and does not fall below this level at any point during the escape phase. The upper limit of the permissible air velocities of 11 m/s is not exceeded.

**Figure 10:** Flow velocity with one emergency exit door open. The train on fire arrives from the east portal (0 m) and reduces its speed so that it stops in front of the emergency exit doors in the emergency station, 12.5 minutes after the emergency is triggered. 1 minute later, one emergency exit door is opened by passengers. Another minute later, a freight train, coming from the west portal (33,000 m), passes the emergency station at 60 km/h. 5 minutes after the first opening of the emergency exit doors, the escape from the event train is completed and the emergency exit door is closed again.

**Temporal effect of emergency ventilation**

To verify whether, in accordance with the criteria set out in the tunnel safety plan, the impact of emergency ventilation occurs within 5 minutes, four extreme cases are now investigated. The results of the corresponding calculations are presented below. It is assumed here that there is no train traffic in either the event tube or the safe tube, and that the train on fire is already in the stop position in the emergency station. The cases investigated are as follows:

1. **Regular operation** - calculation of the development of the air speed over time at an open emergency exit door (no. 9), the axial fans are started from standstill;
2. **Maintenance mode** - calculation of the development of the air speed over time at an open emergency exit door (no. 9), the axial fans in the Leibenfeld ventilation building are in exhaust air mode and those in the Paierdorf ventilation building are in fresh air mode;
3. **Controlled operation** - calculation of the development of the air speed over time for all nine open emergency exit doors (nos. 1 - 9), the axial fans are started from standstill;
4. **Maintenance mode** - calculation of the development of the air speed over time in all nine open emergency exit doors (nos. 1 - 9), the axial fans in the Leibenfeld ventilation building are in exhaust air mode and those in the Paierdorf ventilation building are in fresh air mode.

In cases (2) and (4), the axial fans are already in operation. However, emergency ventilation is only performed with fresh air. For this purpose, the axial fans in the ventilation building Leibenfeld must be switched from exhaust air mode to fresh air mode.
• emergency triggering => the axial fans in the ventilation building Leibenfeld run in exhaust air mode and in the ventilation building Paierdorf in fresh air mode
• the blades of the axial fans in the ventilation building Leibenfeld are turned from exhaust air mode to supply air mode within a period of 6 minutes.

Figure 11 and figure 12 provide a schematic overview of the Koralm tunnel and of the flow situations for cases (1) and (4).

**Figure 11:** System status directly after emergency triggering and flow situation in the whole Koralm tunnel with one open emergency exit door. Both shafts in fresh air mode.

**Figure 12:** System status directly after emergency triggering and flow situation in the whole Koralm tunnel with nine emergency exit doors open at the same time and under maintenance operation. One shaft in fresh air mode, the second shaft in exhaust air mode.

Simulation calculations show how long it takes until the target air velocity of 2 m/s is reached in the open emergency exit, and what the flow velocity is 5 minutes after the emergency is triggered. Figure 13 shows the calculation results for the configuration normal and maintenance operation with only one emergency exit door open. Normal operation, in this case, means that the ventilation has not yet been activated.
When the emergency ventilation is started during normal operation, the target velocity of 2 m/s is reached through the open emergency exit door within approximately 3.5 minutes. After about 5 minutes, the air velocity at the opened emergency exit door is approximately 4.2 m/s. The steady state with a flow velocity of approximately 7.5 m/s is reached after 15 minutes.

When emergency ventilation is started during maintenance operation, and only one emergency exit door is opened, the target velocity of 2 m/s is reached earlier at the opened emergency exit door than when emergency ventilation is started with previously deactivated axial fans (as in normal operation). In this case, the target velocity is reached after approximately 1.5 minutes. After 5 minutes, the air velocity at the opened emergency exit door is about 4 m/s.

**Figure 13:** one emergency exit door open; left: normal operation, right: maintenance operation

Figure 14 shows the calculation results for the configuration normal and maintenance operation with nine open emergency exit doors. When the Koralm tunnel is under normal operation, and the axial fans are only activated by an emergency event, the target velocity of 2 m/s can only be reached after approximately 6.3 minutes with all open doors. However, the lower acceptable velocity limit of 1 m/s is still attained within the required time of 5 minutes.

When the emergency ventilation is started during maintenance operations, the target velocity of 2 m/s is only reached after 8 minutes. Nevertheless, the lower acceptable velocity limit can still be attained within 5 minutes.

**Figure 14:** nine emergency exit doors open; left: normal operation, right: maintenance operation

**CONCLUSION**

In the Koralm tunnel, emergency measures are not triggered automatically. Emergency status is initiated by the emergency coordinator, who is informed of the emergency by the train attendant or the conductor. The emergency coordinator then triggers the emergency manually. When the emergency is triggered, the ventilation system is activated and the emergency station and the safe tube are set to overpressure.
In order to meet the safety goal of keeping areas smoke free, the operational processes, the design of the ventilation system, as well as the corresponding supervision and data acquisition procedures, must all be co-ordinated. The triggering of an emergency must take place as quickly as possible owing to the large volumes of air that need to be moved, and the given limitations of the axial fans. Due to the high train frequencies, it can be assumed that trains are still in the safe tube during the escape phase. These trains must be moved out of the safe tube in order to allow rescue services access.

In the worst case, a passenger or freight train passing the emergency station impairs the local air flow. The above investigations have shown that the speed of such trains must be reduced significantly in order to keep the escape routes and the safe areas smoke-free. In all cases investigated, the required target velocities were achieved within 1.5 minutes of the triggering of the alarm, and were also maintained over the 5 minute period needed for evacuees to reach the safe areas behind the emergency exit doors. However, it was also possible to identify periods of time in which there were short-term backflow effects at the emergency exit doors. These effects occur especially when the rear end of the train passes the ventilation bypass and moves away from the emergency station. However, as such backflows are quite brief, and exhibit very low velocity, significant smoke movement into the safe areas can be ruled out.

Based on the simulation results, a reduction of the driving speed for passenger and freight trains in the safe tube was determined such that tunnel safety criteria could be met. It was found that passenger trains in the safe tube must reduce their speed from 210 km/h or 250 km/h to 80 km/h, and that freight trains need to reduce speed from 100 km/h to 60 km/h.

REFERENCES

Evolution of emergency preparedness:  
A case study of two Norwegian road tunnels

Jeroen Wiebes Kjos¹, Maria-Monika Metallinou¹ & Henrik Bjelland²
¹Western Norway University of Applied Sciences, Haugesund, Norway  
²University of Stavanger, Stavanger, Norway

ABSTRACT

Tunnels are complex sociotechnical systems, involving several stakeholders, e.g., road authorities/owners, road users and the emergency services. A large fire in a tunnel is a potentially high consequence event, which received increased attention after 1999 due to the catastrophic tunnel fire incidents in central Europe. The implementation of European Commission Directive 2004/54/EC in member states led to considerable improvements of the technical infrastructure in tunnels. However, article 15 of the Directive focuses on learning from incidents and sharing the learning points among member countries on a bi-annual basis. Systematic accident reporting and accident investigation are thereby required. In this paper, we focus on two Norwegian tunnels, Gudvanga and Oslofjord, both single tube, with bi-directional traffic and longitudinal ventilation. Between 2011 and 2021, three fire incidents in each tunnel occurred, involving heavy vehicles. The evolution of emergency preparedness in each tunnel is investigated over time. Emergency preparedness was seen as a construct involving technical, operational and organizational measures, thus making changes traceable. The single and double loop theory of organizational learning was used to identify learning processes improving emergency preparedness in the tunnels. Two double loop learning processes were identified regarding safety in Oslofjord tunnel. Context dependent fire ventilation strategy, based on where in the tunnel the fire is located as well as the number and position of road users provides the best prerequisites for successful responses, with minimal smoke exposure for both tunnel users and infrastructure. Additionally, exposed users are provided with shelters, offering temporary protection under TCC supervision, until rescue resources arrive. Several single loop learning processes are identified in both tunnels, while remaining challenging issues are highlighted.

KEYWORD: road tunnels, emergency preparedness, fire safety, organizational learning

INTRODUCTION

Tunnel accident investigations with focus on learning are powerful tools for improving emergency preparedness, thus enhancing tunnel safety [1-3]. However, data collection and reporting has not always been systematic, thus compromising learning potential. Therefore, article 15 in the 2004/54/EC Directive focuses on learning from tunnel fires. Krausmann and Mushtaq [4] detailed and exemplified the reporting requirements, to assist correct implementation of article 15 among member countries.

Norway has around 1,220 road tunnels, which are critical infrastructure, providing safe and efficient alternative routes for difficult crossings over mountains and fjords. This paper will use Gudvanga and Oslofjord tunnels, as a case study to investigate how the emergency preparedness has developed over time. Three serious fire incidents occurred in each of them between 2011 and 2021. The Norwegian Safety Investigation Authority (NSIA) has prepared reports after each of these six fires [5-10]. The mandate of the investigator usually ends upon delivering the report. However, the full learning potential may yet not be extracted [11]. The role of research projects in learning from accident investigation is, among other things, to reveal trends through studying series of accident investigation
reports [12], as well as risk analysis and contingency plans. The latter to pay greater attention to the involved Fire and Rescue Services (FRS) and Tunnel Control Centre (TCC), whose capabilities and procedures are an integral part of a tunnel’s emergency preparedness [12].

Though tunnel fire incidents differ from one another, even when they occur in the same tunnel, there are many similarities. Therefore, learning from one incident may reduce the probability and/or limit the damage of future incidents. This would mean that the emergency preparedness of the tunnel has improved. A deductive research approach was chosen, and the following hypothesis created:

**Based on learnings from relevant tunnel incidents, the emergency preparedness of tunnels in Norway improves over time.**

To reveal proof of changes in emergency preparedness of the Gudvanga and Oslofjord tunnels, incident handling of three serious fires in each of the tunnels, in the period 2011 – 2021, were analysed. The data sources are the six accident investigation reports by the NSIA. This is a limitation of the study, which will be compensated for in further research through interviews and other complementary sources. Our contribution is to reveal changes in the development of emergency preparedness over time. As the chosen tunnels are in different parts of Norway, the study may provide some insight into different approaches to emergency preparedness both by tunnel owners and FRS in different areas in Norway.

**BACKGROUND**

Norway is characterized by high mountains, deep fjords and scattered populations. In the about 100,000 km of national, county and municipal roads, there are about 1,220 tunnels, where around 1,050 are built as a single tube tunnel. Before the EU-directive came in effect, around 830 tunnels were built [13].

The Norwegian Public Roads Administration (NPRA) and Nye Veier AS are tunnel manager for tunnels on the national road network and the respective County is tunnel manager for all other road tunnels within their County. The hierarchy of authority for Norwegian road tunnels is shown in Figure 1. Through the EEA-agreement (European Economic Area), Norway is part of the “internal marked” of the EU. This agreement requires Norway to comply with EU-regulations. The EU-directive 2004/54/EC [14] gives overall requirements for the design of road tunnels on the Trans European Road Network, and has been translated into the Tunnel Safety Regulations [15]. In general this directive adopts a risk-based approach to determine a sufficient safety level (micro-ends), but it also provides some minimal requirements (micro-means) as defined by the TRB [16].

![Figure 1: System hierarchy for tunnel during system operations](image-url)
Through the self-regulation principle, as defined by Njå [17], the NPRA has operationalised the requirements of the EU-directive into a road standard N500 [18] and a guideline R511 [19]. The Road Standard N500 and Guideline R511 detail which technical safety measures are required as a minimum in each tunnel (dependent on tunnel length and Annual Average Daily Traffic (AADT)/speed limit), and which are optional.

The task of TCC is to monitor and manage road traffic. During tunnel incidents, TCC is responsible for monitoring the conditions inside and outside of the tunnel (provided suitable equipment is present), as well as controlling safety measures. TCC operates five control centra with regional responsibility, Figure 2.

![Figure 2: TCC-regions in Norway, including location of Gudvanga and Oslofjord tunnel.](image)

**THEORY**

Road tunnels may be considered what Ropohl [20] characterizes as complex socio-technical systems. This implies that the system involves both social elements (individuals, groups, organizations) and technical elements (equipment, programs, calculations). Learning at individual, group, organization and inter-organizational level is therefore necessary to improve tunnel safety. Single-loop learning consists of deliberate actions to achieve set goals (e.g., achieve a set direction and speed of fire ventilation). In double-loop learning the value of the goal itself is questioned and new goals may be set. The shifting of goals may imply that the organization/network may have to revise itself (e.g., the way they cooperate) to achieve the new goal [21].

Reducing risk implies reducing the probability and/or consequences of unwanted incidents [22]. WHO further details measures to reduce consequences into measures reducing vulnerability, and into measures improving response capabilities [23]. Reducing frequency and reducing vulnerability comprise “primary mitigation measures”, while improving response capabilities is defined as “secondary mitigation measures” according to the definitions suggested by WHO’s emergency training programme [23], making use of the proposed terminology in the widely applied disaster risk management cycle [24].
In a system-theoretic approach, accidents happen when the control system is unable to adequately handle external disturbances, component failures, or dysfunctional interactions between system components. This happens due to inadequate control or enforcement of safety-related constraints on the development, design, and operation of the system [25]. Emergency preparedness is therefore seen as all technical, operational and organizational measures that prevent a dangerous situation from developing into an accidental event, or which prevent or reduce the damaging effects of accidents that have occurred [3, 26]. Thereby, the concept of emergency preparedness, as used in this paper, is closely related to the concept of mitigation in the disaster management cycle, and the WHO terminology.

Reason [27] identified five important characteristics of an organization with a good safety culture:

- **An informed culture**, where the organisation retrieves data on accidents, dangerous incidents and incidents which could have developed into dangerous incidents. Using this data, it implements measures proactively.
- **An open culture**, where all employees report on incidents or dangerous situations and are a part in surveys on safety cultures, etc.
- **A fair culture**, where employees are encouraged to report incidents through the fact that they have confidence that the management treats incident reports and implicated persons in a fair manner.
- **A flexible culture**, where the organization has the ability to change practises.
- **A learning culture**, where the organization can learn from reported incidents, safety audits, etc. to improve safety.

These ideals should also be used on safety regulations, regularly revised based on new knowledge (i.e., new research findings, changes in society or experiences from relevant incidents). This learning process is also encouraged in Norway through the Internal Control Regulation [28], which requires the implementation of measures to improve work environment, safety, prevention of health or environmental damages, etc. Continuous improvement is an important part of safety culture and safety management, making learning from past experiences important to stimulate improvement.

**METHODS**

As mentioned earlier, we adopt a holistic definition of emergency preparedness as involving technical, operational and organizational aspects, to assess its evolution. The synergetic effect of different categories of measures may then be revealed. For example, technical measures may allow for new operational modes, and organizational changes in entities involved during an incident may affect decisions and actions (i.e., FRS, TCC, etc.).

Data for this paper are collected from the investigative reports by the NSIA on the studied incidents. The following fire incidents are included:


These six NSIA reports were reviewed for their factual descriptions of the incidents, and analysed to understand what happened, i.e., how measures and/or actions affected the outcome. The measures were coded in the categories: technical, operational, organizational (using NVIVO). The assessments on what contributed to positive or negative outcomes, were performed by the authors. The analytical parts of the NSIA reports, expressing assessments made by the NSIA, were not used as input data. As the literature reviewed for this paper was limited to NSIA-reports, this might have influenced the accessible information. Changes in incident handling are used to assess the evolution of emergency preparedness.
DESCRIPTION OF TUNNEL SYSTEMS AND INCIDENTS

Gudvanga tunnel
The Gudvanga tunnel (length 11.5 km, with an incline of 3.5% from Gudvangen towards Flåm) opened in 1991 and is part of a longer tunnel system connecting Gudvangen with Flåm (together with the Flenja tunnel, approximately 5 km long). In 2022, the AADT was about 2.295 with ca. 26% Heavy Goods Vehicles (HGVs). The tunnel has a large AADT fluctuation, reaching a peak during the summer with an average daily traffic of 4.426 in July, due to tourist activities.

The Gudvanga tunnel is in Aurland municipality, (area 1.468 km², 1,715 inhabitants in 2014 – 1.766 in 2022), a municipality with 19 tunnels varying in lengths between 500 and 24.510 m. According to the Fire and Rescue Service Regulations [29], based on the number of inhabitants in settlements and special risk moments in the jurisdiction, Aurland has only part time, on-call responders. Estimated response time for Aurland FRS is about 20 minutes, while it will take about 50 min for the FRS from Voss, which is closest to the western Gudvangen portal. This difference in response time has most likely affected the choice to use a predefined ventilation direction towards Gudvangen (from east to west). The Gudvanga tunnel has a single tube with bi-directional traffic. The tunnel was originally based on safety regulations from 1981 but was later upgraded to regulations from 2002. This implies that when the first studied incident occurred, the tunnel had lay-bys, turning points, stopping signals at each entrance, lighting along the roof, SOS niches with hand-held fire extinguishers and telephones, warning signs placed at each turn-around space with the text “Turn and drive out”, as well as radio communication.

The standard procedure when a fire is detected/reported, is TCC to notify FRS in both Aurland and Voss (each approaching from their respective sides), and the FRS from Lærdal and Bergen if needed.

Studied incidents
A short description of each studied incident is given. For more details, see the incident reports [6, 8, 9].

Fire 5th of August 2013
A fire broke out in an HGV driving towards Flåm, 8.5 km from Gudvangen (Figure 4). At the time, there were 58 vehicles inside the tunnel (43 vehicles between the fire and the Gudvangen entrance, 15 between the fire and the Flåm entrance). The tunnel did not have a video monitoring system. The current emergency preparedness plan stated that the fire ventilation system should be activated independent of the fire scenario or position, directing smoke towards Gudvangen (speed 1 – 2 m/s), to provide Aurland FRS access to the fire. Directing smoke towards Gudvangen led to 67 people being...
trapped in the smoke and needing help to evacuate (TCC started fire ventilation 4 minutes after the fire started). After 50-95 minutes they were rescued, and 28 needed further treatment at the hospital.

Figure 4: Figure showing vertical curvature, placement and driving direction for burning vehicles

Technical and operational measures used to conduct each task during the response resulted in experiences and learning points, as described in Table 1. The organization responsible to address each issue is presented in the last column. If an improvement was made in the aftermath, this is also presented. This can be seen as “lesson learned” since an improvement in emergency preparedness was achieved.

Table 1: The 2013 Gudvanga fire incident

<table>
<thead>
<tr>
<th>Task</th>
<th>Solution in Gudvanga</th>
<th>Experience and learning points</th>
<th>Learning point to be addressed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close tunnel</td>
<td>No physical barriers.</td>
<td>Vehicles drove in, despite of red closure lights.</td>
<td>Tunnel owner (Barriers Installed).</td>
</tr>
<tr>
<td>Obtain information about fire location</td>
<td>Phones and hand-held extinguishers on tunnel walls.</td>
<td>Used.</td>
<td></td>
</tr>
<tr>
<td>Obtain information about location and type of vehicles</td>
<td>No video monitoring.</td>
<td>67 persons trapped in smoke.</td>
<td>Tunnel owner (14 cameras installed).</td>
</tr>
<tr>
<td>Inform and instruct tunnel users</td>
<td>Variable signs. Radio coverage.</td>
<td>Malfunctioned, not activated. Not used by the TCC.</td>
<td>Tunnel owner, TCC. TCC.</td>
</tr>
<tr>
<td>Lighting</td>
<td>Lighting (operational), No emergency lighting.</td>
<td>Partly malfunctioned.</td>
<td>Tunnel owner.</td>
</tr>
<tr>
<td>Smoke control</td>
<td>Longitudinal ventilation, reversible direction, predefined ventilation direction towards Gudvangen.</td>
<td>8.5 km (out of 11.5) filled with smoke. Several fans malfunctioned. Use of (many) emergency phones stopped (many) fans. Velocity programmed wrong (too high).</td>
<td>TCC. TCC. TCC. TCC.</td>
</tr>
<tr>
<td>Coordinate emergency resources - equipment</td>
<td>Coaxial cable not protected from the fire, poor coverage, portable signal repeater necessary.</td>
<td>Portable signal repeater forgotten.</td>
<td>FRS, Tunnel owner (Nødnett installed)</td>
</tr>
<tr>
<td>Procedures for coordination</td>
<td>Contingency plan, no individual incident plan.</td>
<td>Voss FRS alarmed after 25 min Incident command procedures.</td>
<td>110-Emergency call centre, FRS</td>
</tr>
<tr>
<td>Combat</td>
<td>Adequate extinguishing capability.</td>
<td>Dimensioning fire smaller than real hazard.</td>
<td>FRS, Tunnel owner</td>
</tr>
</tbody>
</table>

Actions after the fire incident on August 5th, 2013
A video monitoring system was installed, with 14 units (one camera every 820 m), allowing partial coverage of the tunnel. Additionally, lighting was improved as well as communications for emergency services (when the national emergency channel, “Nødnett”, established coverage in this part of Norway). Another technical improvement was the installation of physical barriers at each tunnel entrance. With those upgrades, the Gudvanga tunnel was equipped better than the minimum requirements described in N500. Regarding the ventilation strategy, it was decided to continue with a predefined direction towards Gudvangen, and increase velocity from 1-2 m/s to 2.5 m/s. Aurland FRS bought a mobile fan, to be used for tunnel fires, as well as amplifiers which were installed in the fire trucks for areas with poor emergency network coverage.
On the organizational level, a report by DSB [30] stated that learning from similar tunnel incidents is generally lacking. Knowledge of the possible consequences a similar fire could have with this ventilation strategy (through risk analysis) appears inadequate. Additionally, the report states that:

- FRS did not conduct prevention inspections according to requirements
- Required fire drills were not performed
- Lack of involvement of FRS in preparing emergency preparedness plans

**Fire 11th of August 2015**

A fire broke out in a bus driving towards Gudvangen and the driver stopped approximately 360 meters inside the tunnel (Figure 4). Based on the experiences from the previous fire, rescue services advised the TCC to not activate the fire ventilation system and use the new video monitoring system to get a better overview of the fire. But when the bus driver used a fire extinguisher from the tunnel, the fire ventilation system was activated automatically. This was not discovered by TCC until 8 minutes later.

A similar outcome like the fire in 2013 was avoided, as the 32 buss-passengers were evacuated with the help of a driver of an empty van who stopped at the scene. Being aware of the fire location, the TCC activated the “turn and drive out” signs, which contributed to 19 passenger cars turning around and driving out. Two HGVs also managed to turn around and drive out of the tunnel after TCC “found them” using the new video monitoring system, and interrupted radio broadcasting to warn tunnels users.

When Aurland FRS arrived at the fire scene (after around 15 minutes), they confirmed that no vehicles were east of the fire. When informed of three vehicles being trapped in the smoke downstream (five people), the ventilation direction was changed towards Flåm to support Voss FRS helping them. After 1.5 hours they were rescued and taken to the hospital. Improved communication procedures between FRS and TCC resulted in better cooperation. Communication between FRS and those trapped in smoke prevented them from exiting their cars to evacuate on foot, an advice based on experiences from the 2013 fire.

**Table 2: The 2015 Gudvanga fire incident**

<table>
<thead>
<tr>
<th>Task</th>
<th>Solution in Gudvanga</th>
<th>Experience and learning points</th>
<th>Learning point to be addressed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obtain information about location and type of vehicles</td>
<td>Partial video monitoring.</td>
<td>Inadequate.</td>
<td>Tunnel owner.</td>
</tr>
<tr>
<td>Inform and instruct tunnel users</td>
<td>Warning signs inside the tunnel, radio coverage.</td>
<td>Delayed warning of tunnel users, several tunnel users turned and drove out.</td>
<td>TCC.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Difficult to turn heavy vehicles.</td>
<td>Tunnel owner.</td>
</tr>
<tr>
<td>Smoke control</td>
<td>Predefined ventilation direction.</td>
<td>The FRS required ventilation towards Flåm (east) since the burning vehicle was close to the eastern portal. However, the driver had removed one fire extinguisher from the tunnel wall, starting predefined automatic fire ventilation towards Gudvangen (11 km). The TCC realized that 8 min later and reversed direction.</td>
<td>TCC</td>
</tr>
<tr>
<td>Coordinate emergency resources - equipment</td>
<td>Communication equipment improved, TCC not part of the emergency network, mobile phone coverage is poor.</td>
<td>Communication between TCC and FRS difficult.</td>
<td>Tunnel owner, Nødnett</td>
</tr>
<tr>
<td>Combat</td>
<td>Voss FRS extinguished the burning vehicle.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Actions after the fire incident on August 11th, 2015**

After the incident, several evaluations were carried out and projects were started to understand how to improve safety for long single tube tunnels. This was not based on this incident alone, but the increased frequency of larger tunnel fires in Norway.
The ventilation strategy and activation procedure was not revised after this fire, even though the NSIA strongly criticized that retrieving a manual fire extinguisher would automatically activate the predefined fire ventilation strategy. On the organizational level NPRA arranged a seminar where all TCC participated.

Fire 30th of March 2019
A convoy of four HGVs, led by an escort vehicle, was driving from Flåm towards Gudvangen during upgrading operations. Around 1.5 km inside the tunnel, a fire broke out in the first of four HGVs (Figure 4 and 5). There were 28 tunnel workers and 5 tunnel users inside the tunnel when the fire started. The tunnel workers did not have handheld transceivers (walkie talkies), which made it difficult to warn them. When the driver of the first HGV tried to extinguish the fire using a powder extinguisher from his truck, the second HGV driver thought the cloud of powder was smoke and warned the drivers in the third and fourth HGV to back away from the fire, towards Flåm. The driver of the escort vehicle warned TCC and tried to instruct the other HGVs to pass the burning HGV at the early phase and follow her out of the tunnel. While the drivers of the third and fourth HGV were busy backing and did not perceive the instruction, the second HGV driver complied. The driver of the first HGV entered the escort vehicle.

![Figure 5: Situational overview at the start of the fire](image)

The escort vehicle driver warned tunnel workers to evacuate on her way out of the tunnel towards Gudvangen. HGV three and four managed to back away from the fire for around 200-300 meters before the smoke reduced vision too much. At this point these two drivers abandoned their HGVs and started evacuating on foot towards Flåm. They struggled for 22 minutes to evacuate because of poor vision and breathing difficulty. They used the light from their own mobile phones to illuminate the centre strip of the road, and walked crooked, to be able to see it.

TCC could not see the fire as it was in a blind spot, as the tunnel did not have full video surveillance coverage. When the driver of the escort car called TCC from a SOS telephone on the tunnel wall, she accidentally collided with a hand-held fire extinguisher, which started the predefined fire ventilation towards Gudvangen. Upon hanging the fire extinguisher back in place, the ventilation stopped and went back to its original ventilation velocity and direction (operational, low velocity, towards Flåm). The FRS required TCC to keep this ventilation stable. TCC had also changed its routines, i.e., started the closing procedure and warning of tunnel users without waiting for a confirmation from FRS.
Table 3: The 2019 Gudvanga fire incident (during maintenance work)

<table>
<thead>
<tr>
<th>Task</th>
<th>Solution in Gudvanga</th>
<th>Experience and learning points</th>
<th>Learning point to be addressed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inform and instruct tunnel users</td>
<td>The driver of escort vehicle, and tunnel workers alerting each other. No handheld transmitters.</td>
<td>Difficult to turn heavy vehicles.</td>
<td>Tunnel owner (Handheld transmitters and smoke masks for workers acquired. Both leading and escort vehicle will guide / follow users during future maintenance).</td>
</tr>
<tr>
<td>Smoke control</td>
<td>Predefined ventilation direction.</td>
<td>Use of hand-held fire extinguisher automatically activated predefined ventilation strategy. Upon placing the extinguisher in place, it shall stop. However, it turned east instead. The FRS wanted to keep this mode. The system tried to switch to predefined strategy several times after TCC manually set eastward direction.</td>
<td>TCC.</td>
</tr>
<tr>
<td>Procedures for coordination</td>
<td>Contingency plan.</td>
<td>Aurland FRS was warned of the incident by the TCC 6 minutes after being warned by the escort driver.</td>
<td>TCC.</td>
</tr>
<tr>
<td>Combat</td>
<td>Voss FRS extinguished the burning vehicle.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Actions after the fire incident on March 30th, 2019

After this incident, routines were changed during work inside the tunnel, requiring all workers to carry an escape mask (as well as several extra masks placed in the escort vehicle) and using two escort vehicles (in the front and back). UHF-amplifiers were also installed to improve coverage and facilitate all workers to be able to communicate using handheld transceivers (walkie talkies).

It was also decided to increase coverage of the video monitoring system as well as automatic incident detection (AID). Improvements which were already started before this incident, were completed (new fans, new lighting system, detection radar, loudspeaker system for warning of tunnel users, concrete leading-edge rail with lighting).

The ventilation strategy and the automatic triggering through hand-held extinguishers was still not changed.

Oslofjord tunnel

The Oslofjord sub-sea tunnel (length 7.300 m, inclination 7 % towards both portals, Hurum to the west and Drøbak to the east) opened in year 2000 as a single tube, bi-directional tube. Oslofjord tunnel has an escape tunnel, starting about 500 meters from the deepest point towards Hurum (Figure 6). It is located in the most densely populated area in Norway, among others facilitating the movement of inhabitant’s work commuting to the capital (AADT ca. 10.400 vehicles in 2022, ca. 15 % HGVs).

Follo FRS has the main responsibility to respond to incidents in the tunnel. Follo FRS is an intermunicipal company, protecting a total of 125.000 inhabitants. According to the The Fire and Rescue Service Regulations [29], based on the number of inhabitants in their area and special risk moments in the jurisdiction, Follo FRS has several 24/7 manned fire stations. Additionally, Follo FRS had an agreement with Asker and Bærum FRS for eventual entry from the Hurum. The operational strategy of the tunnel started with a predefined fire ventilation direction from the Drøbak portal towards Hurum. The tunnel had video monitoring and Automatic Incident Detection (AID) since, which was only optional according to N500.
Studied incidents
A short description of the studied incidents is given. For more details, see NSIA reports [5, 7, 10].

![Figure 6: Figure showing vertical curvature, placement and driving direction for studied incidents](image)

**Fire 23rd of June 2011**
A fire broke out in an HGV driving towards Drøbak, 5.5 km from Hurum (Figure 6). The driver tried, but did not manage to extinguish the fire. TCC identified the incident using the video monitoring system and initiated closing of the tunnel. The ventilation system was not activated before getting an overview of the number of vehicles inside the tunnel and their location. The ventilation system was activated according to emergency procedures, towards Hurum at 2-3 m/s. This led to 34 tunnel users having great difficulty trying to escape. All but nine managed to eventually evacuate themselves, while those nine tunnel users needed to be rescued. During the evacuation, dangerous situations arose when people tried to drive through the smoke while others evacuated on foot. TCC managed to communicate with those inside the tunnel using the SOS-phones and guided them towards a small hatch leading to a cavity between the tunnel concrete lining and the mountain where conditions were better. After two hours these people were rescued and transported to the hospital. Both this communication using SOS-phones, as well as the video monitoring system contributed to providing FRS with updated information of the number of people and their locations inside the tunnel.

<table>
<thead>
<tr>
<th>Task</th>
<th>Solution in Oslofjord</th>
<th>Experience and learning points</th>
<th>Learning point to be addressed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close tunnel</td>
<td>Physical barriers present.</td>
<td>Short closure time important.</td>
<td>TCC.</td>
</tr>
<tr>
<td>Obtain information about fire location</td>
<td>Phone boxes, video monitoring, Automatic Incident Detection.</td>
<td>Used.</td>
<td></td>
</tr>
<tr>
<td>Obtain information about location and type of vehicles</td>
<td>Video monitoring and AID present.</td>
<td>29 tunnel users exposed for smoke.</td>
<td>Tunnel owner, TCC, FRS</td>
</tr>
<tr>
<td>Inform and instruct tunnel users</td>
<td>No variable signs, radio coverage.</td>
<td>Delayed warning by TCC.</td>
<td>Tunnel owner. TCC, FRS received confirmation on correct actions.</td>
</tr>
<tr>
<td>Smoke control</td>
<td>Longitudinal ventilation, reversible (slow), predefined ventilation direction towards Hurum. Follo FRS (Drøbak portal) has main responsibility.</td>
<td>5.5 km (out of 7.5) filled with smoke. Some measure should be implemented for users trapped in the unfavourable side.</td>
<td>Tunnel owner, TCC, FRS, Tunnel owner (26 shelters with three hours air constructed).</td>
</tr>
</tbody>
</table>
### Task Solution in Oslofjord

<table>
<thead>
<tr>
<th>Task</th>
<th>Experience and learning points</th>
<th>Learning point to be addressed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinate emergency resources - equipment</td>
<td>National emergency network present.</td>
<td>Functioned well.</td>
</tr>
<tr>
<td>Procedures for coordination</td>
<td>Contingency plan, individual incident plan</td>
<td></td>
</tr>
</tbody>
</table>

#### Actions after the fire incident on 23rd of June 2011

After this incident, 26 shelters were installed every 250 meters, as well as a dynamic guidance system. An operational measure was to reduce speed limit inside the tunnel. Some of the technical measures were improved signage informing on required driving behaviour, digital speed limit signs inside the tunnel which could be used for other purposes and warnings signs “turn around and exit” every 1.5 km. FRS were also granted several ATVs with extra breathing equipment. Additionally, FRS purchased a specialised tanker truck with 11,000 l water, 500 l CAFS (Compressed Air Foam System), 2 cannons (1 on top and 1 in front) and a thermal camera.

#### Fire 5th of May 2017

A fire broke out almost at the same location as the fire in 2011 in an HGV driving towards Drøbak (Figure 6). The HGV stopped 5 km from Hurum. The driver tried but did not manage to extinguish the fire. The driver was picked up by another tunnel user, who drove out of the tunnel. At the start of the fire, 127 vehicles were inside the tunnel. Many vehicles managed to drive out, some closely passing the burning HGV. Several vehicles even continued driving towards the fire below the smoke layer.

TCC was warned of the incident through the tunnels AID and started closing procedures soon thereafter (including stopping operational ventilation). Because of a technical error, the physical barriers took 35 seconds longer time than anticipated to close the tunnel. Within this time frame, seven vehicles entered the tunnel, despite the red flashing light being active (warning that the tunnel was closed). Five of these vehicles managed to evacuate the tunnel. The last two vehicles, which were HGVs, stopped behind the burning HGV and the drivers evacuated to the nearest shelter (installed after the fire in 2011). TCC could monitor the conditions inside this shelter and stayed in contact with the two drivers until they were rescued. However, they received minor burns in the hands caused by the hot metal handle of the shelter door.

Follo FRS entered the tunnel from the Drøbak-side. Around two km inside the tunnel they had to stop because of smoke (250 m from the fire). TCC postponed activation of the fire ventilation for as long as possible to give tunnel users a possibility to evacuate and get an overview of the vehicles and tunnel users inside the tunnel before it filled up with smoke. When Follo FRS reached the smoke front, they requested increased ventilation velocity. The tanker truck, purchased after the 2011-fire, contributed heavily to extinguishing the fire and preventing spread to the two other HGVs. After using the shelter for 40 minutes, both HGV-drivers were rescued by FRS using ATVs and breathing equipment.
Table 5: The 2017 Oslofjord fire incident

<table>
<thead>
<tr>
<th>Task</th>
<th>Solution in Oslofjord</th>
<th>Experience and learning point</th>
<th>Learning point to be addressed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close tunnel</td>
<td>Physical barriers present.</td>
<td>Closed 35 seconds slower than anticipated.</td>
<td>Tunnel owner.</td>
</tr>
<tr>
<td>Inform and instruct tunnel users</td>
<td>Variable signs.</td>
<td>Several malfunctions, two red flashing lights showing closing of tunnel, two signs showing turn around and exit. Problems interrupting radio broadcasting to warn tunnel users.</td>
<td>Tunnel owner.</td>
</tr>
<tr>
<td></td>
<td>Radio coverage.</td>
<td></td>
<td>TCC.</td>
</tr>
<tr>
<td>Smoke control</td>
<td>Predefined ventilation direction.</td>
<td>About 5.5 km were filled with smoke. Follo FRS required stronger fire ventilation because the smoke back-layered about 250 m in the uphill towards Drøbak.</td>
<td>Tunnel owner, TCC, FRS.</td>
</tr>
<tr>
<td>Protection of users from smoke</td>
<td>Shelters.</td>
<td>Some of the shelters were used. The TCC monitored the conditions there and held touch with the users. Several false alarms of (more) shelters being used</td>
<td>Correct use of shelters confirmed to tunnel owner, TCC, FRS, Tunnel owner.</td>
</tr>
<tr>
<td>Combat</td>
<td>Follo FRS extinguished the burning vehicle.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordinate emergency resources - equipment</td>
<td>Emergency network.</td>
<td>Problems in coverage of emergency network.</td>
<td>Tunnel owner (Nødnett)</td>
</tr>
</tbody>
</table>

Actions after the fire incident on 5th of May 2017

After the incident, signage was improved, adding signs requiring 100 m distance between larger vehicles, warning signs with “turn around and exit” were changed to “Turn around and exit – Fire” and warning signs at tunnel entrance were changed from “closed tunnel” to “closed tunnel – Fire”. The time between lights’ signalling “closed tunnel” and the physical closure with barriers was also reduced.

NPRA started with technical inspections of heavy vehicles on the Drøbak-side. For a long time, the tunnel also had a restriction for vehicles over 12 m (later changed to vehicles above 32 tons) during rush hours (between 07-09 and 15-18). This restriction was lifted 2nd of February 2022.

FRS changed its procedures when a fire is detected in the Oslofjord tunnel, increasing the number of vehicles being called out to three fire stations. FRS also changed its procedures to prioritize search for victims inside the tunnel, before searching through shelters for survivors.

The NSIA [7] points towards the following weaknesses:

- Slow processes of fixing known problems
- Low frequency of inspections (also by the FRS)
- Risk analysis not implemented in revised emergency preparedness plan
- Lack of regular drills and exercises

Fire 2nd of August 2021

A fire broke out in an HGV around 60 m before exiting the tunnel towards Drøbak (Figure 6). The incident was identified by the tunnel’s AID-system, which led TCC to close the tunnel and warn FRS. Twelve cars and three HGVs, which were driving in the same direction right behind the burning HGV at the time, managed to drive past the burning HGV. Another group of vehicles driving towards the fire (a HGV followed by seven smaller vehicles), a bit further away, managed to turn around and drive out towards Hurum. The driver of the burning HGV managed to walk out of the tunnel.

After the fire in 2017, the ventilation strategy was changed to push the smoke out of the tunnel towards the nearest portal. This meant that Asker & Bærum FRS now had the main responsibility during this fire. The ventilation direction both pushed the smoke towards the nearest portal and
contributed to slowing down the fire growth. As the fire started in the front and underneath the HGV and the ventilation direction was pushing in the same direction as the HGV was driving, the fire spread towards its cargo was mostly avoided. After 35 minutes the fire was extinguished. Several vehicles continued driving even though signs “Turn around and exit – Fire” were activated.

Table 6: The 2021 Oslofjord fire incident

<table>
<thead>
<tr>
<th>Task</th>
<th>Solution in Oslofjord</th>
<th>Experience and learning point</th>
<th>Learning point to be addressed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoke control</td>
<td>Revised ventilation strategy from predefined to context dependent, (Where the fire is located, and where other tunnel users are located).</td>
<td>The fire was very close to the Drøbak portal. Ventilation towards Drøbak protected the tunnel and the cargo of the burning HGV. TCC activated ventilation at the wrong stage, affecting velocity.</td>
<td>Tunnel owner / TCC / FRS experienced confirmation for correctly chosen strategy. TCC</td>
</tr>
<tr>
<td>Combat</td>
<td>Asker and Bærum FRS extinguished the burning vehicle.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordinate emergency resources – procedures</td>
<td>Emergency preparedness plan.</td>
<td>Asker and Bærum FRS was not on the right channel, which created some difficulties during the early phase of the fire.</td>
<td>FRS</td>
</tr>
</tbody>
</table>

Actions after the fire incident on 2nd of August 2021
The investigative report did not mention any actions taken after this incident.

DISCUSSION

The studied incidents reveal that the minimum safety requirements in tunnels with bi-directional traffic and longitudinal ventilation must be improved to support the self-rescue principle. This is supported by findings from all six incidents studied. This study is the first step towards analysing organizational learning among all stakeholders of the sociotechnical system a tunnel is. To support this analysis, the incidents are presented focusing on experience and learning points, indicating which organization(s) have most of the responsibility to improve each issue (Tables 1 – 6). The analysis will be completed in further research with interviews where each organization describes the undertaken learning processes. Here we conclude only based on their visible actions before and during the next incident.

The theory of single- and double-loop organizational learning [21] describes a single-loop learning process as the sum of deliberate actions to achieve set goals. In double-loop learning the value of the goal itself is questioned and new goals may be set. The shifting of goals may imply that the organization/network may have to revise itself (e.g., the way they cooperate) to achieve the new goal.

In the case of a tunnel, the sociotechnical system must achieve improvements, to provide adequate safety level for tunnel users also in case of a serious fire. Upon studying issues affecting society, the goals are defined out of the interests of the users [31]. In this study we have identified several single loop learning processes, and two double loop learning processes.

In single-loop learning processes, we insist on the goal, and improve ourselves until the goal is achieved, summarized as “doing things right”. The following issues in the two tunnels were improved through single-loop learning processes:

1. **Reduce the number of vehicles that drive in a tunnel despite red blinking lights**

Experiences show that physical barriers are much more efficient to prevent vehicles entering a tunnel when dangerous conditions are developing than red lights are. In both tunnels, physical barriers were installed by tunnel owner, and there is a focus on shortest possible closing time.

2. **Improve situational awareness in the tunnel for emergency response**
Situational awareness implies knowledge of where the fire is located, what is burning, as well as number and position of tunnel users/vehicles. While the location of the fire can be indicated by the position of a hand-held extinguisher lifted off from the tunnel wall, or by the position of a used SOS-phone, this will provide no information about the developing incident or number and type of tunnel users at the time of the incident. Oslofjord tunnel was equipped with video monitoring already before 2011, when the measure was optional. For Gudvanga tunnel the measure is still optional, according to N500, however it is installed by tunnel owner. Partial coverage was established in 2014, and full coverage in 2021.

3. **Informing and instructing tunnel users**

Passenger cars may have good possibilities to turn and drive out, if traffic and smoke conditions allow. Early warning is therefore important. Technical measures to inform, through radio, are mandatory in all tunnels. During the series of the studied incidents, we identified improvement in the time used to inform tunnel occupants. However, since there also was identified a delay in informing FRS in Gudvanga, we state this as “lesson in progress” for the TCC-West.

4. **Emergency communication – technical**

The national emergency network, Nødnett, is now available in the whole of Norway. However, problems with coverage were experienced in Oslofjord 2021. Good cell phone coverage is therefore also desirable, also because cell phones are being used more frequently instead of emergency phones by tunnel users to warn of an ongoing incident. This coverage is adequate in Oslofjord, but poor in Gudvanga. However, it is a back-up solution. The primary solution is Nødnett. An unresolved issue is that TCC does not have access to Nødnett. Solving this would be a double-loop learning process.

In double-loop learning processes the goal itself may be questioned. A deeper analysis is required, to redefine more suitable goals, “doing the right things”. The following issues were improved through doble-loop learning processes.

1. **Protection of tunnel occupants on the smoke-filled side of the tunnel**

Since longitudinal ventilation in a bi-directional tunnel will always direct smoke to some of the tunnel users, protecting them is necessary. This understanding is not common among tunnel stakeholders in Norway. Fire ventilation providing users with large quantities of smoke, with sufficient oxygen mixed in to survive, has been accepted but never documented. In Oslofjord tunnel, 26 shelters were built, offering three hours of air, and communication with TCC. This is seen as a double-loop learning point because it defined a new paradigm in Norway, and the emergency preparedness plan of the Oslofjord tunnel was changed accordingly. The 2004/54/EC regulation advises against shelters that do not lead to the free, since the safety they offer is temporary. However, in an emergency, decisions and actions are directed towards positive outcomes also step by step. Temporary protection until rescue forces arrive is compatible with the subject of Emergency Management. The stakeholders, tunnel owner, TCC, FRS and consulting engineering companies conducted a double-loop learning process to enhance tunnel safety.

2. **Context dependent fire ventilation strategy**

The fire ventilation strategy in Oslofjord tunnel was changed from predetermined towards Hurum to “shortest way out”, preferably. The tunnel owner, FRS, TCC and other safety experts, have reasoned that shortest smoke exposed tunnel length will statistically expose fewer users, and protect infrastructure. Video monitoring is crucial to decide what is best, in the given situation. This is a double loop learning cycle, since the cooperation of the emergency services is altered. The Follo FRS and the Asker and Bærum FRS share responsibility for the tunnel, and conduct main response dependent on the position of the fire.

3. **HGV control before entering the tunnel**
This organizational measure can reduce the likelihood of tunnel fires. It would have been stronger if also heavy vehicles were controlled at the Hurum side. We therefore categorise the measure as double-loop learning process in progress.

Necessary future improvements, out of issues common between incidents and tunnels, indicating the need for further learning processes:

1. **Manual fire extinguishers did not manage to extinguish the initial fires, even when several were used.**

   Experiences have shown that in the case of HGVs or busses, neither brought along nor tunnel-based fire extinguishers have had an effect in supressing fires. Tunnel owners, the transportation industry (including drivers’ associations), FRS and the fire community must address the issue and provide better solutions. The process may result in single loop learning (e.g., install better hand-held extinguishers, or water hoses) or in double loop learning, with for example changing self-extinguishing strategy to fixed firefighting systems (FFFS).

2. **Emergency phones inside the tunnel were often not used to warn TCC of an incident**

   A single-loop learning process would imply making SOS-stations inside the tunnel more visible, and educate tunnel users through the driving course and otherwise to use those for reporting incidents. A double loop approach would perhaps imply relying on video monitoring for information regarding incidents and the use of mobile phone. However, the communication between the tunnel users and the TCC through the SOS-phones seems still valuable. The two studied tunnels have video monitoring, but many other tunnels do not. But the increased use of mobile phones might make this measure less important. This increase, however, also provides a reason to improve cell phone coverage inside tunnels.

3. **Larger vehicles need much time to turn around, smoke often reaches them before being able to turn around.**

   A single loop approach would imply to increase number of turning points and increase their size. Distance between vehicles must also allow some manoeuvring. Investigating the possibility for transverse ventilation in some tunnels might be a valuable double-loop approach (though the St. Gotthard incident did not convince of the effectiveness of transverse fire ventilation in large HGV fires).

4. **Measures to reduce likelihood of fires in fire exposed tunnels may be found outside the tunnel itself**

   The vertical inclination of tunnels has been proven to be a risk factor for fires in heavy vehicles, and the slope has been reduced to below 5% for new tunnels. However, some tunnels that have lower slope than 5% (for example Gudvanga), are overrepresented in fire incidents’ statistics. This indicates that we need to see beyond the single tunnel (double loop approach). Look at parcels of tunnels and road sections, that produce dangerous situations that need to be controlled. Thermal camera inspection of heavy vehicles in both portals of the Gudvanga tunnel may reduce future tunnel fires.

**Organizational aspects**

Prior to the studied fire incident in Oslofjord tunnel June 2011, 12 fires had occurred, 10 of them in HGVs. NSIA [5] reported that only one incident report had been written, earlier the same year (March 2011). This indicates that learning opportunities from earlier (and perhaps smaller) fires had not been exploited [4]. Learning from incidents across countries, jurisdictions, FRS, etc. is a demanding process, that may need central facilitation to happen.

Future research, which will involve more sources and interviews with involved organizations, may reveal whether and how they learned from incidents in other tunnels. Additionally own learning activities, drills, table-tops, full-scale exercises, HAZOP, etc. will be investigated.
CONCLUSION

The hypothesis stating that emergency preparedness in Norwegian tunnels has been improved can be confirmed, if Gudvanga and Oslofjord tunnels are seen upon as representative examples. Several single-loop learning processes have been conducted among stakeholders in both tunnels. Additionally, two double loop processes were identified and described regarding the Oslofjord tunnel, while a third one is in progress. Learning processes appear more deliberate in Oslofjord, compared to Gudvanga, which can be explicable in several ways, e.g., more resources close to the capital compared to rural areas. Further research is necessary to acquire information on undertaken learning processes from each involved organization.

The recommended ventilation strategy during a fire is a topic which has been heavily discussed after several large fires between 2011-2019. Today’s regulatory recommendation describes a ventilation velocity below 2 m/s, in order to establish situational awareness and support self-rescue [18]. Further functioning of the ventilation system should be assessed during an emergency preparedness analysis. This approach is supported by a report by the NPRA [32]. The importance of the ventilation strategy on the safety of tunnel users, has been visible in all incidents investigated in this paper.

It is the authors opinion that one single ventilation strategy should not be adopted for all Norwegian road tunnels. This should be based on a holistic approach for each tunnel, taking both local factors into account (like FRS reaction time, tunnel length, traffic characteristics, etc.) and other ethical considerations. Based on the findings in this paper, a “wait and see” approach should be used during the early phase to allow tunnel users to understand a fire has occurred and provide time to turn around and drive out of the tunnel. This being either by keeping the ventilation system in the current settings or deactivating it, also providing TCC time to establish sufficient situational awareness. Based on information like the position of vehicles and tunnel users, fire development and smoke spread, a strategy should be chosen which allows tunnel users to reach a place of safety. Once this is achieved, access for FRS to the fire should be prioritized. To achieve this, the use of a surveillance system will be critical, providing information on vehicles and tunnel users inside the tunnel, as well as fire development and smoke spread.

REFERENCES

13. NPRA. *Road map*. 2023 [cited 2023 20th Januar]; Available from:
https://vegkart.atlas.vegvesen.no/#kartlag:geodata/@373247,7019606.3.
28. The Internal Control Regulation, *Regulations on systematic health, environmental and safety work in businesses*. 1996, Ministry of Labour and Social Inclusion,
Tenth International Symposium on Tunnel Safety and Security, Stavanger, Norway, April 26-28, 2023

Tunnel fire exercise in the Northern Link

Emil Persson, Björn Hedskog & Bo Wahlström
Brandskyddslaget AB, Stockholm, Sweden

ABSTRACT

A full-scale exercise took place in the Northern Link tunnel network in Stockholm in September 2022. The exercise scenario was dynamic and consisted initially of a traffic incident involving three passengers cars. It was an escalating scenario and following the incident, one of the three cars was set-up to catch fire. At a later stage, the extent of the exercise increased further when two vehicles downstream of the initial incident were assumed to crash due to limited visibility. Emergency services taking part in the exercise included the fire brigade, police, the local road assistance unit and tunnel operators. The drill provided the emergency services a rare opportunity to practice in a tunnel environment. The exercise also provided opportunity for the tunnel owner to test their tunnel systems, including the fixed fire-fighting system (FFFS). The authors of this paper were responsible for planning, coordinating and leading the exercise. Within this paper, lessons learnt from both the perspective of emergency services taking part in the exercise and tunnel owner acting as observer are shared. The paper also aims to share insights and lessons learnt from a planning and conducting perspective. The drill stressed the need for future exercises. This was highlighted by several emergency service organizations. The exercise clearly shows that the majority of practicing organizations generally have low orientation skills within the tunnel network. In addition, the exercise highlighted that there is a need to practice how active safety systems, e.g. ventilation and FFFS, should be used. That this requires collaboration between rescue service personnel and control operators is clear.

KEYWORD: Tunnel fire, road tunnel, full-scale exercise, electric vehicle fire, emergency service response, fixed fire-fighting system, escalating incident scenario

INTRODUCTION

According to Swedish legislation, full scale tunnel exercises should be conducted at a minimum once every fourth year. With this background, a full-scale exercise took place in the Northern Link tunnel network in Stockholm in September 2022.

Due to the importance of a tunnel network with the magnitude of the Northern Link, emergency services rarely get to exercise within such environment. Hence, the exercise provides a rare possibility to practice and find improvement opportunities.

AIM

Aim of exercise
Except for meeting the legal requirement of recurring full-scale exercises, the aim of the exercise was to confirm that emergency services were able to carry out emergency operations within the tunnel.

The prospect was also to conduct a learning exercise regarding:
• Communication, coordination and cooperation between different emergency services.
• Processes and safety systems being used in the tunnel network including the FFFS.

In addition to above, each emergency service organizations had specific goals with the exercise not mentioned within this paper.

**Aim of paper**
The authors understand that each tunnel network, and tunnel owner is different, and that emergency service structures differ depending on location. However, many challenges regarding exercise are common within all parts of the world, highlighting the importance of sharing knowledge. As such, the paper herein aims to share lessons learnt both from the perspective of emergency services taking part in the exercise and from the tunnel owner acting as an observer. The paper also aims to share insights and lessons learnt from an exercise planning, and conducting, perspective.

**NORTHERN LINK TUNNEL NETWORK**
The Northern Link tunnel network is located in the north part of Stockholm, Sweden. The Northern Link consists of a road tunnel network with a combined total length of 13 kilometers. The longest tunnel is around 4 kilometers. Number of lanes differ from one to four. Traffic in all tunnels are unidirectional.

The network consists of two main tunnels and several shorter tunnels connecting to the main tunnels. Most of the tunnels were opened to the public in 2014. An overview of the tunnel network is shown in Figure 1.

![Figure 1: Overview of the Northern Link tunnel network](image)

The tunnel network is fitted with longitudinal ventilation, CCTV and a fixed fire-fighting system (FFFS). The longitudinal ventilation system consists of jet fans amounted to the ceiling of the tunnel. Brandskyddslaget AB took part in the design of the FFFS which consists of a deluge system. Sprinkler heads are of sidewall type. The FFFS for the Northerns Link project was designed with off-the-shelf products due to time constraints. The system is designed for a minimum water density of 5
mm/min (= 5 litres of water per square meter and minute). Each section of the FFFS covers about 80 metres of the tunnel with two sprinklers mounted “back-to-back” at 5 metre intervals.

The geometry of the tunnel network is complex and emergency services can enter the tunnel network from several tunnel openings. Based on emergency plans in place, during a fire within the tunnel network, emergency services are not to approach the fire through the incident bore. Instead, emergency personnel are supposed to reach the fire location through cross-passages between the tunnels.

The Northern Link is provided with emergency exits, i.e., cross-passages, every 150 meters. Tunnels are located on different elevations and the distance between tunnel bores is extensive in some parts of the network, including the parts around the fire incident. Some of the cross-passages are extensive and have an elevation difference of over 15 m.

PLANNED EXERCISE SCENARIO

The exercise focused, among other things, on the risks with electric vehicles and operation of the FFFS. This because the number of electric vehicles is increasing and there is a risk of re-ignition in electric vehicles due to the battery configuration. In addition, the FFFS was installed within the tunnel 2014, to allow for queuing but the emergency services ability of working with the system is rarely tested.

Active safety systems within the tunnel were available and functioning during the exercise. Activation of the FFFS and the emergency ventilation system and other emergency system is part of the existing response plan in case of a fire. Based on the actions of the emergency services and the tunnel operator, systems can therefore be activated and deactivated.

Expected overall sequence of events

Overall conditions for the scenario are described as follows:

- Evening time, same season as actual practice day (September).
- Initial accident – collision between an electric driven passenger car and two passenger cars with an internal combustion engine in the Galax_tunnel (northbound tunnel), see location in Figure 2. Length and height differences within the cross-passages is extensive in this part of the tunnel network. The tunnel consists of a single lane at the location of the initial accident.
- Cars involved within the accident block parts of the tunnel tube where the initial accident occurs.
- People are stuck in cars involved in the accident.
- A fire breaks out in one of the cars (electric vehicle).
- FFFS activates and impulse fans are activated since response plan “fire” is activated.
- Secondary accident – two more passenger cars collide downstream of the initial event.
- Two “maintenance workers” are stuck in operating space downstream of fire.
Initial accident
The incident consists of a collision between an electric car and two passenger cars with the consequence of a fire in the electric car after a certain time. That one of the vehicles is an electric vehicle is evident if typing in the registration plate number in the database. People are trapped in the cars and when the emergency services arrive, several people show symptoms of exposure to hydrogen fluoride (HF), some of whom have serious symptoms.

The FFFS is activated, after control room personnel manually activates the fire emergency plan. The FFFS limits the spread of the fire but does not extinguish the fire completely. In the event of a fire in an electric car’s battery pack, the car’s body and the battery’s casing prevent the FFFS from directly acting on the fire source and cooling the battery. A battery fire normally requires extensive amounts of water in order to reduce the temperature during a thermal runaway. Due to the risk of the electric car re-igniting, a re-ignition is also simulated during the exercise some time after the emergency services have extinguished the initial fire.

The initial accident occurs just downstream of cross-passage 3 (CP3), see Figure 3. Passengers in the electric vehicle start evacuating and no occupants remain within the vehicle during the exercise. Instead, it is simulated that the driver in the electric vehicle escapes to cross-passage 3. In each of the crashed cars that do not catch fire, there are two smoke-injured occupants left who cannot leave the vehicles on their own because they are trapped or have suffered neck/back injuries.

Secondary accident
Several cars are simulated to drive past the initial accident after the fire has started. Two of these cars collide downstream of cross-passage 4 (CP4). A location leading to passengers in the cars being exposed to smoke from the fire. In one of the cars involved in the secondary accident, three injured occupants are not able to leave the car themselves. Passengers in the other car evacuate towards cross-passage 4 and 5.

Maintenance workers in ancillary space downstream of fire
While the events described above occur, two contractors are simultaneously in the ancillary space between cross-passage 3 and cross-passage 4. The workers are conducting simple maintenance work and are not expected to evacuate towards the cross-passages.
Exercise management group and documentation
The planning of the exercise started in 2021, around a year before the exercise was conducted. For the exercise, there was an exercise management group that consisted of representatives from the various actors who were supposed to participate in the exercise. The group met continuously in 2022 to plan and coordinate the exercise. In addition to these meetings, informal and formal meetings and discussions were held between the authors of this paper and responsible people within the organizations taking part in the exercise.

During the planning phase, the authors shared several documents with the exercise management group. This includes a general exercise plan describing the scenario along with practical management instructions for the exercise among other things. The document has been distributed in several revisions.

Management tabletop exercise
In May 2022, a theoretical management exercise was carried out as a “tabletop exercise”. The exercise was carried out digitally with the authors being the drill leaders. The focus of the exercise was on the initial phase, as this part of the procedure was deemed not possible to practice fully during the full-scale exercise. During the tabletop exercise, it was played out how each organization was expected to act from the time the initial event occurs until the emergency services are underway at the scene of the accident. A specific purpose of the tabletop exercise was to find the strategic locations where resources needed to be located before the full-scale exercise started. This is due to the facility’s complexity with several tunnels and a part of the tunnel network being open for public traffic during the night of the exercise.

Site visit
A site visit was conducted where representatives from all organizations who were supposed to participate in the exercise were given the opportunity to partake. The representatives got the opportunity to study the tunnel environment, study cross-pasages and visualize the activation of the FFFS. During the site visit, the setup of the accident sites was also discussed. A complementary site visit was also carried out later with the aim of evaluating in more detail how the accident sites would be constructed during the full-scale exercise.

Figure 3: Setup of exercise scenario

PLANNING PROCESS
CONDUCTED EXERCISE

Organizations taking part
The following organizations took part in the full-scale exercise:

- Traffic Stockholm (TS) – the tunnel operator.
- SOS and ambulance – including emergency medical services (EMS) and emergency medical dispatchers.
- Police – including both field personnel and alarm center personnel.
- Fire brigade – including both field personnel and alarm center personnel.
- Local road assistance unit

All in all, slightly less than 100 people took part in the exercise. In addition to the personnel taking part in the exercise, several observers and spectators were witnessing the exercise. All spectators were located upstream of the fire incident.

Use of markers
During the exercise, several markers were used. Markers consisted of both real people and mannequins. The people who participated as damage markers were local volunteers. Markers being placed at the height of, or downstream, of the fire in the affected tunnel tube were mannequins. Markers placed upstream of the fire and in cross-passages were made up of real people. A total of nine real people and seven mannequins were used in the exercise.

Evening of exercise
Before the exercise started, all practitioner and exercise management gathered at a location close by the tunnel network. At this time, observers, spectators and people who would be acting as markers in the tunnel also gathered. Around 150 people were present at this time. At this gathering, the drill leader held a briefing regarding, among other things, the following:

- Basic principles for the practice where each practicing unit received an info card. The info cards indicated basic technical exercise information and described how the units were expected to act in the initial stage of the exercise. The start card indicated where the practicing unit would be located at the start of the exercise, based on the previous management tabletop exercise. Practicing units were assigned fictitious lead-up times to the starting position after being alerted. During this time, the unit was not allowed to leave its starting position but could communicate with other units and organizations. The info card also included basic safety rules for conducting the exercise.
- Safety briefing for people who would be in the tunnel environment during the exercise.
- Communication in the event of a real accident or in the need to interrupt exercise.

During this time, the accident sites within the tunnel were being prepared, see Figure 4 and Figure 5 below. The car used as an incident fire vehicle had covered side windows, shown in Figure 4, a closed tailgate and the front window removed. It was transported into the tunnel network at the evening of the exercise. The car was fully burnt in a safe environment the day before the exercise. In order to simplify transportation before and after the exercise and to protect the underlying roadway during the fire it was placed on a platform. After being fully burnt out the day before, the car was filled with wood pallets and fiberboard being used as fuel during the exercise.

In order to practice a scenario with a re-ignition, similar to an electric vehicle fire, fiberboard and Bengal torches were wrapped in plastic and placed under the incident car. The package was connected to a remote ignition mechanism allowing the exercise management to ignite the fire underneath the car after initial extinguishment of the fire inside of the car. The setup of the package used during the exercise is shown in Figure 6 and a test burn of a similar package setup is shown in Figure 7.
After the briefing, practicing units went to their respective starting locations and parts of the exercise command group drove to the prospective outer command location. Parts of the exercise management group were also already situated at command centres.

Figure 4: Preparation at initial accident (fire vehicle to the right).

Figure 5: Setup at secondary accident
Conducted exercise
The start of the exercise was the initial accident. Thereafter the exercise followed the sequence of events shown in Table 1.

Table 1: Sequence of events

<table>
<thead>
<tr>
<th>Event</th>
<th>Comment / sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start (initial accident)</td>
<td>After all organizations announced that they were ready, the exercise was initiated by the drill leader notifying the local exercise leader at Traffic Stockholm (TS) to initiate the exercise. The start of the exercise was slightly delayed due to the time-consuming arrangement of the accident sites in the tunnel and the exercise started a few minutes after midnight. At the start of the exercise, control personnel at TS received an alarm about stationary traffic in the tunnel, meaning the exercise was started. Around 1 minute after the exercise started, the drill leader initiated for a fictive road user in the tunnel to also contact SOS.</td>
</tr>
<tr>
<td>Alerting based on traffic accident</td>
<td>Alerting of units (fire brigade, police, ambulance and road assistance) initially took place based on a traffic accident in the tunnel. After the drill leader received information confirming that units had been alerted from the police, ambulance and fire brigade, the drill leader informed personnel in the tunnel to start the fire. Shortly thereafter, a fire was started. This happened around 8 minutes after start of exercise.</td>
</tr>
</tbody>
</table>
| Fire and activation of emergency plan “Fire” | Shortly after the fire was initiated (about 4 minutes), the “Fire” emergency plan was activated and the FFFS was activated. Initially, the wrong deluge zone was activated. Instead of the zone affected by the fire, the zone downstream of the fire was manually activated by personnel in the control room. The correct zone was activated about 6 minutes after the start of the fire.  

After the correct FFFS zone was activated, the temperature of the smoke appeared to decrease and the size of the flames decreased. However, the fire continued inside the car and flames were also visible outside the vehicle. It should be mentioned that as the sides of the car were intentionally covered, the fire was relatively shielded.  

After the fire was noted, all units were redirected to the adjacent tunnel bore which was not affected by the fire, as this is the emergency services' regular routines in case of a tunnel fire. Additional units from all emergency service organizations were alerted. It is noteworthy, however, that a unit from the fire brigade drove towards the fire-affected tunnel and requested the opening of the roadblock. The roadblock opening was denied by the exercise management based on the technical rules established before the exercise.  

During this time, calls were also staged from a fictitious person (maintenance worker) who was in the ancillary space between cross-passage 3 and cross-passage 4. The call was made to TS (tunnel operator). |
| Start of emergency operations at fire location | Units made their way from the non incident tunnel bore through the cross-passages to the incident tunnel bore. The first unit from the fire brigade started operating at the scene of the accident approximately 18 minutes after the start of the fire. The fire brigade initially began to work in an environment with the FFFS in operation.  

After arriving at the fire location, fire brigade personnel started extinguishing the fire. After the FFFS was turned off and the fire brigade had stopped extinguishing the fire it was still smouldering. The fire was thereafter left unattended for some time and started growing again without any interference of the exercise management personnel. Fire brigade personnel therefore had to perform additional extinguish.  

Once again, after extinguishing the fire the second time, the incident car was left unattended. In order to simulate an electric car fire, the exercise management therefore activated the secondary fire (underneath the car) and the intensity of the fire increased again. When noticed by the fire brigade personnel, the fire was extinguished a third time. |
| Outer command location setup | The outer command site was set up at a parking lot just north of one of the entrances to the tunnel network. First on the scene of the emergency services management vehicles were the fire brigade. Shortly afterwards, management |
| **Secondary accident downstream of fire** | Exercise management staged a call from evacuees to TS approximately 13 minutes after the start of fire. The caller stated that he was within cross-passage 4 and that he had crashed his car after driving past a burning car. TS then notified the fire brigade that the secondary accident site was downstream of the fire. The emergency services likely lost this information. Therefore, it took an extensive amount of time before the emergency services arrived at the secondary accident scene. After arriving at the secondary accident site, the rescue work continued without any major complications.

In general, after having troubles with initial wayfinding, the communication and coordination at the accident sites was efficient among the emergency services. |
| **End of exercise** | The exercise was scheduled to end no later than 02:00. Due to the long intervention times, the decision was made to continue practice for another 15 minutes.

After the end of the exercise, the drill leader held a short evaluation at the outer command location where each practicing organization got a chance to comment on what they had experienced and how they thought the exercise played out. A similar evaluation was held by the deputy drill leader at the site of the initial accident in the tunnel. After that, all practitioners left the area and cleaning was carried out. |
RESULTS AND EVALUATION

In addition to the evaluations that were carried out directly after the end of the exercise, the various practicing organizations also had internal evaluations after the exercise. Furthermore, the exercise management group has met and jointly evaluated the exercise. Some main conclusions from these evaluations include:

- The place of the accidents within the tunnel were perceived as suitable due to the hardship with wayfinding within the network and difficulties to attack incident tunnel bore from adjacent tunnel bore.
- Full-scale exercises of this size are appreciated since it gives an opportunity to test personal protective equipment, vehicle functions and technical equipment in a realistic environment.
- It was perceived as difficult for units at the outer command post to obtain an overall picture of the situation in the tunnel.
- Orientability in the tunnel is generally low.
- It was difficult to understand for the rescue personnel and unclear to the emergency medical dispatchers that the car on fire was an electric vehicle.

Some conclusion from the writers regarding the tunnel systems also include the following:

- FFFS – As expected, the system was able to lower the size of the flames and decrease the temperature of the smoke. However, it was not able to fully extinguish the shielded car fire. This highlights the obstacles regarding shielded fires.
- Ventilation – Once the ventilation system was running, even not at full capacity, no backlayering was visualized. The capacity of the ventilation system is designed based on a much higher heat release rate than a single passenger car fire which also was evident during the exercise.
RECOMMENDATIONS

The execution of the exercise is considered to fulfill the overall purpose and the objectives. Based on the preparatory work performed and the exercise carried out, the following recommendations are given for future exercises, tunnel owners and for emergency personnel.

Exercise technique and preparation:
- Establish each organization’s objectives early on.
- Determine the exercise scenario early in the planning process and determine that all stakeholders accept the scenario.
- If possible, determine early on what resources different organizations will provide. This includes both organizations taking part in the exercise and personnel acting as support.
- Clearly communicate expectations and critical points to key people. Follow up regarding expectations throughout the preparation phase.
- Make sure throughout the preparation process to follow up and ask control questions to responsible people. This is especially important the days before practice.
- It is important to ensure communication and operational reliability within the exercise management group during the exercise. Ensure that several means of communication are available.
- Ensure a margin for time to prepare accident sites at the time of the exercise. This to ensure that accident sites can be setup sufficiently and to minimize waiting time for practicing personnel.
- Ensure that escorting of units into the tunnel or tunnel network is well planned and prepared.
- To the greatest extent possible, allow practicing units to act with as little interference as possible from exercise management.

Exercise scenario for future exercises:
- The size of the exercise is recommendable also for exercises to come in order to practice communication and cooperation between organizations in an applicable way.
- As this exercise clearly shows that the majority of practicing organizations generally have low orientation skills within the tunnel network, it is obvious that orientation skills need to be practiced in the future as well.
- The exercise has highlighted that there is a need to practice how active systems, i.e. FFFS, must be used. That this requires collaboration between control room personnel and the rescue services is clear.
- In advance of a full scale exercises it is recommended to launch smaller drills and tabletop exercises in order to practice specific parts of an rescue operations. Examples are orientation drills in the specific tunnel systems and communication exercises between different rescue organisations.

Recommendations for emergency service, tunnel operators and tunnel owners:
- It was not clear to the tunnel operators nor the emergency services that the fire scenario was an electric car. This will obviously be easier to notice in a real fire event. However, the exercise highlights that there is a need for clarifying responsibilities of recognition and research regarding vehicles involved in accidents and fires.
- Due to the complexity of the tunnel network and high number of emergency units there is a clear risk that emergency personnel will try to access the incident tunnel bore. This was highlighted during the exercise when a fire brigade unit requested the opening of a roadblock into the incident tunnel. It is important that the tunnel operators are aware of this risk.
- Since the exercise clearly shows that the majority of practicing organizations generally have low orientation skills within the tunnel network, it is considered that, in addition to orientation skills needing to be practiced, better quality maps and drawings should be available for those concerned and that knowledge and routines for guidance to the correct places are available at the relevant control center.
• During a real fire event, a search operation should always be conducted downstream of where the fire occur. This could be done using CCTV or through search and rescue (SAR) activities. This procedure is already part of the fire brigades routines in case of a fire within the tunnel network.

• Differences in elevation between the tunnel bores sometimes require actions which may violate current routines due to carrying of equipment and people becoming demanding. This applies to both the collection point for injured occupants, as well as the fire brigade carrying extrication equipment and hose routing from the fire hydrant. Based on experience, possible new routines should be developed.

• An outer command site far from the scene of the accident entails a different way of working compared to most emergencies. The experiences should be taken into account for possible customized solutions. For example, the outer command site could have been in a control room as well as outside of the tunnel network.
Evacuation shelters in single-tube road tunnels – From a poor reputation to emerging interest

Jeroen Wiebes Kjos¹, Henrik Bjelland², Ove Njå³, & Inger Lise Johansen³, Sverre Kjetil Rød⁴

¹Western Norway University of Applied Science, Haugesund, Norway
²University of Stavanger, Stavanger, Norway
³Norwegian Public Roads Administration, Lillehammer, Norway

ABSTRACT

Since the Mt. Blanc fire, evacuation shelters have been debated as a means for road user safety, and due to the EU directive, they generally have not been built in Norway. One exception is the Oslofjord road tunnel, which experienced a serious fire in 2011. Nine road users were trapped in the smoke. Based on instructions from operators at the Tunnel Control Center (TCC), some of them took shelter behind the tunnel walls that were not designed to protect people in the case of fire. Several people were injured in the fire, but no one died [1]. After the fire it was decided to establish evacuation shelters in the tunnel, as a temporary measure until a second tube was built [2]. The second tube is still not built, and several fires have occurred in the Oslofjord tunnel since 2011. During an HGV fire in 2017 the drivers of two separate HGVs became trapped in the smoke and evacuated into one of these evacuation shelters. They only sustained minor injuries [3]. In this paper we investigate the foundation for the prohibition of evacuation shelters in road tunnels. A review of important historical fires, application of similar shelters in other industries, as well as a theoretical review of tunnel users’ behavior in emergencies, supports a discussion of how evacuation shelters might be included as an element in road tunnels’ evacuation systems. We conclude that evacuation shelters could provide a cost-effective solution to a major challenge of enhancing the self-rescue principle in many Norwegian single-tube road tunnels.

KEYWORD: evacuation shelters, fire protection, system safety

INTRODUCTION

Shelters and Norwegian road tunnels

The Mt. Blanc tunnel in 1999 started in a heavy goods vehicle (HGV) and eventually spread to 25 vehicles. It was estimated that the fire reached a peak of about 190 MW and temperatures above 1000 °C. It took the fire department 53 hours to extinguish the main fire and hot spots were dealt with even after five days. Close to 40 people died because of the fire, two of which in an emergency shelter designed to protect lives in the case of fire [4]. In 2004, the Directive on minimum safety requirements for tunnels in the Trans-European Road Network (EU directive) stated that “shelters without an exit leading to escape routes to the open shall not be built” [5].

Norway is a mountainous and coastal country with more than 1,200 road tunnels, among them the world’s longest tunnel (24.5 km) and the world’s longest subsea tunnel (292 m deep, 14.4 km long). Many of the tunnels are single tube constructions with limited traffic volume, complex geometry, and steep gradients. Longitudinal ventilation is the governing fire ventilation principle. Due to the large number of tunnels, Norway has yet to fulfil its commitment to upgrading all tunnels on the Trans-European Road network (TERN) according to the provisions in the EU-directive.

The governing principle for safety in Norwegian road tunnels is the self-rescue principle. This means that when an emergency occurs, drivers and passengers cannot rely on assistance, but must evacuate by
themselves by car or by foot [6]. After several serious fire events since 2011, the Norwegian Safety Investigation Authority (NSIA) raised critique towards the Norwegian Public Roads Administration (NPRA), claiming that the premises for successful self-rescue is generally not in place for long one-tube tunnels without emergency exits. Norway has more than 500 single tube tunnels over 500 m, of which 98 are over 3000 m. There are no absolute requirements for emergency exists in existing tunnels. For new tunnels, the EU directive states that emergency exits shall be provided where the annual daily traffic (ADT) exceeds 2000 vehicles per lane. Norway has been granted the possibility of approving exceptions for tunnels shorter than 10 km and with an ADT of less than 4000 vehicles per lane, given that a risk analysis can demonstrate an equivalent or higher level of safety.

In practice, the most relevant solution for establishing emergency exits is by establishing a second tube. If not justified by traffic volume, this is considered an extremely costly solution. Consequently, emergency exits are - when not absolutely required- generally dismissed due to cost arguments. Against this backdrop, the NPRA is investigating whether the use of evacuation shelters can provide an efficient and cost-effective measure to improve self-rescue in long, single-tube tunnels. The assumption is that such shelters, given appropriate design and management, can provide a positive contribution to safety, and that a general prohibition, as in the EU-directive, is not reasonable. This calls for revisiting the premises behind the prohibition, and, whether there has been development in technology, procedures, or analysis tools that call for derogations from or even alterations of the directive. Eventually, it might be relevant to reconsider the requirements for emergency exists, i.e., if emergency shelters prove to offer a feasible alternative even when emergency exits are required. As part of the investigation, the NPRA has approved the establishment of evacuation shelters in two pilot projects. Both projects represent long, single-tube subsea tunnels with steep gradients, that shall be upgraded to fulfil the requirements in the Norwegian adaptation of the EU-directive for County roads [7]. The purpose of the pilot projects is to gain experience with the design and use of evacuations shelters and strengthen the knowledge base concerning their effect on safety.

**Challenges related to evacuation**

The first Norwegian road tunnels were built already in the 1960s. In many of the tunnels, especially the subsea tunnels, there is a steep gradient resulting in an increased risk of heavy goods vehicle fires due to engine and brake failures [8]. The uniqueness of these old Norwegian tunnels is their single-tube construction with no evacuation shelters (i.e. relatively limited means of escape in emergencies) and bi-directional traffic. In case of a fire, tunnel occupants need to evacuate to the outside environment as fast as possible to not be overcome by fire smoke. This is a demanding process for a diversity of occupants where time is critical.

The self-rescue principle is foundational in the built environment, such as road tunnels and buildings. Drivers and passengers must evacuate unassisted by foot or by car when an emergency occurs (i.e. before the fire brigade arrives). The owner of many Norwegian tunnels – the Norwegian Public Roads Administration (NPRA) – has only to a limited extent distributed information about the fire risks in tunnels. As such, information about what to do in emergencies (self-rescue) in tunnels has been scarce –until December 2019, when the NPRA launched a national PR campaign for the first time. The campaign consisted of six different videos with instructions on what to do in emergencies, reaching out to the youngest drivers, adult drivers, and truck drivers, by utilizing social media, such as Instagram, Snapchat, and Facebook. The videos were also used in connection with drivers’ education.

Evacuation from a road tunnel can be a very difficult and traumatic experience for those involved. This is evident after reading the testimonies in the accident investigation reports after the fires in the Oslofjord Tunnel in 2011 [1] and in the Gudvanga Tunnel in 2013 and 2015 [9, 10]. The main problems of tunnel occupants were caused by the fact that they had to evacuate through dense smoke, which in turn is partially explained by the fact that evacuation was initiated relatively late. Immediate and effective evacuation in the case of fire is necessary in order not to be injured, which means that the tunnel and the surrounding infrastructure must be designed to meet this need.
Major issue
This paper is a presentation of the preliminary findings of an ongoing study into evacuation shelters in the Norwegian road tunnel context. We report on the findings of a literature study that investigates 1) the foundations for the decision to prohibit evacuation shelters in 2004, 2) current knowledge about design and technology associated with evacuation shelters, and 3) the effects of evacuation shelters in different industries. The goal is to revisit the assumptions from 2004 and analyze whether the assumptions are still justified.

METHOD
The study is currently ongoing and presents preliminary results from:

- A review of public documents associated with the foundation and development of the EU-directive 2004/54/EC. The document review is supported and informed by conversations with professionals involved in the tunnel safety discussions during the early 2000s and onwards.
- A review of the major European road tunnel fires around year 2000, and especially the Mt. Blanc and St. Gotthard fire, due to its implications on the evacuation shelter discussion.
- A review of selected investigation reports from major Norwegian road tunnel fires since 2011. The events are considered important because they contributed to our collective knowledge about road tunnel safety, but also contributed to raised political and social awareness and a questioning of existing safety management principles.
- A literature review which builds on recent Norwegian research activities on the safety of evacuation shelters in road tunnels. A broader literature review is planned for the next phase of the project.

These reviews serve as a foundation for an analysis and discussion about whether the assumptions made for prohibiting evacuation shelters in single-tube road tunnels are still justified and/or whether there are knowledge gaps that inhibit recommendations for an adjusted practice.

FOUNDATIONS FOR THE DECISION TO PROHIBIT EVACUATION SHELTERS
To facilitate innovation and technological development for egress systems in road tunnels, we need to understand the background for existing attitudes, decisions, and regulations. In this section we present findings from a review of public documents and procedures which led to the EU-directive 2004/54/EC and some of the incidents which were identified as the possible reasoning for the need for a harmonized directive.

Due to considerable variation between national legislations for tunnel safety, several major tunnel fires (among others: Isola delle Femmine 1996, Tauern tunnel 1999, Mt. Blanc tunnel 1999, Gleinnalm 2001 and St. Gotthard 2001), and several major tunnel projects which were in the planning phase at the time (among others the Somport tunnel between France and Spain, Øresund rail/road link between Denmark and Sweden and the Brenner project), the EU commission proposed in its white paper on transport policy in 2001 an EU directive on the harmonization of minimum safety standards for road and rail tunnels of the trans-European network [11].

In the first proposal for a directive on minimum safety requirements for tunnels in the trans-European Road Network (COM/2002/0769 final), the objective of the directive was discussed [12]. The primary objective was to prevent critical events, while the reduction of possible consequences was mentioned as a secondary objective. Where the original proposal transferred the responsibility for requirements on the provision of emergency exits to local authorities, the version of the EU-directive, which was approved on March 31st 2004, included a prohibition on the use of evacuation shelters. This prohibition was not mentioned in comments on the original proposal (52003AE0746 dated 16.09.2003 and 52003AR0093 dated 24.10.2003) but was added later as an amendment, stating that there was a need to provide stricter requirements on egress provisions.
It is a matter of further investigation to fully understand the evolution of the Directive, but the prohibition does not, however, represent a new attitude in international tunnel safety discussions. In December 2001, the UNECE, supported by the European Commission, published a report from an ad-hoc multidisciplinary expert group on tunnel safety. Their mandate was to develop a recommendation on minimum requirements for road tunnel’s safety. The experts conclude that “[s]helters without an exit leading to escape routes to the open represent an unacceptable risk; this type of closed-in shelters should not be built any more” [13]. Similarly, a technical guide on road tunnel safety, issued by the French government, did also require that any emergency shelters in single-tube road tunnels should have a separate (independent from the tunnel) connection to the open [14].

EXPERIENCES WITH EVACUATION SHELTERS IN ROAD TUNNEL FIRES

Catastrophic accidents are central drivers for political and social awareness of risks, regulation development and enforcement [15]. This also applies to the field of road tunnels [11, 13, 16]. The following include a short summary of four major tunnel fires with special relevance to the discussion of evacuation shelters.

The 1999 Mont Blanc tunnel fire
The Mont Blanc tunnel is a single-tube tunnel with bi-directional traffic. After a serious fire on the 11th of January 1990, 18 evacuation shelters were installed (around every 600 m). These shelters were supplied with fresh air through ventilation ducts, surrounding constructions had a fire resistance of two hours and they were connected by telephone to the control room. In the investigation report concerning the major fire in 1999, it was mentioned that shelters were essential in saving the lives of the firefighters and other personnel who tried to save the lives of passengers inside the tunnel [17]. Two people died inside evacuation shelter 20 close to the fire, while others reportedly survived up to seven hours inside other shelters further away before being rescued. The investigation report argues that based on past experiences during fires in other tunnels, and the fact that people who died in the tunnel did not use any of the shelters, it is likely that evacuation shelters would not be used by tunnel users unless being led there by qualified personnel [17].

The 2001 St. Gotthard tunnel fire
The St. Gotthard tunnel is a single-tube tunnel, with bi-directional traffic. It has a parallel evacuation tunnel, where access galleries between the main and evacuation tunnel are built as evacuation shelters which are placed every 250 m. These shelters were designed so tunnel users can evacuate the tunnel and wait inside shelters before being rescued through the evacuation tunnel. Henke and Gagliardi [18] mentioned that nearly all tunnel users close to the fire evacuated safely, either moving upstream or using one of the shelters. A truck driver that died during the fire left one of the shelters and returned to his truck, while another driver that died was found inside the tunnel several hundred meters downstream of the fire. Firefighters used the shelters often as a safe starting point to attack the fire [19].

Some of the findings from the Mont Blanc fire in 1999, were also reported during the fire in the St. Gotthard tunnel fire in 2001. Tunnel users close to the fire, were all aware of the situation, and most of them were able to reach one of the available shelters. Those downstream of the fire, between 300 to 600 m, were not aware of the fire and were surprised. Several died inside their vehicles or did not reach any of the available shelters in time [18]. Around 30-35 people were evacuated from the evacuation shelters. It was also reported that no smoke or heat penetrated into the shelters, although no specifics were mentioned on the fire resistance of surrounding constructions [18]. One reported issue, was that a door between the tunnel and the shelter closest to the fire jammed due to the high temperatures [19].

The 2005 Fréjus tunnel fire
The Fréjus tunnel was at the time a single-tube tunnel, with bi-directional traffic. It was equipped with eleven ventilated and pressurized evacuation shelters (ventilated via the fresh air duct) [20]. The distance between each shelter varied between 615 m–1716 m. The surface area of each shelter varied between 20-60 m², while all had direct access to the fresh air duct. The shelters were improved with thermal insulation and installed with doors with a 120-minutes fire-rating. The shelters had two
functions: 1) provide refuge for tunnel users, for a limited time, before being rescued, 2) provide a logistical zone for rescue services.

None of the evacuation shelters were used by tunnel users during the fire. A total of nine vehicles, with an unknown number of people, were located downstream the fire. Two people died while attempting to evacuate through the tunnel space, while the others managed to escape from the fire either by foot or by turning and driving out. It is reported that drivers of HGVs were picked up by lighter vehicles, indicating a cooperating behavior, which was also seen in the Oslofjord tunnel fire [3]. One of the reported reasons behind the shelters not being used, was a combination of poor visibility and marking of the shelters. On the other side, the shelters were a vital resource for the rescue services [20].

*The 2017 Oslofjord tunnel fire*

After a major fire in the Oslofjord tunnel in 2011, 25 evacuation shelters were installed around every 250 meters. These shelters are between 9-64 m² and can fit between 30-50 people. The shelters are monitored by the tunnel control center using ITV, as well as a door alarm. Every shelter is equipped with first aid equipment, blankets, and water. Shelters are supplied with 3 hours of air (either through its size or additional air bottles). The shelters are also equipped with information signs and equipment to communicate with the control center. They are designed to withstand a 200 MW fire for a duration of 3 hours. A dynamic wayfinding system is present inside the tunnel, directing tunnel users towards the closest shelter. This system has the possibility to exclude guidance towards a specific shelter if it is too close to the fire [3].

During the fire, two truck drivers used a shelter and survived. The investigative report mentions that these two most likely survived because of these evacuation shelters. Because of communication and video surveillance inside the shelter, rescue services were informed on the location and conditions inside the shelter in use. Based on this information, the rescue services could prioritize extinguishing the fire (after verifying no tunnel users were inside the tunnel), while postponing assistance to shelter users [3]. The users of the shelter only sustained minor injuries, caused by touching a warm metal door handle while opening the shelter’s door.

**Evacuation SHELTERS IN OTHER INDUSTRIES**

The use of evacuation shelters or similar solutions is an accepted solution within several other industries, such as the tunnelling industry, mining industry, oil & gas industry, and high-rise buildings. In the mining industry evacuation shelters are credited for saving more than 20 lives the last decade [21].

**Requirements for evacuation shelters in tunnels under construction**

The International Tunnelling and Underground Space Association’s guideline for refuge chambers in tunnels under construction [22] introduce minimum requirements and some important restrictions. The main emergency scenarios where tunnellers might use an evacuation shelter, are smoke and atmospheric contamination. An evacuation shelter is not designed to protect against direct exposure to fire. During a fire, tunnellers should not use the evacuation shelter but evacuate the tunnel. An evacuation shelter is not normally designed to resist the blast wave from a flammable gas explosion. Evacuation shelters should not be used as protection against flooding or inundation and is not designed to withstand a lining collapse, ground collapse or major rock fall. These limitations indicate that a shelter close to the fire, should not be used.
The guideline requires a performance-based approach to provide requirements for evacuation shelters (based on a risk analysis), but give some prescriptive requirements to ensure a minimal safety level:

- Occupancy time of minimum 24 hours.
- Placed around every active face and placed free from combustible materials.
- Safe distance from gas cylinders, explosives, and tunnel face.
- Provision of respirable air (air quality, temperature, humidity, air supply volume).
- Communication system.
- Internal temperature control, lighting, toilet, first aid kit and a water supply of 3 l/person.
- At least 0.5 m²/person of floor area, at least 0.75 m³/person of volume and at least 1.5 m headroom.
- Window of at least 150 mm.
- Door and escape hatch which can be opened both from the inside and outside.
- 1 kPa overpressure inside the room to prevent smoke spreading into the room.

There is also a requirement that regular training exercises should be undertaken, to make sure everyone is familiar with the use of the evacuation shelters on site.

**Provisions for underground electrical supply facilities or those inside mountains**

Norwegian regulations [23] and its guidance documents [24, 25] require the use of evacuation shelters for electrical power facilities where evacuation can be difficult or a secondary evacuation option is not possible (for example for underground facilities). These regulations give a combination of performance-based and prescriptive requirements:

- Placement should be assessed to provide a realistic secondary evacuation option.
- Designed as a fire compartment, smoke tight and should be able to resist an explosion.
- Equipped with 4 hours of air for the expected number of users, first aid equipment, and a communication system, to a control centre outside of the facility, with an independent power supply.
- Shelter size should be design for 1 m² per person the room is designed for.

**Provision of evacuation shelters or rescue floors in very tall buildings**

One of the most crucial challenges with high-rise structures is emergency evacuation. When a disaster occurs, it is impossible to evacuate everyone from these types of buildings to a single location due to the sheer quantity of occupants, as well as the physical strain to evacuate these structures can be-challenging to some. There are several strategies to evacuate high-rise structures: 1) full evacuation, 2) staged evacuation, and 3) delayed evacuation [26]. In the Hong Kong Code of Practice for Fire Safety in Buildings a refuge floor is defined as: “a protected floor that serves as a refuge for the occupants of the building to assemble in case of fire, for a short period of time, before reaching an ultimate place of safety” [27]. This means that this strategy would fall under the first category, full evacuation, as these refuge floors are only used as to rest and to provide rescue services an area for staging activities.

With this purpose in mind, it can be seen as a part of the escape route instead of an alternative evacuation possibility. But Chow and Chow [28] mention that their use can also be extended to a place of temporary safety, which would fall under category 3. The requirement in Hong Kong regulations is that the use of rescue floors (or refuge floors) should be connected to an ultimate place of safety by a route designed as a protected exit (as defined in Hong Kong regulations). Some other main features are:

- Net floor area for refuge, at least 50 % of gross floor area.
- Fire compartmentation from remainder of the building.
- Emergency lighting, clear signs to show its use.
- Any staircase passing through, should be discontinued, pass over part of the refuge area before continuing downwards.
- Open-sided above parapet height on at least two opposite sides to provide adequate cross ventilation.
Evenson and Vanney [29] present a summary of their design of the Burj Khalifa in Dubai. The traditional “Defend in place” crisis response strategy for super tall buildings, was modified for the Burj Khalifa with refuge floors, elevator-assisted evacuation, and life safety communication systems. The design is comparable to requirements in the Hong Kong Code of Practice [27]. Refuge floors are placed approximately every 25 floors, pressurized, and separated from the remainder of the building by 2-hour fire rated constructions. The difference can be seen is how these floors are initially used. In Hong Kong Code of Practice [27] these floors are intended as an area for those in need of a short break from evacuating the building. For the Burj Khalifa, these floors are used for a staged evacuation (second category) which could provide a more controlled evacuation of occupants. Occupants evacuate to their designated refuge floor, awaiting instructions before evacuating the building. These refuge floors also allow rescue services to coordinate the evacuation of the building. All refuge floors are connected to several protected stairwells, to provide multiple evacuation options if needed.

The SPFE handbook of Fire Protection Engineering expresses some concern on the use of refuge floors [30]. Some of the concerns are on whether occupants will evacuate to their assigned refuge floor or proceed to the closest refuge floor, which might cause overcrowding of some refuge floors. This again can cause the blocking of stairs for those that are meant to evacuate. Another concern is that these floors over time might be used as storage, which reduces available space and increase the fire hazard.

CURRENT KNOWLEDGE ABOUT DESIGN AND TECHNOLOGY ASSOCIATED WITH EVACUATION SHELTERS

In the event of a fire, the safety of tunnel users greatly depends on how fast they react and choose their escape route [31]. A delayed response or choosing not to evacuate can become fatal in prolonged fires in single-tube tunnels with longitudinal ventilation [17, 18]. On the contrary, during the shorter duration fire in the Gudvanga tunnel in 2013, delayed reaction/evacuation was mentioned as a factor which reduced injury to those on the smoke filled side of the tunnel [9]. This difference in outcome depends on many factors and points to major uncertainties. As concluded by the Norwegian Safety Investigation Authority [1, 9, 10], the outcome of the 2011 Oslofjord tunnel fire, as well as the 2013 and 2015 Gudvanga tunnel fires could easily have had a more severe outcome if certain factors had been different.

Being confined inside a room without a safe means of egress could make one uncomfortable for various reasons, including a fear of isolation or being trapped [32-34]. In order to minimize the risk of post-traumatic stress disorder (PTSD), it is important to provide users with a feeling of safety and control when designing an evacuation shelter [35]. Another important factor when designing an evacuation shelter and its supporting measures, is to ensure that people follow instructions and use safety measures correctly, which call for a human-centered design. There is generally a lack of knowledge on human behavior and experiences with the use of evacuation shelters in road tunnels. Some research on similar settings exist, like underground spaces and parking garages, which can provide some relevant insight when designing evacuation shelters [35].

Stress reactions and implications for design

Occupants involved in accidents tend to act rationally based on available information [36, 37] and clear information triggers faster response [38]. Still, experiencing a serious fire emergency inside a road tunnel is associated with stress, which may be defined as “something that causes a state of mental or emotional strain, tension, or anxiety; an adverse or demanding event, situation or circumstance” [39]. Stress is not unilaterally negative. The Yerkes-Dodson law, indicate that there is an optimal level of arousal to improve performance. A level of arousal too low, or high, affects performance negatively [40]. This is also referred to as worrying by others, which have documented that worry is positively correlated with the willingness to evacuate [41-44]. Worrying can prepare someone for future events by creating mental scenarios or images [45]. When evacuating from a tunnel fire, one can assume that the level of arousal is high. This implies that reducing stress is an important feature for an evacuation shelter, as well as reducing the feeling of being trapped or isolated (as mentioned earlier). The degree of perceived control and coping mechanisms are linked to causing stress [32, 46, 47].
To reduce stress, measures are to be taken to increase a feeling of control and support different coping mechanisms. LeBlanc [48] mentions the importance of understanding that stress is a personal and subjective response and proposes three main coping strategies: 1) Problem-focused coping (addressing the source of stress actively), 2) Emotion-focused coping (addressing emotional distress, rather than the actual cause of stress), 3) Avoidance coping (avoid or distract from the cause of stress). Sul and Fletcher [49] mention that there is no clear conclusion on which strategy is most efficient, as each strategy might be most effective under certain conditions. The use of an evacuation shelter provokes a passive behavior, as its aim is to provide a safe place awaiting rescue. This might indicate that an emotion- and avoidance-focused coping will be important for the design of shelters.

SINTEF [50] performed a full-scale laboratory study using VR on simulated 3D-models of evacuation shelters. The focus of the study was to gain insight on how different designs affect the perceived level of safety of test subjects. A good level of lighting was seen as an important factor, consistent with earlier research. The level of lighting also contributed to the room being perceived as larger. The use of blue lighting on the ceiling reduced stress levels as this was seen as a simulated connection to the outside. Separations between different functions was preferable consistent with Kaplans preference model [51]. The placement of the communications system was important. Its placement next to the entrance door improved visibility and reduces confusion.

Based on a literature study by Liven [35], the following design guidelines for evacuation shelters were recommended:

1. The evacuation shelter should be designed with consideration of the reduction of claustrophobia and a feeling of entrapment or isolation; Soh et. al. [52] mention lighting as an important factor to reduce a claustrophobic reaction, while Roberts et. al. [33] mention avoiding crowding as an important factor. Other architectural factors like the shape of the room, partitioning and seating arrangement can increase a feeling of control [46].

2. The evacuation shelter should provide people with adequate information about the situation; Ringstad [46] mention that information can increase the perception of control, while Proulx [53] mention that information can reduce stress and motivate for correct behavior.

3. The evacuation shelter should provide means to communicate with the outside world; Providing two-way communication during an unfamiliar event in an unfamiliar environment is highly desirable [46]. This will provide the possibility to provide information, but also provide the control center with information about the incident and/or room users.

4. The evacuation shelter should be designed to meet people’s expectancies for safety; Ursin and Eriksen [54] mention that a possible stress factor might be when expectancies are not met

5. The evacuation shelter should provide people with means to cope with their stress and fears.

**Communication facilitating evacuation**

Numerous studies demonstrate that preparation, e.g., training and information, leads to improved performance in emergency evacuation situations [55-58]. Vatsvåg [59] confirms that knowledge about safety behavior and equipment in tunnels, along with trust in authorities, had a positive influence on peoples’ perception of safety when driving through tunnels. The importance of pre-accident communication is illustrated by the explanatory timeline model [60]. The model is useful for identifying the information needs of different tunnel occupant groups in case of evacuation. As shown in Figure 1, the evacuation process starts before the incident has occurred and indicate an important time space to inform tunnel users about fire risks in road tunnels, relevant cues, and appropriate actions to take in case of a fire. Preparing the tunnel users before the accidents could lead to improved performance in an emergency event.
Figure 1: The RSET model (top) and the explanatory timeline model (bottom)

Once inside the tunnel, the explanatory timeline model claims that occupants need to go through the process of discovery, recognition, and evacuation action.

**Discovery** implies that tunnel users need to acknowledge a change from a normal situation to an emergency. Such acknowledgement, and the time it takes, depends on the users’ involvement in the situation and the detection and notification technologies in the tunnel. When detection and notification systems are not present, the discovery phase often ends when occupants see fire, smoke, or stopped vehicles. **Recognition** is about making sense of the received cues to adequately understand the situation, which is strengthened by providing ample means of notification [38]. Appropriate information and training before an incident increase awareness of the meaning of different cues and a quicker interpretation. Social influence is also an important cue that affect the behavior of other tunnel users [31, 56], indicating that people seek reassurance through the actions of others, which may have both positive and negative effects in a tunnel emergency. The **evacuation action phase** involve movement toward a safe location or an attempt to address the threat directly (e.g. extinguish the fire). It has been shown that evacuation systems can be valuable for tunnel occupants during the evacuation action phase [31, 56, 61], but knowledge about evacuation procedures in road tunnels could arguably improve the effectiveness of existing evacuation systems. The correlation between the people’s trust in the government and their willingness to comply has also been studied in several studies, showing an increase in trust increases someone’s willingness to comply with recommended actions [62-64]. Training on required behaviour and knowledge on equipment inside a tunnel, has been shown by Vatsvåg [59] to increase the perceived safety. Experience from emergencies and research suggest that a significant amount of time is spent in the pre-movement phase [60]. This indicates a major potential for enhancing self-rescue processes through communication before and during emergencies. According to Sattler et. al. [65], past experiences contribute to disaster preparedness. When taking this statement into account, it is understandable that those who live around or travel through road tunnels more frequently are more likely to react to evacuation warning signs than those who have no experience with such [65, 66].

**Tunnel users’ ability to find evacuation shelters**

Experiences from the Mt. Blanc and Fréjus fire, reported herein, show that tunnel users do not use evacuation shelters even if such facilities exist. To gain better understanding of this phenomenon, SINTEF [67] performed a laboratory study using VR on evacuation towards evacuation shelters during a simulated fire in a single tube road tunnel with bi-directional traffic. The study is especially focusing on the impact of distance between evacuation shelters, comparing a situation of 250 and 500 m, and whether the test subjects can find the entrance/emergency exit towards the evacuation shelter.

During the tests several measures were used to guide towards the emergency exit: signs, both a static and dynamic lighting system and an acoustic system. The study indicate that greater distance may increases the evacuee’s uncertainty about their ongoing actions. When the distance between shelters was 500 m, it was found that 46 % turned around, thinking that they may have passed an evacuation shelter. Some even turned around several times. Placing shelters on both sides of the tunnel space was effective, as everyone eventually found a shelter regardless of used wayfinding system.

The test also indicate variances in what different safety measures affords [68-70] to the evacuee. For instance, using an arrow pointing downwards to indicate that an evacuation shelter is placed on the other side of the tunnel, was perceived as confusing by many. Placing a handrail and/or continuous
lighting system on the side of the evacuation shelters, led to faster reaction and higher percentage of correct behavior. Using an acoustic system above the door to the evacuation shelter, made 97% find this emergency exit on the other side of the tunnel. It is also reported that 20% of the participants tried to open all available doors, including doors to technical rooms, which indicate a potential to improve the affordance of emergency exit doors.

**DISCUSSION**

We should not repeat mistakes of history. There are similarities between the development of safety strategy in Mt. Blanc and the Norwegian Oslofjord tunnel. In both cases, serious fires led to construction of evacuation shelters, and later fires in both tunnels show that the shelters had positive safety effects. Still, we also need to keep in mind the trauma of two people losing their life in what is to be considered a safe area in the Mt. Blanc tunnel. Similar negative experiences are not available in Norway, but should we exclude the possibility of this happening in the future? Being aware of the consequences of the Mt. Blanc fire, we are obliged to ask ourselves what such a potential trauma would mean for the Norwegian attitude towards evacuation shelters. It is obvious that the positive effects experienced in both Mt. Blanc and Oslofjord is not due to evacuation shelters without escape routes to the open. Shelters with escape routes to the open, such as the St. Gotthard tunnel, would have a similar, and possibly even better, effect. However, the costs are very different between the two concepts, at least when considering the large number of Norwegian tunnels that might benefit from improved evacuation systems. The question then becomes whether we should accept the existing situation, where no means of escape besides the entrances from the tunnels exists, or whether evacuation shelters, with or without escape routes to the open, is an appropriate measure to consider as part of the tunnel safety strategy?

**System perspective**

Njå [71] emphasizes that the evacuation shelter is just one element in an evacuation system. All the system’s elements must appropriately interact to produce safety in each situation. For an evacuation shelter and all its supporting measures to produce the required results, the design needs to support tunnel users to make the choices as intended in the safety design or otherwise required by the situation. Several fires have shown that people reacted differently from what was expected from them. The red flashing lights and physical barriers at each tunnel entrance are to show oncoming traffic that the tunnel is closed (some tunnels don’t have a physical barrier), but the fire in the Oslofjord tunnel in 2011 showed that these signs are not perceived as threatening enough to produce the wanted reaction [1]. On the other side, creative and cooperative behavior also emerges in emergencies, e.g., drivers picking up other evacuees or tunnel operators guiding evacuees to spaces behind the tunnel wall [1].

There are great uncertainties associated with what emergency scenario a tunnel user could be exposed to, and quite a few relevant decision options to consider in such a situation, e.g.: stop or continue; notify external parties (SOS telephone or own mobile phone); assist in accident management, e.g., fire extinguishment and/or help people in acute danger; attempt to escape from situation and/or evacuate the tunnel in one of two directions, either by foot or by car, using the safety measures available in the tunnel, and; assist or instruct others in the evacuation process. The decision making is undertaken in a stressful and dynamic situation. Considering that most tunnel users are inexperienced in tunnel emergencies, the need for high quality decision support is obvious.

Decision support is not just information or recommendations provided to the tunnel user before and/or in emergency situations. It is also how the tunnel design affords and signifies certain behavior to the user. If evacuation shelters are integrated as an element of the evacuation system, the shelter’s design and supporting systems need to provide tunnels users with a clear situational awareness for them to adapt behavior accordingly. This applies for the process of selecting and finding evacuation shelters if the situation calls for such actions. It also applies to the following situation when people are waiting inside the shelters, where the design need to produce a feeling of trust that they are safe and that users will be rescued eventually, as well as rescue services need to receive information on the use of these rooms during an incident.
Do tunnel users find emergency shelters?
Both the Mt. Blanc and the Fréjus fire indicate that people have trouble finding evacuation shelters. The Mt. Blanc investigation report state that usage of evacuation shelters is unlikely unless tunnel users are led by qualified personnel [17]. This is hardly an argument against evacuation shelters without escape routes to the open, as it also applies to shelters or cross-passages leading to escape routes to the open. This is generally a challenge that needs a solution in any case. On the one side, there are examples of people staying in their vehicle, and on the other side, there are examples of people using the means of egress inside road tunnels in emergency situations (St Gotthard, Mt Blanc, Oslofjord). In 2018, SINTEF, Lund University and the NPRA [50, 67] conducted experiments using VR-simulator to investigate whether people would leave their vehicle and use evacuation shelters. The conclusion from the experiments is that there are technology available and design solutions that improves wayfinding in road tunnels. Twenty years of technology development, implies that today’s potential for providing decision-support and human-centered wayfinding systems in road tunnels is substantially different than the early 2000s. Such system could, first and foremost, prevent the need for using the evacuation shelters by prompting early actions where tunnel users are not threatened by smoke or other hazards.

For those evacuating through a smoke-filled tunnel, reaching a shelter might give an initial feeling of relief (or reduction of stress). But in general, it is well established that underground spaces are viewed negatively due to associations with phobias, past experiences or cultural reasons [33, 52]. Ringstad [46] mentions that the perceived level of control is one of the reasons for the negative attitude towards underground spaces. Single-tube road tunnels usually only provide one way in and one way out, which can limit the feeling of control on reaching a place of safety. Communication with the outside world with updated information about the incident and their rescue could reduce stress levels by providing a perceived increase of control, as mentioned by Ursin and Eriksen [54] and Gandit et. al. [72]. It is also likely that those evacuating a tunnel fire might be injured, like those during the Oslofjord tunnel fire in 2017 where the entrance door to the shelter was made of steel and caused burns to those who opened the door [3]. Providing first aid equipment might also aid to a perceived level of control. In situations that calls for evacuation shelters, the supporting systems should make this evident for the users both in terms of finding the shelters and staying in the shelters.

Is it relevant to compare with other industries?
In this and other studies the prohibition of evacuation shelters in road tunnels are compared with other societal areas where evacuation shelters are allowed. In many cases, evacuation shelters without an escape route to the open are used in a professional setting, e.g., tunnel construction, mining, and underground power plants. The potential users are generally a more homogeneous group than road tunnel users and there are requirements for training and possibility of “informed consent” in taking part in an activity that may call for the use of evacuation shelters. If we look to skyscrapers or earthscrapers, the group of users becomes less homogeneous. An important difference, though, might be the control associated with fire hazards. In Norwegian road tunnels, there are practically no restrictions on transport. This means that any combination of fire load and occupant load is possible, insofar the vehicles are approved for the roads. Experience with different types of buildings over the years, indicate that uncertainty associated with maximum fire and occupant load is limited. It is also common to install automatic extinguishing systems that effectively controls fire development. Still, there is the possibility that the fire load exceeds our expectations, that an automatic extinguishing system fails, or that there is a terrorist attack not accounted for during design. There is always some uncertainty, or in other words, a small probability that a catastrophe could occur. It is not necessarily relevant to compare the technical solutions for refuge floors in skyscrapers and evacuation shelters in road tunnels, but its functional requirements could be similar. In essence, it is about providing an opportunity for self-rescue when everything else fails.

Why not just build shelters with escape routes to the open?
From a safety perspective, it seems obvious that constructing shelters with escape routes to the open is preferrable over shelters without. However, improving the safety of road tunnels is a matter of both economy and safety, and several other issues. As stated in the introduction, there are more than 500 single-tube road tunnels with a length above 500 m in Norway, and nearly 100 of these are more than
3000 m. Improving the evacuation systems in these tunnels is extremely expensive in the first place. The traffic volume is often low, and do not justify construction of a parallel tube. A separate, smaller, tunnel for egress is a possible solution, but is also an expensive solution. Construction would require intervention with, and adoptions along, the full length of the tunnel. Evacuation shelters are more localized measures, although space is needed for the advancement of cables for electrical power and communication systems, as well as ventilation ducts (depending on the shelter design). The major issue should not be to construct evacuation shelters without escape routes to the open at any cost. However, if it boils down to a question of doing nothing to improve means of egress, versus constructing shelters without escape routes to the open, shelters should be seriously considered. Also, if it boils down to a question of improving a few tunnels with separate evacuation tunnels, versus many tunnels with evacuation shelters, the latter should be seriously considered.

Fundamentally, the decision to implement, and how to design, evacuation shelters should be part of the safety management strategy. If tunnel managers implement an effective safety management system, the design of evacuation shelters becomes a matter of balancing road use scenarios (load) with protection measures (capacity). The degree of protection becomes a function of the constraints governing the potential load scenario, e.g.; restrictions on HGVs or dangerous goods; active fire protection measures, such as a fixed fire-fighting system, or; rapid and effective response from the fire and rescue service. Without imposing any constraints to balance the load scenario versus protection capacity, there should be major protection requirements for the design evacuation shelters. If there are effective constraints controlling the load scenario, less protection might be needed for the evacuation shelters.

**Increasing the distance for improved protection?**
Increasing the distance between the fire and the evacuation shelter generally implies lower thermal loads on the construction. For fires lasting for hours or even days, the thermal load becomes an important issue. Ingason et. al. [73] performed several fire tests in the Runehamar tunnel in 2003. Based on these tests, Eq. (1) was proposed to calculate the temperature downstream of a fire:

$$\frac{\Delta T_c(x)}{\Delta T_{c,\text{max}}} = 0.57 \exp\left(-0.13 \frac{x}{H}\right) + 0.43 \exp\left(-0.021 \frac{x}{H}\right)$$

Where $\Delta T_c(x)$ is the excess ceiling gas temperature at $x$ (°C), $\Delta T_{c,\text{max}}$ is the maximum excess ceiling gas temperature (°C), $x$ is the downstream distance from the fire source (m) and $H$ is the tunnel height. The equation was verified using several large-scale fire tests, including results from the four Runehamar fire tests, the Memorial fire tests, as well as one model-scale test. This equation shows an exponential drop of maximum gas temperature $x$ meters downstream of a fire. The equation implies a 50 % drop in maximum ceiling temperature when $x/H$ is increased by 10. This implies that an evacuation shelter further away from a fire, would take on a much lower thermal load compared to the evacuation shelter closest to the fire. This effect was seen in practice during the Mt. Blanc tunnel fire in 1999, where rescue room 20 lasted for around four hours before failing (while being designed for two), while rooms further away were used for up to eight hours without failing.

When the fire-rated construction cannot be designed to withstand the thermal loads from a fire, there is the option of providing access to clusters of, say, two or three interconnected evacuation shelters, or even an escape route to the open if no other solution is acceptable. This would keep the distance between emergency exits limited within the tunnel space, while allowing for the movement of shelter users if needed, and thereby increasing the distance from the fire source.

**How could evacuations shelters affect rescue services efforts during tunnel fires?**
In the Oslofjord fire in 2017 it was confirmed that two HGV drivers were present and currently safe in one of the evacuation shelters and there were no tunnel users downstream from the fire. Based on this information the fire and rescue service could prioritize extinguishing the fire. In the Fréjus fire, tunnel users did not use any of the rescue rooms, but they were essential as logistical zones for the fire and rescue service. It should be a matter of further studies to investigate how evacuation shelters could affect existing strategies for the fire and rescue services, in combination with the smoke management strategy.
The study should take into consideration the varying response time in different regions, competence and capacity limitations, firefighting equipment, etc, against the safety design of the road tunnel.

CONCLUSION

This paper explores the history of evacuation shelters in single-tube road tunnels. After gaining a poor reputation after the Mt. Blanc fire in 1999, and the following prohibition through the EC-directive 2004/54/EC, there is now emerging interest to consider evacuation shelters as an element in the evacuation system to improve self-rescue challenges. The NPRA has installed evacuation shelters in the Oslofjord tunnel as a preliminary measure until a second tube is built. After ten years of operation the shelters may have saved two lives. Additionally, the NPRA is involved in two pilot projects for establishing evacuation shelters in road tunnels on the regional road network. The purpose of the pilot projects is to gain experience with the design and use of evacuations shelters and strengthen the knowledge base concerning their effect on safety.

The UNECE expert group, established in 2000 to develop a recommendation for minimum requirements for safety in road tunnels, state that “there is no such thing as absolute safety in traffic, for it is in the nature of traffic that incidents will occur, some of which have grave consequences for people, the environment and property” [13]. Presently, the statistics of fatalities due to major fires in Norwegian road tunnels is comfortable reading. None of the major fires since 2011 resulted in fatalities. Still, they were strong reminders of the catastrophic potential inherent in road tunnel systems.

Previous events are also reminders of the complexity inherent in managing major fires in single-tube bi-directional road tunnels. Situational awareness, communication and prompt actions are critical for appropriate interactions between tunnel users, tunnel operators and emergency responders. In many Norwegian road tunnels, the preconditions for such interactions are lacking. There are no automatic detection systems, no surveillance systems or communication systems that target specific tunnel users. Generally, there is a need to improve the preconditions for self-rescue in many Norwegian single-tube road tunnels through improved evacuation systems. Considering the number of tunnels that might fall under this category, it is evident that there is a need to develop cost-effective solutions. Therefore, we consider evacuation shelters without an escape route to the open as a potential element of an evacuation system in single-tube road tunnels. The following are a set of selected recommendations for follow-up actions based on the ongoing study:

- **Adopt a system perspective:** it is inappropriate to discuss requirements for evacuation shelters without considering the system which it is a part of. The goal is to balance system elements against each other. For instance, the response time and capacity of the local fire and rescue service should affect how the evacuation system in the tunnel is designed and managed.
- **Implement active safety management:** a system perspective on safety implies that safety is a control problem. To maintain an appropriate level of safety within the tunnel, active safety management is required as a response to changing conditions.
- **Understand humans in road tunnels:** The tunnel users are the most important assets to protect. Successful safety management implies a better understanding of, e.g., human responses to emergency situations and cues in road tunnels; tolerability to toxic gases, heat, and pressure waves; psychological effects of prolonged stays in confined spaces; the tunnel design’s affordance to humans.
- **Develop design scenarios:** there is a need to better understand what performance is required by the evacuation system under different situations. Fire is an important event to consider, but other events should also be included.
- **Understand barriers to change:** In this study, we have investigated the foundation for prohibiting evacuation shelters. Presently, we seem to understand where the prohibition comes from, but there is yet a potential to understanding why.
REFERENCES

7. Tunnel Safety Regulations for County roads, Regulations on minimum safety requirements for certain tunnels on the County road network and city roads in Oslo (in Norwegian). 2015, Norwegian Ministry of Transportation.
12. EC, Proposal for a directive of the european parliament and of the counsil on minimum safety requirements for tunnels in the Trans-European Road Network. 2002.
22. ITA, Guidelines for the provision of refuge chambers in tunnels under construction. 2018.


59. Vatsvåg, N., *A study of the importance of various factors in relation to perceived safety in tunnel driving - a study based on focus group interview and a survey among Norwegian road users (in Norwegian)*. 2016, University of Stavanger (UiS).


Analysis of spatial and design factors for users' acceptance of rescue rooms in road tunnels: An experimental study using Virtual Reality

SINTEF Community, Dept. of Mobility and Economics, Trondheim, Norway

ABSTRACT

In emergency situations in road tunnels in which vehicles cannot exit the tunnel, evacuation on foot might be the only alternative. In such scenarios, self-rescue using rescue rooms might provide provisional safe shelter to people trapped in tunnel emergencies. Yet, a stay in a rescue room with unsatisfactory design might contribute to higher levels of distress to the users. The present study examines five different designs of rescue rooms via virtual reality, to study how the different design and spatial factors might affect users' acceptance of such rooms. Thirty-seven people participated in the study, in which both objective (Eye-tracking and heart rate measurement) and subjective data was collected. The results suggest that two factors (i.e. lighting and use of separate areas) increased the feelings of safety and users' acceptance of the rescue rooms. In particular, a container room with blue lighting and separate area for injured people was the favourite among the study participants. The outcomes of this study show that design and spatial factors are crucial if rescue rooms are to be implemented and used in road tunnels.

KEYWORDS: rescue room, road tunnel, self-rescue, spatial design, virtual reality.

INTRODUCTION

Road tunnels are an important part of a country's road infrastructure. They connect different geographical locations together, reduce driving travel time and are important for transport policy. Norway are among the countries that have a large amount of road tunnels. The complexity of the country climate and topography (e.g. cold weather, fords, glaciers, and very steep mountains) are one of the reasons Norway builds many road tunnels, as it improves the road system, with more tunnels opening each year. Indeed, Norway has over 1100 existing road tunnels, 50 to 60 road tunnels are currently under construction and 150 to 200 are under planning [1].

Although there is no doubt regarding the benefits that road tunnels have for the transport system of a country, there are also risks and challenges related to their operation. Tunnels can become a trap under emergency situations. Due to its enclosed environment nature, tunnels can concentrate heat, smoke or gasses that might arise due to vehicle collisions, fires or escape of hazardous liquids or gasses. In special cases in which vehicles cannot exit the tunnel, evacuation on foot might be the only alternative. Yet, challenges arise when evacuation to the tunnel entrance/exit is not possible due to the tunnel length and/or blocking elements. In a period of 6 years (between 2011 and 2017), Norway faced 6 tunnel fires with potential catastrophic consequences [1, 2]. As a consequence of this, the Accident Investigation Board of Norway (AIBN, Statens Havarikommisjon) carried out an investigation of the tunnel fires, in which they indicate that 'self-rescue conditions have not been present in the case of a number of the fires', and that is crucial to 'discuss what conditions must be in place to allow self-rescue to work'. Not only the AIBN points out the need for self-rescue measures,
but also the Road Inspectorate (Vegtilsynet) and the Norwegian National Audit (Riksrevisjonen) call for measures that can provide conditions for self-rescue in tunnels.

Rescue rooms are one of several measures that the Norwegian Public Roads Administration might consider for improving the conditions for self-rescue, particularly for low traffic single-tube tunnels, where it is not possible to build a new parallel tunnel. Previous feasibility studies have indicated a need for research in rescue rooms, as these are a relevant measure to safeguard the principle of self-rescue [3].

Although rescue rooms are not permitted under current European and Norwegian tunnel regulations, the Norwegian road authorities together with research institutions are exploring the possibility of having rescue rooms as a self-rescue measure for improving safety in road tunnels. For the purpose of this study, rescue room is defined as: ‘a room in which people can seek refuge and find protection from danger. The room is used temporarily in crisis situations, until the danger is over, or one is rescued by rescue teams (assisted rescue). Rescue rooms have a fixed and permanent position’.

Yet, how people react to staying in rooms underground is individual and influenced by social and psychological conditions. An emergency situation where people who do not know each other are crowded together and must share a limited area, can be very challenging for people without knowledge of each other or without education or training in the use of safe rooms. There may be people of different age groups, genders, and nationalities. Some may have burns, difficulty breathing or other physical injuries. Measures that can counteract unfortunate aspects of a stay in an underground room then become even more important. According to recent literature studies, the feeling of danger and of being trapped is one of the biggest challenges people experience with staying in rooms below ground level. During longer stays below ground, problems are experienced in relation to isolation and monotony [4-6]. These are studies where the duration can be several months, and they are therefore not representative of shorter stays (up to 3 h). The knowledge of what creates unwanted emotions even during short stays is thus needed.

Aspects of design, functionality and furnishing of rescue rooms can give an indication of what can play a role also for shorter stays. Feelings of isolation and monotony are linked to a lack of window as an obvious way out, and to limited visibility to the outside world. Concerns about fire and water leaking in or the rock space collapsing are also frequently mentioned as a concern [7]. Rooms below ground level are also more easily perceived as cramped and oppressive, even for shorter stays. Visible pipes, as well as the smell of mould and dust can contribute greatly to a negative basement feeling [8].

Research studies have identified important design aspects in underground rooms that have been shown to influence feelings of safety and perceived comfort [1, 4-6, 9]. These include i. entrance zone, ii. perceived ceiling height, iii. lighting, iv. air inflow, and v. communication with the outside world. To the authors’ knowledge, there is no experimental study examining different design factors in which the users can test these factors in full-scale in order to evaluate their acceptance. This lack of effort leaves a thin body of knowledge about design and spatial factors that can contribute to a more pleasant stay in rescue rooms, and at the same time contributing to an adequate use of the rooms.

Although in principle, the EU’s tunnel directive does not allow such rooms without access to the open air today, the directive has an opening for innovative solutions that can provide an equivalent or higher degree of protection than current solutions. Thus, if rescue rooms are to be implemented in road tunnels, it becomes necessary to perform testing of rooms that are accepted by the users and provide a feeling of safety. This paper presents the results of an experiment designed to answer the following research question: Which spatial and design factors are important for users’ acceptance of rescue rooms?

This paper is part of a wider study divided in two parts. The first part addresses the use of visual and acoustic measures for guiding evacuations to emergency doors which suppose either passage to the
outside or to rescue rooms (presented in another paper by the authors). The second part explores the users’ acceptance of different rescue rooms with varying spatial and design factors (the present paper).

**METHOD AND PROCEDURE**

To address the logistical constraints that studies at full-scale usually present (e.g. construction of full-scale rooms with different design in a road tunnel, carrying both challenges related to time and resources), the present experimental study was conducted making use of virtual reality (VR). The experimental sessions in this study made use of a within-subjects design, meaning that all the participants evaluated all the tested scenarios. This allowed to eliminate the variance between participants, meaning that the individual differences were not linked providing more statistically powerful results. Moreover, the experimental sessions occurred at the Climate Chamber of the SINTEF Work Physiology Laboratory, in the city of Trondheim, Norway, during March 2019. For brevity, a more in-depth exploration of the experimental setup, the VR implementation, and overall project setup can be found in [10] (Norwegian only).

**Stimuli**

The SINTEF Work Physiology Laboratory has an ISO certified climate chamber with 32 ºC and 70 % humidity. These conditions were selected taking into consideration parameters such as the heat and sweat each individual can generate, and the volume of the tested rescue rooms. Considering that every fire event is affected by diverse circumstances and factors, it is not possible to estimate whether the temperature and humidity levels stabilise at such levels when reached or they continue increasing. Such calculation was outside the scope of the study. However, these conditions represent a stay in a rescue room during a demanding scenario, in which the room temperature with the intended size and capacity of a maximum of 50 people will quickly rise to around that temperature and humidity under insufficient ventilation. The capacity was considered based on the researchers’ assumption that a rescue room could accommodate a bus load of passengers.

For the development of the rescue rooms, a focus group consisting of six people (3 male, 3 female) was created. The focus group sought to have members of different age groups and backgrounds. The goal of the focus group was to identify consensus in design factors for the creation of rescue rooms with a low user threshold and future acceptance. Three different factors were identified as preferred by the users: ceiling height (spatial factor), room elements (design factor), and informative and communication elements (design factor). For brevity, the selection process of the rooms are not described in depth in this paper; however, this information is available from the authors upon request. Based on the results from the focus group, five different scenarios depicting rescue rooms were modelled and created as virtual environments. These five rescue rooms were called Basic room 1, Basic room 2, Basic room 3, Container room 1 and Container room 2, see Figure 1. The study considered these rescue rooms as placed in a traffic single-tube tunnel. The five rescue rooms maintained the same dimensions in regard to width (5 m) and length (10 m). The height for Basic room 1 and both Container rooms was of 2.4 m, whereas basic rooms 2 and 3 presented a vaulted ceiling design with the lowest and highest point of 2.4 m and 3.15 m for the Basic room 2 and of 3.25 m and 4.75 m for the Basic room 3, respectively.

All the simulated rooms were dimensioned for 50 people. The lighting settings of the 3D models were experience-based and decided to achieve a design-wise lighting level for each scenario, i.e. these were not taken from actual light definitions from light manufacturers. Thus, the study does not entail any guidance for or against the use of specific light fixtures, but rather provides a guide to particular light scenarios for further research.

In addition, different elements were simulated in the rescue rooms, including speakerphone/telephone for road and traffic control centre, first-aid kit/cabinet on the wall, water source, folding seats along walls and centre row, toilet (portapotty-style in one corner), CCTV placed in the room, and different wall signs showing instructions for use of the telephone or first-aid kits. It is important to indicate that the telephone was of a public type, i.e. it consisted of a speaker that could be heard by everyone in a
similar room, and a screen that allowed to see a person from the road and traffic control centre. A screen connected to the telephone was available only in Basic Room 3 and Container Room 2. The speakerphone was placed on the wall to the left of the front door of the rescue rooms in all the basic rooms, while it was placed straight ahead in both container rooms.

The stimuli was studied through the use of full-scale laboratory simulation with a walking platform in combination with virtual reality (VR) headset and 3D model of a Norwegian road tunnel, see Figure 2. This provided a realistic reproduction of the scenarios, correct depth vision, realistic walking speed, as well as great flexibility in the 3D model for use in VR regarding the design of scenarios and experimental parameters. A Head Mounted Display (HDM) with a built-in eye-tracker was used to document what people focused on for how long and how often. The focus was on the evaluation phase which started when a participant leaves the vehicle to evacuate.

![Screenshot views of the five scenarios (rescue rooms) used in the study: [a] Basic room, [b] Basic room 2, [c] Basic room 3, [d] Container room 1, and [e] Container room 2.](image)

**Evaluated parameters**

The study made use of a mixed research design, encompassing both objective and subjective parameters. The objective parameters included:

i. registration of participants' behaviour, in which the participants were asked to perform different tasks such as: finding the telephone and conduct a conversation with the Road traffic control center (VTS for its acronym in Norwegian), finding first-aid kit and try to help the (simulated) injured people. The registration of the behaviour was used as an important KPI, reflecting how safe or how stressed the participants felt during such situations.

ii. collection of physiological data, in which the Heart Rate Variability (HRV) was registered as a means to examine whether the participants experienced stress during the experiments. According to research in psychophysiology, variations in heart rate appear to be associated with recent experiences of emotional stress. This has been found to be independent of a
person’s physical form and how one experiences anxiety [11]. The heart rate measurements were performed using a POLAR RS800CX wrist heart rate monitor.

iii. Eye-tracking data, in which the Tobii’s eye-tracking system included in the HTC Vive VR headset was used to record what the participants focused on, how many times and for how long.

The subjective parameters included the room preference among the five alternatives and the participants’ evaluation of the perceived safety of each rescue room. To this end, a questionnaire survey was developed considering five variables, evaluated using a 5-points Likert scale, from (1) Strongly disagree to (5) Strongly Agree. The five variables with their respective statements were: Appearance (‘The rescue room looks good’), Feeling of safety (‘It feels like a safe place to be’), Placement of speakerphone (‘I like the location of the speakerphone’), Lighting (‘I like the lighting of the room’), and Room acceptance (‘I would easily accept to sit in this room for a couple of hours’).

Figure 2  VR equipment used in the study. Left: VR walking platform, Right: VR headset with eye-tracking system incorporated.

Participants
The participants in the study were recruited via announcements on social media and through SINTEF’s network. Efforts were made to recruit participants aged 15-65 with different ages, genders and cultural backgrounds. Each participant spent approximately two hours completing the study. A total of 44 people participated in the study, of which 18 were women and 26 were men. It is important to point out that although 44 people participated in the experiment, the final sample size consisted of data from 37 people. Of the 44 people who participated, 3 people had to stop the experiment due to discomfort connected to the use of VR, and complete data from 4 people could not be stored due to technical errors. The final sample size had an average age of $M = 34.5$ ($SD = 12.7$). More than half of the participants (56 %) reported to have a higher education at university level. While 99 % of the participants reported not to have a reduced hearing, 54 % of the participants reported to have reduced vision. However, this was not considered critical as the participants who reported to have reduced vision used either glasses or contact lenses. The participants who used glasses reported not to have felt any discomfort related to the use of glasses together with the VR headset.

Experimental procedure
The participation in the experiment was voluntary. Each participant was welcomed to the laboratory, where information about the study was provided, and the participant had the opportunity to ask questions. The participants who wished to participate, signed a consent form. First, each participant was asked to fill out a pre-test questionnaire, containing questions about demographic information. After filling out the questionnaire, the participant was shown an introductory film on how to get in and out of the walking platform, as well as how to walk and move using the walking platform.
participant was helped to get on the walking platform, offered time to get used to walk in the platform, and was helped to adjust the VR glasses.

After the participants mastered the walking platform, the implementation of the actual scenarios began. All five scenarios were run and tested for all participants, following a randomization principle. There were short breaks (2-5 min) between the scenarios. Within each room, the participants were asked to complete different tasks (see section 2.2). The time to complete each task was controlled and eye movements were recorded via eye-tracking. The tasks were:

- To open the door to the rescue room,
- To find a telephone and carry out advice from VTS (via audiovisual speaker/telephone),
- To find first aid equipment,
- To pick and place a bottle,
- To pick and place a blanket, and
- To try to help the injured.

Although the same tasks had to be performed in all the rooms, the order of these was varied. The participants could make their own decisions, i.e. they were free to talk to VTS first to get information and then help the injured, or help the injured first and then communicate with VTS. It is important to point out that one simulated injured person could talk and ask for help: ‘I’m freezing’, ‘I’m thirsty’.

After completing all five scenarios and tasks, participants completed a Post-test form, in which they had to rank the evaluated rescue rooms and answer the scale questions about their opinions about the rooms, see section 2.2.

Each participant had 20 min as a maximum time in each of the scenarios, regardless of whether they had completed the tasks or not. Each participant received two cinema tickets as compensation for participating in the study.

RESULTS

This section presents the results of both the objective and subjective parameters evaluated in the study. It is important to notice that the results are summarized for brevity and not all the graphical results (e.g. box plots for each eye-tracking analysis and histograms for each subjective evaluation in each rescue room) are shown here. The findings concerning the registered behaviour and completion of tasks are given as part of the Discussion. An initial overview of the findings can be found (in Norwegian only) at [10].

Physiological data

The results from the physiological data related to HRV shows the distribution of the average heart rate the participants had when they entered the rescue room until they had completed the last task, see Figure 3. Although it does not appear that there were large differences between the rooms, the results show that the participants had a significantly lower heart rate in Container Room 2, where it was likely that they experienced less stress compared to the other rooms. Upon closer analysis of the maximum registered heart rate at the same time interval (from the participants entering the room until they have completed the last task), Figure 3 shows that both Basic room 2 and Basic room 3 affected the heart rhythm and thus the stress level of the participants to a greater degree than the others the rooms. Figure 4 shows a visual indication that Basic room 2 obtained the maximum heart rate of all the rooms.

The y-axes of Figure 3 and Figure 4 show mean RR-interval, and maximum RR-interval, respectively. The RR-interval is the distance between two identical points with successive electrocardiogram waveforms. This duration is divided into 60 to calculate the heart rate in beats per minute (BPM).
Figure 3  Average heart rate from the participants entered the room until they completed the tasks.

Figure 4  Maximum heart rate from the participants entered the room until they completed the tasks.

Eye-tracking data
Three factors were analysed with the eye-tracking data. This was done in order to evaluate the type of information the participants took in and processed, or what objects the participants focused on and used in the decision-making process to complete the tasks.

i. Average Fixation Duration: Average duration where participants focused on a specific object.
ii. Fixation Count: The number of times participants looked at a particular object.
iii. Time to First fixation: Time until an object was seen for the first time.

Since the tasks were about finding a telephone and talking to VTS, finding first-aid equipment, picking and placing a water bottle and a blanket, and helping an injured person, the results are focused on these five objects (i.e. speakerphone, first-aid equipment, water bottle, blanket, and simulated injured person). Due to the large amount of box plots (3 eye-tracking factors x 5 objects), only a selection of the graphical results for the speakerphone are presented in this paper. The speakerphone was selected to be presented due to its possible connection with the physiological data, see Section 4. The complete set of the graphical plots containing the 15 box plots of the eye-tracking results can be found at Jenssen et al, 2020 [10]. Due to unexpected technical errors with the eye-tracking function in some cases, there is a lack of data in some scenarios. For most objects, however, there is a comparable sample size (i.e. around 35 data sets for eye-tracking analysis).
Regarding the average duration the participants focused on these objects, results show that there were no large variations between the five tested scenarios, see Figure 5. The difference between them was minimal (i.e. between 0.05 and 0.10 s). Even minor differences were found for the injured person. Here the focusing duration was almost the same in all the rooms.

![Figure 5](image_url)  
**Figure 5**  
Average fixation duration on the speakerphone presented for the 5 rooms.

Regarding the fixation count which indicates the number of times the participants focused on the room objects, the results show that the objects were seen more times in Basic room 3 compared to the other rescue rooms. This was true for most objects with the exception of the blanket.

![Figure 6](image_url)  
**Figure 6**  
Number of times the participants looked at the speakerphone presented for the 5 rooms.

Regarding the time to first fixation, the time it took to discover the different objects for the first time was also recorded. The results show that it took slightly longer to detect the speakerphone in Basic room 3, see Figure 7. At the same time, the first-aid kit was discovered later in Container room 2, while the simulated injured person was seen for the first time later in Container room 1 compared to the other rescue rooms. Variations in time were minimal for all scenarios (less than 1 minute).
Subjective evaluations
The five different rescue rooms were ranked by the participants. When asked ‘Which room did you like best?’ a 5-point Likert scale was used to evaluate the rooms, where 1 was the best room and 5 was the worst room. A clear majority of the participants ($n = 30; 81\%$) selected Container Room 2 as the preferred and best rescue room, whereas the majority ($n = 30; 81\%$) agreed that the Basic Room was perceived as the worst room. For each ranking, the subjects could justify in writing what they liked about the rooms evaluated. All comments were read and analyzed to search for common concepts in the answers. Two indicators were found to be particularly important for ranking preference: i. Lighting, and ii. Separate areas for different functions.

Moreover, the descriptive statistics (data means and standard deviations) for the five studied subjective variables presented in the questionnaires (see Section 2.2) are reported in Table 1. Based on the numerical results of the means and standard deviations, Table 1 is colour-coded to represent positive responses (dark grey), neutral responses (light grey) and negative responses (white).

<table>
<thead>
<tr>
<th></th>
<th>Basic Room 1</th>
<th>Basic room 2</th>
<th>Basic room 3</th>
<th>Container room 1</th>
<th>Container room 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>1.94 (1.25)</td>
<td>3.27 (1.24)</td>
<td>3.03 (1.30)</td>
<td>4.50 (0.86)</td>
<td>4.62 (0.79)</td>
</tr>
<tr>
<td>Feeling of safety</td>
<td>2.76 (1.37)</td>
<td>3.89 (1.02)</td>
<td>3.92 (1.00)</td>
<td>4.62 (0.78)</td>
<td>4.73 (0.73)</td>
</tr>
<tr>
<td>Place of speakerphone</td>
<td>3.12 (1.12)</td>
<td>3.43 (1.07)</td>
<td>3.39 (1.18)</td>
<td>3.88 (1.12)</td>
<td>4.27 (0.99)</td>
</tr>
<tr>
<td>Lighting</td>
<td>1.82 (1.24)</td>
<td>2.86 (1.22)</td>
<td>3.33 (1.07)</td>
<td>4.38 (0.89)</td>
<td>4.49 (0.87)</td>
</tr>
<tr>
<td>Acceptance</td>
<td>2.91 (1.33)</td>
<td>3.68 (1.29)</td>
<td>3.75 (1.23)</td>
<td>4.26 (0.99)</td>
<td>4.46 (0.96)</td>
</tr>
</tbody>
</table>

DISCUSSION
The present study explored which spatial and design factors have an effect on the users' acceptance of different rescue rooms. An important parameter to evaluate was how the participants acted inside the rescue rooms and whether they were able to complete simple tasks. For this evaluated parameter, the results show that, with the exception of one person, all participants managed to complete the tasks. The participant who did not complete the tasks, could not complete these in the Basic room and the Basic room 2. In addition, data from the event log shows that 10 people did not contact VTS first in some scenarios, but still managed to complete all the tasks. Most of these 10 people contacted VTS in the first test scenario, but for the rest of the scenarios they did not contact VTS. Considering that all
the tasks were the same in all rescue rooms, the fact that they did not contact VTS after the first scenario could imply a learning effect.

In addition, the experimenter noted in the events log that after completing the tasks, everyone was encouraged by VTS to sit down and wait until a rescue crew came to help them evacuate. Everyone sat down and wait, and no participant tried to leave the rescue room. Only one person sat down immediately and did not try to help the injured or seek contact with VTS. No one showed signs of aggressive behavior either in the tunnel outside the rescue room or inside the rescue room. Several participants stopped and checked if there were people in abandoned cars out in the tunnel.

The findings from both of the studied objective parameters (i.e. eye-tracking and physiological data) show small variations between the five studied scenarios. Indeed, the results from the eye-tracking data show that variations in time were less than 1 s. Moreover, the results also show very small variations between the average duration the participants focused on a particular object, the number of times the participants looked at a particular object, and the time of an object was seen for the first time. However, Basic room 3 presented slightly higher time to discover the speakerphone, higher fixation counts compared to the other rooms.

Although there were also small variations in the heart rate measurements among the five scenarios, there were still observable differences between the rooms. Container room 2 had the lowest heart rate measurements, and Basic room 3 presented the highest heart rate measurements. This suggests that the stress level was lower in Container room 2, while it was a little more stressful to be in Basic room 3. The reason why Container room 2 got the lowest heart rate measurements may be related to the general experience of the room which, as previously indicated, was the favourite of all rooms. These results are in line with previous research and guidelines from the World Health Organization (WHO), which point out that a person's health (including stress level) is the result of the interaction between human function and contextual factors, e.g. the design of the physical environment that can facilitate human activities [12, 13].

For the slightly higher heart rate measurement results for Basic rooms 2 and 3, it can be hypothesised that these may be related to the eye-tracking results. The majority of the objects were viewed for a longer time and several times in Basic room 3, compared to the other rooms. This can be observed in the results concerning the task of finding the speakerphone. The speakerphone was seen the longest, most times, and it took longer to discover it in Basic room 3. It is important to indicate that the speakerphone was an important object to complete all the tasks, as the participants had to communicate with VTS and follow the advice to complete the rest of the tasks. The telephone was also the only source of communication with others outside the rescue room, which increases its importance, and may explain the higher heart rate measurements in Basic room 3. Indeed, the fact that it took longer before the participants discovered the phone for the first time may suggest higher stress levels related to the higher heart rate measurements in that particular rescue room.

Regarding the placement of the speakerphone in the room, clear answers were given by the participants. The participants disliked the location of this in all the Basic rooms, but liked the location in both Container rooms. These are particular results, because the speakerphone was placed on the wall to the left of the front door of all the Basic rooms, while it was placed straight ahead in both Container rooms. One possible reason for this preference may be the immediate visibility of the speakerphone. This is discussed in psychophysical studies which indicate that a perceived acoustic object is affected by the location of a related visual object, e.g. a message from a speaker can be experienced louder if the speaker is visible [14, 15]. In a critical situation in a rescue room where the speaker/telephone can be the only source of communication with others outside the room, visibility of the speaker can be important for a better understanding of messages and thus increase the sense of security.

The findings of the subjective evaluations show that both Container room 1 and Container room 2 were preferred by the participants over all the basic rooms. Container room 2 was ranked highest for
all the five studied variables among the five different scenarios. On the other hand, the Basic room was the least liked by the participants with no factor achieving positive responses. The ranking provided by the participants confirmed Container room 2 as the favourite rescue room. Through analyses of the participants' comments, two main reasons for the rankings were revealed: i. Lighting; and ii. use of separate rooms.

The satisfactory level of lighting (described as 'well lit' by most participants) was crucial for a positive perception, feeling of safety and acceptance of the Container rooms. These results are in line with previous research showing that lighting affects users' well-being and stimulates a positive evaluation of a room [16]. Light and lighting are by far the most important link between people and the environment [17], and it is also considered an important source of aesthetic experience [18].

Regarding comments from participants who liked to have separate rooms, this can be explained by the human preference for 'context' and 'readability' from the Kaplan's preference model (i.e. Kaplan’s framework of predictors of preference): People prefer environments that can make sense of activities that are supposed to happen in that space (context), and that can be understood (readability) [19]. By having separate rooms, where each activity had its separate space (e.g. rooms for hospital beds and rooms for WC), the rooms became more readable, better understood within the context and better liked.

Another reason that was discussed by the participants as important in their evaluations (to a lesser extent than lighting and separate rooms), was the perceived spaciousness in Container Room 2. Although the floor area was the same in all the tested scenarios, only Container Room 2 was indicated as spacious by some participants. This suggests a psychological effect of the room, which may well be related to the reported lighting satisfaction. Light and color are known to influence the experience of the feeling of spaciousness in a room [20, 21]. Container room 2 with the blue light in parts of the ceiling could have given an illusion of sky above. This has been shown in previous studies to provide a positive experience [8].

On the other hand, the Basic room was the least favorite of all the five options. The comments given by the participants here also indicated that the lighting and the possibility of having separate rooms were important for their evaluations. For the Basic room it was pointed out that the room was 'dark' or 'poorly lit', and that not having separate rooms for WC was a disliked factor.

**CONCLUSIONS**

This paper describes the results of a full-scale Virtual Reality (VR) study on simulated 3D models of rescue rooms. Five different types of rescue rooms (i.e. one basic room, two other types of basic rooms (as refuge caverns or rock rooms) and two types of container rooms) were evaluated. It is worth noting that as part of a wider study, the visual and acoustic measures for guiding evacuees to emergency doors which suppose either passage to the outside or to rescue rooms is presented by the authors in a subsequent study.

The findings of the present paper show that there was little difference in the time spent performing tasks in all rooms despite the different spatial and design factors, suggesting that a general space experience does not necessarily affect the ability to perform tasks in critical situations.

Although there were found small variations in both the eye-tracking data and the heart rate variability (HRV), both data can be related to the slightly higher levels of HRV in Basic room 3. In particular, the eye-tracking data showed that it took longer time for the participants to discover the speakerphone in the room. Considering that the speakerphone was necessary to communicate with the Road traffic management center (VTS, for its acronym in Norwegian) and to receive instructions, it increased the object's importance. This could explain the slightly higher levels of stress related to the HRV measured in the room. Moreover, according to the participants' evaluations, there is a greater preference for the speakerphone to be placed in a visually accessible place in the room. This may be
due to a multisensory need in people who experience acoustic messages as higher if they can relate it to a visual object (e.g. the speaker or the person speaking). In a critical situation, in which a speaker/telephone is the only source of communication to the outside world, its visibility becomes crucial for creating a better sense of safety and security.

Finally, the subjective evaluations of the participants showed a clear preference for both Container rooms compared to all the Basic rooms. In particular, Container room 2 was the favourite among the participants, while the Basic Room 1 was the least favourite. Two factors, one related to the spatial configuration of the room (i.e. separate areas for different activities), and the other related to the room design (i.e. lighting design), were the most important aspects for the acceptance of specific rescue rooms.

The study underscores the importance of spatial and design factors on the user evaluations of rescue rooms. Although more research is needed to uncover new spatial and design dimensions around rescue rooms (possibly in further studies using real environments in controlled settings), these results are particularly promising for its applications in evacuation measures in tunnels. The findings presented in this paper aim to contribute in the discussion regarding the development and eventual implementation of rescue rooms in road tunnels.

ACKNOWLEDGEMENTS

This work was funded by the Norwegian Public Roads Administration (NPRA). The authors gratefully acknowledge the contributions of Harald Buvik, Anine Kalmo Larsen, Espen Ødegård, Per Einar Pedersli and Kjetil Sverre Rød (NPRA). In addition, the authors are also thankful to SINTEF Health for the use of the ISO-certified Work Physiology Laboratory, to Hilde Færevik and Øystein Wiggen from SINTEF Digital - Dept. Health for their input and comments throughout the project, to NTNU master student Ragnhild Finsveen Liven for their support carrying the focus group, and to Trond Foss from SINTEF Community – Dept. Mobility and Economics for quality assurance.

REFERENCES


Analysis of visual and acoustic measures for evacuations in road tunnels using virtual reality

Jo Skjermo¹, Claudia Moscoso¹, Daniel Nilsson², Håkan Frantzich³, Åsa S. Hoem¹, Petter Arnesen¹ & Gunnar D. Jenssen¹

¹SINTEF Community, Dept. Mobility and Economics, Trondheim, Norway
²University of Canterbury, Christchurch, New Zealand
³Lund University, Lund, Sweden

ABSTRACT

Emergency fire situations in tunnels can be especially dangerous when occurring in long underground or subsea tunnels, particularly when evacuation on foot is the only alternative. This paper presents the results from a study testing visual and acoustic measures to facilitate efficient and safe emergency evacuation and their effect on people's self-rescue behaviour in response to a tunnel fire. Eighty-one participants evaluated seven different scenarios in virtual reality with or without visual and acoustic supporting measures (i.e. signs, lights, acoustic beacons) to find their way to emergency doors. Objective behavioural data, such as orientation, and walking speed, were collected. The results suggest that the distance between the emergency doors increases uncertainty and affects the time to self-rescue significantly, with four times longer times for 500 m than 250 m between doors. Additionally, the use of continuous guiding lights positively supported orientation and walking speed, with 97 % of the participants finding their way and showing a reduction of time to reach the emergency door of 10 to 20 s. The study underscores the importance of proper visual and acoustic evacuation measures for the wayfinding of emergency exits, improving self-rescue of people.

KEYWORDS: Evacuation, tunnel, guiding lights, acoustic beacons, walking speed, virtual reality

INTRODUCTION

Emergency situations in roads due to collisions, fires, hazardous liquids, volatile gases, or terrorist activities may be especially dangerous when occurring in long underground or subsea tunnels. The closed environment in the tunnel can accumulate heat, smoke and toxic gases resulting from different events. It is not surprising that tunnels are perceived as hostile environments producing a higher risk compared to open roads [1]. Although these emergency situations in tunnels are rare, there is always a likelihood of them happening. In such complex situations, self-rescue measures should be taken. Time to evacuate may be short as seen in the recent tunnel fire the Skatstreum subsea tunnel when 16,500 liters of petrol caught fire inside after a tank trailer broke loose from the truck and ran into the tunnel wall. Road users had 2 min to evacuate before 1 km of the tunnel was engulfed in fire [2]. Self-rescue calls for the road users, who are involved in emergency situations, to evacuate the tunnel either on foot or by using their own vehicle [3]. However, in single tube tunnels with limited cross section and lane width, it means that even a partially blocked lane or a fire can potentially trap vehicles and prevent access for rescue services. In dense smoke, it is difficult to turn around in a narrow tunnel. Vehicles collide with the tunnel wall, with each other or other objects. This was the case in the Oslofjord subsea tunnel fire in 2011 and 2015 as well as in the Gudvang tunnel fire in 2014 [4, 5]. As a result, evacuation on foot to emergency exits or other safe areas is often the only alternative.

According to the Appendix I of the Norwegian regulations on minimum safety requirements for certain road tunnels "Safety measures to be implemented in a tunnel shall be based on a systematic
assessment of all aspects of the system constituted by the infrastructure, use, road users and vehicles" [6]. This means that measures need to be evaluated based on what road users are actually assessing and doing at different stages of an event and not just what they should do. Safety equipment should make it easier to evacuate in a smoky tunnel and guide road users to the desired behaviour. How the tunnel is designed and equipped can affect the possibility of self-rescue [7]. Physical distances, ventilation, signage and various management systems are crucial.

Specific measures for effective self-rescue are needed when evacuation on foot is to be expected. These include alarms and messages via different technical installations such as visual and acoustic guiding systems that can indicate the road users the seriousness of the situation in order to react. In comparison to other built environments, tunnels are simpler environments, in which visual and acoustic signage to safe locations should be easy to detect and understand. However, in fire emergency situations, dense smoke and noise can influence the visibility and hearing of the users, affecting the walking speed and the evacuation time of the pedestrians [8-11]. Indeed, guiding lighting has been shown to be effective at attracting people's attention towards emergency exits [12-14], and acoustic messages have also been proved useful in motivating users to start evacuation [15-18].

Experimental studies including people and tunnel fires can be problematic. Although valid studies have been conducted in real tunnel environments [10, 19], logistical, methodological and ethical challenges are present if participants are to be exposed to real conditions. In order to overcome these challenges, virtual reality (VR) has been successfully used in evacuation research. Indeed, investigations using VR include the study of social influence on evacuation behaviour [20], the use of flashing lights at emergency exit portals [13], and the analysis of evacuation travel paths [21]. Furthermore, the high level of control of the study variables is a great advantage recognized with the use of VR in experimental research [22].

The focus of the present study was to investigate whether road users find their way to emergency doors with or without visual and acoustic measures to safeguard self-rescue. If road users do not find the emergency exit when they need to, it can mean two things: i. establishing emergency exits has no effect on self-rescue; and ii. the guiding system leading to the emergency exits must be improved so that road users can find them. Hence, the study was designed to answer the following research question: How do different tunnel technical installations affect people's self-rescue behavioural reaction to a tunnel fire?

To this end, different tunnel technical installations were evaluated, including visual and acoustic measures such as visual emergency signage, guiding lights and audio messages, and their effect on orientation and walking speed in case of a tunnel fire. Finally, the study makes use of virtual reality (VR) as an experimental tool (see Section 2.2) and was carried out at two VR-laboratories with identical equipment: one at SINTEF in Trondheim, Norway, and the other at Lund University in Lund, Sweden. For brevity, a more in-depth exploration of the experimental setup, the VR implementation, and overall project setup can be found in [23] (Norwegian only). This study is divided in two parts. The first part addresses the use of visual and acoustic measures for guiding evacuations to emergency doors which suppose either passage to the outside or to rescue rooms (the current paper). The second part explores the users' acceptance of different rescue rooms with varying spatial and design factors (a subsequent paper by the authors).

METHOD

Scenarios
A total of 7 different scenarios were evaluated in the study, where a baseline scenario with basic conditions (tunnel without special measures, i.e. simple form of installation and design of emergency door) was included. The other scenarios differed according to: i. guiding systems - presence of either visual, acoustic or visual and acoustic technical installations, in which there are guiding lighting systems, emergency signage, and/or audio messages via acoustic beacons; ii. visibility - depending on the presence of smoke which reduces the visibility to 0.5 m or 1 m; and iii. location of emergency

499
doors - varying in distances from 250 m up to 500 m, and with regards to their position, i.e., either on both sides of the tunnel, or positioned on the opposite side of the tunnel wall that participants chose to follow. Distance signs were placed every 50 m. Signs for both directions on both sides of the tunnel were visible to the participants in the starting position. Signs in the starting position were visible 100 m and 150 m away from the fire in scenarios 1-5 (see Figure 3). In scenario 6, the signs were visible from 50 m and 450 m. The guiding systems for each scenario varied according to their design. For a better understanding of the different tested guiding systems, see Table 1. In addition, detailed information about the different test scenarios is described in Table 2.

Table 1 Characteristics of the tested guiding systems.

<table>
<thead>
<tr>
<th>Guiding system</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Green door and illuminated emergency sign above and on each side of the door. Sign (ISO 7010; &quot;running man&quot; symbol). No extra strong lighting.</td>
</tr>
<tr>
<td>B</td>
<td>Improved design of emergency green door, with an additional green LED frame around the door and big lit arrows on each side.</td>
</tr>
<tr>
<td>C</td>
<td>Directional acoustic beacons located at the emergency door. The sound is audible at a maximum of 48 m from the emergency door (but is drowned out by fan noise at a distance of around 30 m or more) and is perceived as directional. Full spatialized audio is however not used, so not to introduce cues that might be better than what is easily achievable in a real tunnel setting (tunnels are a difficult audio environment). Audio messages were in three languages: <strong>English: Exit here, Norwegian: Utgang her, German: Ausgang hier</strong>.</td>
</tr>
<tr>
<td>D</td>
<td>Emergency sign showing a running man and an arrow pointing towards the ground for signalling the exit on the opposite side of the tunnel.</td>
</tr>
<tr>
<td>E</td>
<td>Continuous guiding light visible from start position until the emergency door.</td>
</tr>
</tbody>
</table>

Figure 1 Images of the guiding systems used in the experiment. The letters A, B, D and E refer to the description provided in Table 1.
## Table 2  
The scenarios and their associated variables.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Physical variables</th>
<th>Visibility distance</th>
<th>Location of emergency doors</th>
<th>Guiding systems (based on Table 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Baseline</td>
<td>• Simple door without special measures</td>
<td>1.0 m</td>
<td>Emergency door every 250 m, on both sides of the tunnel</td>
<td>A</td>
</tr>
<tr>
<td>2. Visual</td>
<td>• Extra visible door with static arrows towards the door</td>
<td>1.0 m</td>
<td>Emergency door every 250 m, on both sides of the tunnel</td>
<td>A + B</td>
</tr>
<tr>
<td>3. Acoustic</td>
<td>• Audio messages</td>
<td>1.0 m</td>
<td>Emergency door every 250 m, on the opposite side of the chosen tunnel wall</td>
<td>A + B + C</td>
</tr>
<tr>
<td>4. Visual and emergency sign</td>
<td>• Extra visible door with static arrows towards the door</td>
<td>1.0 m</td>
<td>Emergency door every 250 m, on the opposite side of the chosen tunnel wall</td>
<td>A + B + D</td>
</tr>
<tr>
<td>5. Visual and emergency sign</td>
<td>• Extra visible door with static arrows towards the door</td>
<td>0.5 m</td>
<td>Emergency door every 250 m, on the opposite side of the chosen tunnel wall</td>
<td>A + B + D</td>
</tr>
<tr>
<td>6. Visual and acoustic</td>
<td>• Extra visible door with static arrows towards the door</td>
<td>0.5 m</td>
<td>Emergency door every 500 m, on the opposite side of the chosen tunnel wall</td>
<td>A + B + C + D</td>
</tr>
<tr>
<td>7. Continuous guiding light</td>
<td>• Continuous guiding light</td>
<td>0.5 m</td>
<td>Emergency door every 250 m, on the opposite side of the chosen tunnel wall</td>
<td>A + B + C + D + E</td>
</tr>
</tbody>
</table>

### Virtual Reality

The present study was carried out using a laboratory simulation with the aid of VR, based on 3D modelling of an evacuation scenario in a long and steep subsea road tunnel. Although in previous research studies participants have acquired a degree of movement using hand controllers, that method could not be perceived as realistic compared to when participants can walk on a treadmill/platform. In order to acquire realism and immersion in the testing scenarios, the experiment was performed using the Cyberith Virtualizer Research & Development Kit, and HTC Vive Head mounted display (HMD). The Vive HMD presented a resolution of 1440 x 1600 pixels per eye (2880 x 1600 pixels combined), a refresh rate of 90 Hz, and a field of view of 110 degrees. The position of the participants was registered via tracking sensors mounted in the ceiling over the VR platform, together with the direction of the body and the walking speed from the motion platform. Additionally, participants of
the experiment used stereo headphones to be able to hear the audio messages and the background noise in the tunnel. Figure 2 shows the Cyberith Virtualizer equipment at the SINTEF VR-laboratory.

![Image](image.png)

Figure 2  The Cyberith Virtualizer in use at the SINTEF VR-Lab. Identical equipment was used at the VR-Lab in Lund University.

A single tube tunnel was modelled for the experiment. The 3D model presented equal conditions as other subsea tunnels, involving a lane in each direction of the tunnel, and was interiorly built to resemble a concrete construction of approx. 3.5 m high. The tunnel was modelled to resemble a 7.3 km long subsea tunnel. In addition, the 3D model of the tunnel was equipped with common installations such as emergency lay-by, fire extinguishers, emergency telephones and signage. Finally, there were modelled doors corresponding to doors to technical rooms. These doors are in reality locked and are not possible to open by common road users. Thus, despite having a handle, these doors were not possible to open in the 3D model (see Figure 3).

Emergency doors were placed at different distances and positions depending on the scenario evaluated (see Section 2.3). Background sound was also included, as it was important for both realism and orientation. Noise from fans and fire ventilation (approx. 60 dB) is present from different places in the tunnel, specifically in places where fans are located. Finally, to evaluate conditions of self-rescue under more complex circumstances that can arise in fires of high magnitude, propagation of black smoke was included in the VR scenarios. Overall smoke was visualized using an adapted volumetric fog shader for overlapping volumes placed every 10 m along the tunnel, that was controlled by results from a smoke propagation simulation. Initially, when close to the fire, there was also added in a particle smoke effect to give an impression of initial air/smoke movement. The location of the emergency doors and the opaqueness of smoke were dependent on the planned test scenarios, which are further described in the subsequent section.
Experimental procedure
Before initiating each experimental session, screening of participants was carried out. Participants who scored high on the Apfel criteria [24] were excluded. The duration of each experimental session was between 1.5 h and 2 h. The following procedure was followed for all participants: Each participant was welcomed to the study and was asked to respond a pre-test questionnaire containing general questions and questions regarding their experience and attitude when driving through a tunnel. Next, a validation of walking speed was performed (i.e. the time that a participant used to walk in a flat and straight direction of 30 m was registered). A simulation training was carried out, in which the participants were shown an instructive video on how to walk in the VR platform. Once in the simulator, the participants did a training scenario in a virtual model of a sidewalk in a city, in which they received instructions to walk towards a defined point and practice opening doors. After the participants had mastered the VR platform and succeeded with the tasks of the training scenario, a priming video was presented. The video was seen from a driver’s perspective and depicted the tunnel driveway towards the traffic stop and a view of a parked truck that is on fire (see Figure 4). When the smoke comes and surrounds the vehicle, the video is toned down, and in the next scene the participant is standing outside the vehicle on its right side, between the vehicle and the tunnel wall. The experiment starts in this position. Following this step, the presentation of the test scenarios started. Each session had a randomization principle, so that each participant could have different order of scenario presentation, and to avoid bias related to previous evaluated stimuli. Three scenarios were tested, before the participants were offered a break. After the pause, three other scenarios were evaluated. At the end of the VR session, the participants were asked to fill out a post-test questionnaire, including questions about their perception and opinions of the different solutions presented in the test scenarios. At the end of this first experimental session, each person received two movie tickets as a compensation for their participation in the study. Scenario 7 was performed several weeks later.

Participants
Eighty-one persons were recruited via social media and the networks of SINTEF and Lund University. The participants were of different background (30 Norwegian citizens, 40 Swedish citizens and 11 of other nationalities), gender (female = 35, male = 46) and age $M= 34.2$ (SD = 13.9), range 18 – 69 years old). The group of participants consisted of people with different educational levels and different driving experience. Most of the participants have had a valid driver's license for over 5 years and had a neutral attitude about driving in tunnels. Not all the participants completed the experimental sessions as some felt uncomfortable conditions in the form of physical discomfort (e.g. dizziness and nausea), and psychological discomfort (e.g. one participant was scared from hearing voices in a non-understandable language). The data of these participants were thus, not included in the analysis of all scenarios. The number of data sets for the scenarios ended up as: scenario 1=78; scenario 2=76, scenario 3=77, scenario 4= 77, scenario 5=75, scenario 6=52, scenario 7=21.
Evaluated parameters
The primary aim of the study was to see if road users find their way to an emergency door as a function of measures taken to strengthen self-rescue. That is, if acoustic or visual instruments enhance orientation and guide road users to the nearest emergency door in a fast and secure way. To this end, three parameters were used in the study:

i. **Wayfinding and opening of door:** A successful choice is that the person finds the door to the room and intentionally (actively) tries to walk through such a door. The exact indicator from the VR environment is that the subject is pressing a hand controller to open the emergency door.

ii. **Road choice:** The trajectory/walking path of the participants is recorded to see the direction they take and whether they take the shortest route. This allows to see the observable differences between different scenarios and measures. The start position was always between two emergency doors, where the shortest way was always towards the fire, and the longest way was away from the fire.

iii. **Walking speed:** How fast the participants walk is registered as a function of visual and acoustic guiding systems.

A separate software was implemented to analyse the log files from the VR simulation for each scenario for each participant. This software also enabled visual inspection of the path a participant had walked, by plotting it from a top-down perspective. An addition, the walk speed was shown in a graph together with coloured points/tags for when the participant was close to points of interest, as seen in Figure 5.

![Figure 5 Screen capture from the analysis software, showing walking speed and walked path compared to points of interest.](image)

**RESULTS**

This section presents the results obtained from statistical analyses, which were evaluated with a p-value of 0.05. All the data was filtered, which means that the observations disrupted by the
experimenter were removed. The number of observations in each scenario vary, as previously pointed out. Scenario 6 was tested with fewer participants in both Norway and Sweden and thus naturally has a lower number of valid observations than the others. It is important to mention that due to the lower number of participants in scenario 7 compared to the other scenarios, the statistical analyses were mainly focused on testing the differences between scenarios 1 to 6. For the evaluation of each parameter, different statistical tests were applied. These are indicated and further described in each section as appropriate. A more in-depth analysis can be found in [23].

Wayfinding and opening of emergency door
An important indicator of the effect of the guiding systems is whether people find emergency doors by self-rescue in dense smoke conditions. The results revealed that 66% of the participants found and opened the emergency doors. Twenty-nine percent did not find their way to any door. Out of the participants who did not find the door, 11% went in a wrong direction towards the fire in an early phase. Eighteen percent of participants walked past the door without discovering it. The results presented in Table 3 show that the proportion of participants who turned and went towards the fire in scenario 6 (46%) is greater than in the other scenarios. As stated in Table 2, scenario 6 was the only scenario with 500 m between emergency doors. In addition, Table 3 shows that the proportion of participants who did not find the emergency door in scenarios 1 and 2 (8% and 4% respectively) is significantly smaller than in the other scenarios. When comparing between these different scenarios (1-2 vs. 3-6), results indicate that those who passed the emergency door did so exclusively in scenarios with dynamic placement of the emergency door, i.e. on the opposite side of the tunnel wall the road user followed (scenarios 3 to 6; see Table 2).

Scenario 7 presented a continuous guiding light always placed on the same side as the emergency door, one meter up on the wall. The results suggest that the use of the light influenced orientation, as 96% of the participants chose immediately the correct side in which the emergency door was located. The participants followed this light line to the nearest emergency door without crossing the tunnel or passing by the door. Likewise, the continuous guiding light affected the walking speed of the participants, showing a decrease in time of 10-20 s. This means that with the use of the continuous light, the participants walked 10 to 20 s faster towards the emergency room.

Furthermore, statistical analyses were performed on: Differences between binomial distributions, in which the statistical test allows to see whether two scenarios present the same distribution for successful/not successful. The results indicated that, regarding the wrong direction, only scenario 6 was significantly greater than the others. The other scenarios did not show a significant effect. In relation to the participants not finding the emergency doors, the statistical analyses indicate that scenarios 1 and 2 are significantly lower than the other scenarios, and that there was no significance within these two groups.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Proportion of the participants who went in the wrong direction (towards the fire), and who did not the emergency door distributed in the different test scenarios.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
<td>Number of observations</td>
</tr>
<tr>
<td>1</td>
<td>73</td>
</tr>
<tr>
<td>2</td>
<td>72</td>
</tr>
<tr>
<td>3</td>
<td>73</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
</tr>
<tr>
<td>5</td>
<td>72</td>
</tr>
<tr>
<td>6</td>
<td>49</td>
</tr>
</tbody>
</table>

Moreover, differences in age distribution were also analysed. Figure 6 shows that most of the group of older people (i.e. over 50 years old) did not find the doors, while the largest number of young people did find them. Contingency tables and Chi-square test were used to check for differences between groups. Columns are normalized for each group, the number of observations displayed with red
numbers. As with the previous analyses, the observations disrupted by the experimenter were filtered out. The nationality of the participants (i.e. Norwegian, Swedish, and others), driving experience in tunnels, and safety feelings in tunnels had no significant effect on the participants finding their way to the emergency door.

Figure 6  Number of participants who found the emergency door distributed by age.

Finally, according to the statistical analyses, factors such as gender, age, and how often a person drive in the tunnel did not have a statistically significant impact on the wayfinding to an emergency door.

Fear induced stress can potentially impact one’s ability to understand signs in an emergency. 11% of the participants stated in the post questionnaire that they were somewhat or very afraid during the test. None of those that stated they were very afraid during the tests (n=3), understood the sign pointing downwards (see Figure 1-D). On the other hand, n=32 (40 %) of those that did not indicate fear also did not understand the meaning of the sign with a downward pointing arrow. Answer in the post questionnaire also indicated that fear was not a significant issue here, but that it was just difficult to understand the meaning. The arrow pointed straight down, and several participants did search for a hatch in the floor instead of crossing the tunnel. When analysing nationality in relation to the participants who understood the sign pointing downwards, the results indicate that 25 % of the Swedish participants and 23 % of the Norwegian participants did not understand the meaning of the sign, and a further 9 % of all participants were uncertain on what the sign meant. The proportion who did not understand the sign from other nations was surprisingly much lower (4 %), but the low number in the group of others (N = 8) does not provide a basis for robust conclusions.

Route choice
The results from Table 4 show the average distance (in meters) which the participants walked before they found their way to the emergency door in the different test scenarios. The distance the participants walked in the other scenarios in which there were 250 m between emergency doors varied between 132 m in scenario 1 to 154 m in scenario 3. The distance the road users went in scenario 3 was significantly greater than scenarios 1, 2, 4 and 5.

As stated before, scenarios 6 and 7 were in principle similar, in which one of the most notorious differences are the use of the continuous guiding light. In order to study the effect of the continuous light on the selection of tunnel wall of the participants, i.e. analyse if the participants use the left wall (with the continuous light) or walk along the tunnel wall on the right. The statistical analysis indicates that there were found differences at a 5 % significance level. The results show that: 21 of 22 participants (96 %) chose the left wall in scenario 7, 56 of 76 participants (74 %) chose the left wall in scenario 6 without the continuous guiding light.
Table 4  
Mean (M) and Standard Deviation (SD) values of the distance walked by the participants before they found their way to the emergency door in the different test scenarios (unit = m).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Number of observations</th>
<th>M - distance</th>
<th>SD - distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67</td>
<td>132</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>69</td>
<td>129</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>68</td>
<td>154</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
<td>144</td>
<td>35</td>
</tr>
<tr>
<td>5</td>
<td>64</td>
<td>145</td>
<td>33</td>
</tr>
<tr>
<td>6</td>
<td>26</td>
<td>424</td>
<td>100</td>
</tr>
</tbody>
</table>

Walking speed
As expected, the walking speed in dense smoke was significantly lower than with a good view. The results from Table 5 show the average walking speed (m/s) that the participants used while they were finding their way to the emergency door in the different test scenarios. The walking speed is lowest in scenario 6 and 5, with 1.0 m/s and 1.1 m/s respectively. These two scenarios presented the densest smoke conditions and a visibility distance of 0.5 m. The walking speed was highest in scenarios 1, 2, 3 and 4 with visibility distance of 1.0 m.

Table 5  
Mean (M) and Standard Deviation (SD) values of the walking speed in the different test scenarios (unit = m/s).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Number of observations</th>
<th>M - walking speed</th>
<th>SD - walking speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67</td>
<td>1.229</td>
<td>0.539</td>
</tr>
<tr>
<td>2</td>
<td>69</td>
<td>1.281</td>
<td>0.599</td>
</tr>
<tr>
<td>3</td>
<td>68</td>
<td>1.244</td>
<td>0.518</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
<td>1.191</td>
<td>0.551</td>
</tr>
<tr>
<td>5</td>
<td>64</td>
<td>1.139</td>
<td>0.468</td>
</tr>
<tr>
<td>6</td>
<td>26</td>
<td>1.005</td>
<td>0.468</td>
</tr>
</tbody>
</table>

Other important indicator of the effect of the guiding systems and the location of the emergency door (i.e. distance between the doors) is the total time the participants used to find their way to the emergency door in dense smoke by self-rescue. The results shown in Table 6 indicate that the average time used in scenario 6 was considerably greater than the rest. The time used in scenarios 3, 4 and 5 are greater than in scenarios 1 and 2. The statistical test Differences between binomial distributions show that the scenario 6 is significantly greater than the rest. Scenarios 3, 4 and 5 are significantly greater than scenarios 1 and 2. There was no significance within the latest two mentioned groups. In addition, the time to rescue was four times higher (increase from 2 min to 8 min) when the distance between emergency doors is 500 m (scenario 6) than when the distance is 250 m (scenarios 1 to 5). One should note that this study did not consider the participants physical fitness, nor the impact the walking platform could have on physical exertion. Also, the walking speed of a participant in the walking platform was not validated against longer distances of several hundred meters.

Statistical analysis at a 5 % significance level show that, in relation to walking speed, participants walked faster in scenario 7 than scenario 6. Although fewer observations give less statistical certainty, the results are still valid, as they suggest a tendency to walk faster in scenario 7 compared to the other test scenarios.
Table 6  
Mean (M) and Standard Deviation (SD) values of the time used in the different test scenarios (unit = s).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Number of observations</th>
<th>M – time used</th>
<th>SD – time used</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67</td>
<td>138</td>
<td>92</td>
</tr>
<tr>
<td>2</td>
<td>69</td>
<td>139</td>
<td>119</td>
</tr>
<tr>
<td>3</td>
<td>68</td>
<td>148</td>
<td>74</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
<td>155</td>
<td>108</td>
</tr>
<tr>
<td>5</td>
<td>64</td>
<td>153</td>
<td>102</td>
</tr>
<tr>
<td>6</td>
<td>26</td>
<td>488</td>
<td>246</td>
</tr>
</tbody>
</table>

DISCUSSION

The focus of the study was to investigate whether road users find their way to emergency doors with or without visual and acoustic measures to safeguard self-rescue. In the present study, the starting position was always between two doors where the shortest road was always towards the fire and the longest road was away from the fire. The distance to the emergency door signage both ways was always visible for the first 10 s before the participants were surrounded by dense black smoke. In the scenarios with fire and smoke development, it was assumed to be considered very risky to go towards the fire. The fire is therefore referred here as going in the ‘wrong direction’. The results show that 66% of the participants found the emergency door by going in the right direction (away from the fire), 11% went in the wrong direction (never exposed to the door), and 18% of those who walked in the right direction passed the door because they were walking following the tunnel wall on the opposite side. The fact that 11% went towards the fire correlates well with observations based on the interview of road users caught in the smoke during a fire in the Gudvanga tunnel in 2013 [25], in which, in a real fire situation, a similar proportion went toward the fire, although at an early stage time the road users were aware in which direction the fire was located [5, 7, 26].

Results suggest that those who passed the emergency door did so exclusively in scenarios with dynamic placement of the emergency door. It is important to highlight that in scenarios 1 and 2, there was an emergency door on both sides of the tunnel, but for the others there was a dynamic placement of the door. That is, in scenarios 3-6 the door was always on the opposite side of the wall that the road user followed initially. Such dynamic placement of doors was designed to test whether people find the door when they follow the opposite wall in dense black smoke with visibility distances of 1.0 m and 0.5 m respectively, as a function of visual and acoustic guiding systems. Although a learning effect at an individual level can be discussed, the overall results are not considered to be affected by learning considering that the stimuli presented to the participants followed a randomization principle.

In scenario 6, with a 500 m distance between the emergency doors, as many as 46% got turned around and went towards the fire at one time or another. It is important to note that at a distance of 30-48 m it was possible to hear directional audio messages from speakers located at the emergency door. After going in the right direction for several minutes, the participants in this scenario were uncertain about whether they had passed an emergency door, and thus turned. Some changed their walking direction several times in search of the doors. Of those who continued in the right direction (53%) in this scenario and came within audible distance to speakers, 97% found the emergency door on the opposite side of the tunnel. These results emphasize the importance of acoustic conduction when people are on the opposite side of the tunnel in relation to the emergency door. In scenarios 1 and 2, with emergency doors on both sides, everyone found their way whether the door had extra visual reinforcement with large green LED arrows facing the door from both sides and green LED stripe that framed the door or not. These were high visibility scenarios (i.e. 1.0 m). The results cannot conclude as to whether road users would find such emergency doors at a short visibility distance (i.e. 0.5 m).

Moreover, the study investigated whether signs for exits on the opposite side could help road users find emergency doors if they followed the wrong wall. The sign was composed of ISO 7010 ‘Running man’ and an arrow pointing down (see Figure 1-D), in accordance with international and national
guidelines for the composition of elements in evacuation signs. However, such a sign does not yet exist in national or international tunnel sign guidelines. The results of the study revealed that many had trouble understanding the meaning of the sign. Both nationality and level of stress were evaluated in search for a correlation with the proportion of participants who did not understand the sign. Neither of the results provided a basis causing the sign’s meaning to be misunderstood. Open-ended answers post experiment suggest that the sign is simply difficult to understand. The arrow points straight down and several bent down searching for a staircase or an escape hatch in the floor. The results are in accordance with previous studies [27, 28], in which participants believed particular signs indicated stairs, elevators or downhill slopes.

Furthermore, the results of the study suggest that the walking speed is affected by the presence of dense smoke (visibility distance), gender, cultural and experience with tunnel (i.e. attitude and driving frequency), and age. The results concerning the visibility distance and the age are in accordance with previous research [27, 29-31]. In relation to the distance between emergency doors, the results suggest that distance between these doors significantly affects time to rescue. Time to rescue is four times (increase from 2 min to 8 min) when the distance between emergency doors is 500 m (scenario 6) than when the distance is 250 m (scenarios 1 to 5). Although some of the increase can tentatively be due to shorter visibility in scenario 6, the visibility is equal (i.e. 0.5 m) in both scenarios 5 and 6. When analysing the results, these suggest that uncertainty could have played a role. Registered movement patterns were different in scenario 6 than in the other scenarios. The participants moved back and forth more in scenarios with 250 m between emergency doors. Open-ended responses in the post-test questionnaires indicated that the participants became uncertain about whether they were heading in the right direction or whether they had passed an emergency door without detecting it when the distance increased to 500 m. The results indicate that acceptable distance between emergency doors should not exceed 250 m to safeguard the possibility of self-rescue. In some cases, it should probably be shorter. By comparison, the American Road Tunnel Guidelines - NFPA 502 [32] recommend a distance of 90 m in certain types of tunnels.

Finally, the findings show that the use of continuous guiding lights results in faster and more correct behaviour. Ninety-seven percent of participants immediately chose the right side with continuous light rail, walking 10 to 20 s faster to the emergency door. The results suggest that when a fire situation occurs, a continuous light strip can facilitate orientation so that the road user chooses to follow the wall with continuous strip/hand strip. It provides road users with a conscious and intuitive fixed point of view that can lead them faster to emergency exits than without such measures.

**Immersion**

How realistic the experience is perceived both totally and with respect to specifics such as smoke, vehicles, signs, speaker messages and so on, will impact the participants immersion and as such will have serious impact on the ecology validity of this study. Throughout the post questionnaire there was a high score for visual fidelity and general realism. Just as important was the observed behaviour during the trials. Examples of high immersion behaviour that indicate high face and outer validity was observed throughout the study, such as participants checking vehicles to save others, bending down to avoid signs and installations, attempting to open doors and searching on the ground for hatches when observing sign with an arrow pointing downward.

There are however several limiting factors when considering outer validity (the extent to which results from a study can be generalized to other situations). Obvious limitations are that the participants are: not subjected to real danger; not subjected to smell of smoke; not subjected to directional heat and air currents; not subjected to walking on gravel or in ditch next to road; not subjected to speech messages over speakers with same reflection as in real tunnel; signs was 10 % larger than in real life.

We observe that 63 % (n=51) answered in the post questionnaire that they felt very safe when trapped in the simulated smoke (although many of them did express an increase respect for the dangers after participating). 37 % (n=30) stated that they felt somewhat unsafe when getting exposed to / trapped in the smoke. One participant aborted the study from fear that was not related to smoke (related to cultural...
beliefs, where the underground is considered the domain of the dead, and voices, i.e. speaker messages, was perceived as especially scary). The results indicate that the participants had different degrees of immersion in the scenarios. Even if the scenarios are given high score for realism, 6 out of 10 say they felt safe. Also, psychophysiological indicators for stress and fear such as heart rate or blood cortisol levels were not measured.

Exposing people for real smoke in a trial is ethical dubious. This means that the simulation is limited as the participants do not experience aspects such as smoke smell, eye stinging, being covered by soot and experience heat to such a degree as in a real tunnel fire (could potentially be enabled by performing the study in a controlled heat lubritorium). From these, and previously mentioned limitations, here is an assumption that it is somewhat easier to actually find a rescue room in the simulation than in a real-life situation. However, we argue that from the validation it follows that it is reasonable to assume that the results show behaviour and valid results for relative differences between the different approaches for guiding, even if the results will not necessarily give exact results for walking speed and percentage that will find a rescue room in a real-life situation.

CONCLUSIONS

The present paper explored how different visual and acoustic measures could support evacuation in road tunnels by analysing their impact on wayfinding, road choice, and walking speed towards an emergency door which suppose either passage to the outside or to a rescue room. It is worth noting that as part of a wider study, the acceptance of rescue rooms as an evacuation measure in road tunnels is presented by the authors in a subsequent study.

The findings of the present study show that the locations of emergency doors affected their wayfinding by the participants. The study reveals that the participants found emergency doors faster when the doors were located on both sides of the tunnel compared to only on one side. Moreover, the time used for the participants to find the emergency doors was four times higher (time increase from 2 to 8 min) when the distance between the emergency doors was of 500 m than when the distance was of 250 m.

Regarding the visual measures, it can be pointed out that, among the studied visual measures, the continuous guiding lighting increases both orientation and probability of finding the emergency door. The results indicated that the walking speed increases slightly – participants walk 10 to 20 s faster to the emergency door when they can follow continuous lighting.

Regarding the acoustic measures, the results indicate that acoustic guidance systems work better to guide road users across the tunnel compartment. From the participants who escaped from the fire (i.e. walked in the right direction) and came within audible distance to the speakers, almost all (97 %) found the emergency door.

Moreover, and as expected, it is important to notice that other factors proper to a fire emergency and that are not always controllable might play a role on evacuation. For example, the study showed that the vicinity to the smoke has a negative effect on self-rescue time. Walking speed decreases by up to 0.3 m/s in scenarios with 0.5 m visibility versus 1.0 m visibility. Time to rescue is shortest in scenarios with 250 m distance and 1.0 m visibility distance in smoke.

Although the findings of this study are restricted to a virtual reality setting, warranting validation studies in real environments, these results shed light to specific visual and acoustic measures and on how they impact both wayfinding and walking speed towards the emergency doors. The results imply that for the design of road tunnels, continuous guiding lighting as a visual measure and shorter distance between acoustic beacons (to provide proximity to acoustic measures) could be implemented to improve self-rescue.
ACKNOWLEDGEMENTS

This work was funded by the Norwegian Public Roads Authority. The authors gratefully acknowledge the contribution by Kristen Opstad, ComputIT (DNV GL), for the excellent work on generation of propagation data for the smoke simulation.

REFERENCES

6. Tunnelsikkerhetsforskriften, Forskrift om minimum sikkerhetskrav til visse vegtunneler [Eng: Regulations on minimum safety requirements for certain road tunnels], in (FOR-2016-12-13-1597), Samferdselsdepartementet, Editor. 2007: Norway.
NFPA 502 Critical Velocity Calculation Methodologies and Dimensionless Heat Release Rate

Yinan (Scott) Shi\textsuperscript{1}, Iain Bowman\textsuperscript{1}, Natasha De Los Rios\textsuperscript{2}, Norris Harvey\textsuperscript{2}, Kyle Lopez\textsuperscript{2} \& Luke Pelessone\textsuperscript{2}
\textsuperscript{1}Mott MacDonald, Canada
\textsuperscript{2}Mott MacDonald, U.S.A.

ABSTRACT

The equation-based longitudinal smoke control methods have been widely practiced for designing Tunnel Ventilation Systems (TVS). As an area of ongoing research, the National Fire Protection Association (NFPA) 502 Standard maintains the equation-based Critical Velocity calculation methodologies in an information-only prescriptive Annex section. During the past decade, the standard has published many iterations of the methodologies. With the continuing debate, the standard has been scrutinised for including methodologies of varying degrees of accuracy. The most recent edition of the standard included two methodologies from the 2014 edition and the 2017 edition. As an improvement, it has also included known limitations for each method\textsuperscript{1}.

An additional limitation of the 2017 methodology was discovered by the authors of this paper, and was published in a previous paper\textsuperscript{2}. The 2017 methodology has limited applicability when dealing with different tunnel sizes.

This paper further develops concepts introduced in reference\textsuperscript{2}. It describes an update to the 2017 methodology which improves on applicability for different tunnel sizes. It takes inspiration from the NFPA 502 2017 Annex D references (\textsuperscript{3}, \textsuperscript{4}, and \textsuperscript{5}), by changing the variable Froude number dependency from total Heat Release Rate (HRR) to dimensionless Heat Release Rate. The new methodology improves on the 2017 methodology, however other areas for research remain.

KEYWORD: Critical Velocity, Froude number, dimensionless Heat Release Rate, total Heat Release Rate, convective Heat Release Rate, NFPA 130, NFPA 502

NOMENCLATURE

\begin{itemize}
\item $V_c =$ Critical Velocity (m/s or fpm)
\item $V_c^* =$ Dimensionless Critical Velocity
\item $K_f =$ Froude number factor, Fr\textsuperscript{-1/3}
\item $Fr =$ Froude number, ratio of gravity (buoyancy) forces to inertia forces
\item $K_g =$ grade factor
\item $g =$ acceleration caused by gravity (m/s\textsuperscript{2} or ft/s\textsuperscript{2})
\item $H =$ the height from the base of the fire to the tunnel ceiling at the fire site (not tunnel height) (m or ft)
\item $H_t =$ tunnel height (m or ft)
\item $H_d =$ tunnel hydraulic diameter (m or ft)
\item $Q =$ total Heat Release Rate (kW or Btu/s)
\item $Q_c =$ heat fire is adding directly to air at the fire site, convective Heat Release Rate (kW or Btu/s)
\item $Q*$ = dimensionless total Heat Release Rate based on tunnel height
\item $Q'' =$ dimensionless total Heat Release Rate based on tunnel hydraulic diameter
\item $Q' =$ dimensionless total Heat Release Rate based on the height from the base of the fire to the tunnel ceiling at the fire site
\end{itemize}
For decades, Critical Velocity has been a key concept for the design of longitudinal smoke control TVS around the world. Critical Velocity is defined as “the minimum steady-state velocity of the ventilation system’s airflow moving toward a fire within a tunnel or passageway required to prevent backlayering at the fire site” in NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways 2023 Edition [1]. To satisfy such a requirement, equation-based methodologies are widely used as design criteria by the industry. Since 1996, NFPA 502 has been the only widely adopted standard that has maintained recommendations on the methodologies in its Annex material, which is provided as informational only and not as part of the requirement. This is because the Critical Velocity calculation methodology is considered as an active area of research.

However, many Authority Having Jurisdictions (AHJ) and practitioners routinely rely on the Critical Velocity calculation methodologies to design TVS. It is crucial for the NFPA 502 Annex D users to understand the limitation of each calculation methodologies. The 2023 Edition of NFPA 502 has recognized the gap. The current Annex D material has included the limitations of each calculation methodology [1].

In a recent publication at ISAVFT 2022, an additional limitation of the NFPA 502 2017 Critical Velocity calculation methodology was described by the authors of this paper in Reference [2].

This paper explores the possibility of further improving the applicability of the current NFPA 502 Annex D Critical Velocity calculation methodology.

**NFPA 502 CRITICAL VELOCITY CALCULATION METHODOLOGY HISTORY**

For the first time, as part of the 1996 edition, NFPA 502 published a Critical Velocity calculation methodology as part of its Annex material [6]. The methodology is shown below. Equations (1) and (2) are intended to be solved iteratively, while the effect of the slope is captured by Eq. (3). The derivation and application were published by Kennedy et al. in 1996 [7].

\[ V_c = K_1 K_g \left( \frac{g H Q_c}{\rho C_p A T_f} \right)^{\frac{1}{2}} \]  
\[ T_f = \left( \frac{Q_c}{\rho C_p A V_c} \right) + T \]  
\[ K_g = \begin{cases} 1 + 0.03747(G)^{0.8}, & G < 0 \\ 1, & G \geq 0 \end{cases} \]

These equations are based on the Froude number modelling concept. The critical Froude number factor, \( K_1 = 0.606 \), was chosen conservatively based on scale-model fire tests in ducts [8] [9] [10]. Soon after the original publication, an update was issued by Kennedy in June 1997. In the revision, the authors pointed out that based on the Memorial Tunnel Fire Ventilation Test Program (MTFVTP),
for small fires (less than 10 MW), the equations slightly underpredict the Critical Velocity. For large fires (50-100 MW), the equations overpredict the Critical Velocity by 4 to 20 percent [11].

Despite several research publications’ attempt to improve the calculation methodology, the methodology remained unchanged in NFPA 502 Annex D up to the 2014 edition. For simplicity, the calculation methodology will be called the 2014 methodology in this paper. It was not until 2017 (NFPA 502 is on a 3 year revision cycle) that NFPA 502 updated its Critical Velocity Annex methodology based on publications from Oka and Atkinson [3], Wu and Bakar [4], and Li et al [5]. The 2017 NFPA 502 Critical Velocity calculation methodology retained the 2014 equations but added a variable Froude number factor table (Table 1), where the Froude number factors vary with the total Heat Release Rate (HRR).

<table>
<thead>
<tr>
<th>Q (MW)</th>
<th>K_i</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;100</td>
<td>0.606</td>
</tr>
<tr>
<td>90</td>
<td>0.62</td>
</tr>
<tr>
<td>70</td>
<td>0.64</td>
</tr>
<tr>
<td>50</td>
<td>0.68</td>
</tr>
<tr>
<td>30</td>
<td>0.74</td>
</tr>
<tr>
<td>&lt;10</td>
<td>0.87</td>
</tr>
</tbody>
</table>

NFPA 502 2017 edition introduced a new set of equations. However, they were removed by a Tentative Interim Amendment (TIA) issued in 2021.

To fill the void resulting from the TIA, NFPA 502 2023 Edition published the 2014 and 2017 Critical Velocity calculation methodologies. Several improvements were made, including the emphasis that the equation-based Critical Velocity calculation is an area of active research and discussion in the industry, the inclusion of the limitations for both the 2014 and the 2017 methodologies, as well as the recognition that other smoke control equations, on-site test results, and numerical modelling can be applied to determine Critical Velocity [1].

However, an error was subsequently identified in the NFPA 502 2023 Annex D. The title of the Table D.3.1.2 claims the Froude number factors vary based on convective HRR. It was confirmed by Li and Ingason [13] that the original 2017 variable Froude number factor table is based on total HRR and not convective HRR. Consequently, Figure D.3.1.2 from NFPA 502 2023 Annex D [1] is incorrect as well. A corrected Figure D.3.1.2 is shown in Figure 1. The 2017 methodology plot is lower in Figure 1 than in Figure D.3.1.2 of NFPA 502 2023 Edition.

As presented in Figure 1, NFPA 502 2017 methodology exhibits better Critical Velocity predictions than the NFPA 502 2014 methodology for small fires when compared to MTFVTP data. For large fires, the 2017 methodology predicts higher Critical Velocity values than the 2014 methodology. As claimed by Kennedy [11], the 2014 methodology overpredicts the Critical Velocity values when compared to MTFVTP for HRR values between 50-100 MW. Therefore, the 2017 methodology also overpredicts the Critical Velocity for large fires.
Figure 1  NFPA 502 2017 Figure D.3.1.2 Corrected: 2014 and 2017 Critical Velocity Calculation Methodologies vs. MTFVTP Data [1], noting that the MTFVTP “backlayering controlled” data are included for indicative purposes only, they are not true Critical Velocity [14] [15].

Additionally, when compared to Figure 6 of Kennedy’s paper [11], the MTFVTP data plotted in Figure 1 are not identical. The MTFVTP data set shown in Figure 1 uses a 17% blockage ratio correction on the air velocity values (as stated in NFPA 502 2023 [1]) while the MTFVTP data set shown by Kennedy is the average bulk air velocity. Although discussion of the treatment of the MTFVTP data is not the focus of this paper, it is important to recognize that Kennedy’s statement [11] on the 2014 methodology of underpredicting critical velocity for small fires is shifted from below 10 MW to approximately below 20 MW total HRR as shown in Figure 1. The overprediction range has not shifted because of the asymptotic relationship; it remains at approximately above 50 MW total HRR.

The 2023 edition of NFPA 502 Annex D also highlighted the MTFVTP’s limitations. The “backlayering controlled” results obtained from MTFVTP are generally not considered as Critical Velocity. They are often either under-ventilated (not achieving the Critical Velocity) or over-ventilated (exceed the Critical Velocity). According to the MTFVTP reports [14] [15], when backlayering was “controlled”, smoke was noted to be generally confined to within 12 m of the fire location. Smoke confinement air velocity is considered under-ventilated when compared to Critical Velocity. On the other hand, it was also noted that it was difficult to fine tune the ventilation power to achieve the exact Critical Velocity. Therefore, in some backlayering controlled cases, the smoke may be over-ventilated.

ADDITIONAL NFPA 502 2017 EDITION CRITICAL VELOCITY CALCULATION METHODOLOGY LIMITATION

NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems, is another standard that references the concept of Critical Velocity [16]. However, it does not provide a calculation methodology for determining Critical Velocity. NFPA 130 users often reference the NFPA 502 Annex for guidance. NFPA 130 is applicable for transit infrastructure. Single guideway transit tunnels are often smaller in cross-sectional area than that of multi-lane highway tunnels. When the authors of this paper performed the Critical Velocity calculation on a transit tunnel rehabilitation project, the limitation of the NFPA 502 2017 Critical Velocity calculation methodology for different tunnel sizes became apparent. This anomaly subsequently led to the publication at ISAVFT 2022 [2].
Reference [2] demonstrated that when the 2017 methodology was applied to a smaller size tunnel than that of the MTFVTP, the behaviour of the Critical Velocity versus total HRR graph cannot be explained. For example, the 3 m by 3 m tunnel Critical Velocity calculation results are illustrated in Figure 2. In addition to the NFPA 502 2014 and 2017 methodologies, Wu and Bakar’s [4], as well as Li et al.’s [5], scale-model experimental calculation methodologies are also plotted in Figure 2. These are two of the supporting references for the 2017 edition of NFPA 502 Annex D:

1. Wu and Bakar [4] equations:

\[
V_c = \begin{cases} 
0.4 \left( \frac{Q'}{0.20} \right)^{\frac{3}{5}} \sqrt{gH_d}, & Q' \leq 0.20 \\
0.40 \sqrt{gH_d}, & Q' > 0.20 
\end{cases} 
\]  

Where \( Q'' \) is the dimensionless total HRR based on hydraulic diameter of the tunnel (\( H_d \)):

\[
Q'' = \frac{Q}{\rho_c \sigma_p T g^\frac{1}{2} H_d^\frac{5}{2}} 
\]

2. Li et al. [5] equations:

\[
V_c = \begin{cases} 
0.81 (Q^*)^{\frac{1}{5}} \sqrt{gH_t}, & Q^* \leq 0.15 \\
0.43 \sqrt{gH_t}, & Q^* > 0.15 
\end{cases} 
\]

Where \( Q^* \) is the dimensionless total HRR based on the tunnel height (\( H_t \)):

\[
Q^* = \frac{Q}{\rho_c \sigma_p T g^\frac{1}{2} H_t^\frac{5}{2}} 
\]
The following input parameters and assumptions were used to perform the Critical Velocity calculations on a hypothetical tunnel to produce Figure 2:

- Base of the fire was set on the floor of the tunnel to eliminate discrepancies between the three parameters: $H = H_t = H_d = 3$ m;
- Square aspect ratio tunnel geometry was used to eliminate the difference between Li et al. tunnel height parameter and Wu and Bakar tunnel hydraulic diameter parameter: $H_t = H_d$. The difference between using tunnel hydraulic diameter and tunnel height will not be discussed; this paper will limit its applicability to square tunnels;
- 30% Radiative fraction was assumed;
- Standard ambient conditions were applied with air temperature = 15°C, air density = 1.225 kg/m³, and specific heat of air = 1.006 kJ/(kg-K);
- 0% Tunnel gradient was used.

Of the four methodologies plotted, the NFPA 502 2017 methodology displayed an incorrect trend where the Critical Velocity was highest at approximately 15 MW total HRR. Mathematically, and in practical physics, it is unrealistic to predict a higher Critical Velocity value for a small total HRR fire than a large total HRR fire. The NFPA 502 2017 referenced publications [4] [5] do not display the same trend. This indicated an inconsistency in the NFPA 502 2017 edition, where the applicability limitation was not captured.

This discovery led to an investigation on the NFPA 502 2017 methodology. It was identified that the variable Froude number factor table (Table 1) uses HRR while the referenced publications [3] [4] [5] use dimensionless HRR. The dimensionless HRR is proportional to tunnel size (either height or hydraulic diameter) as shown in Eq. (5) and Eq. (7). The unusual behaviour of the NFPA 502 2017 edition methodology demonstrated in Figure 2 may be explained and corrected by using Dimensionless HRR.

**THE DIMENSIONLESS HRR METHODOLOGY**

To convert Table 1 into a relationship between the variable Froude number factors and the dimensionless HRR, Eq. (7) is used. The following parameters are used for the conversion. They are provided by Li and Ingason from the history of NFPA 502 working group discussion for the publication of the 2017 methodology [13].

- Ambient air temperature: $T = 15^\circ$C
- Ambient air density: $\rho = 1.225$ kg/m³
- Specific heat of air: $c_p = 1.006$ kJ/(kg-K)
- Tunnel height: $H_t = 5.0$ m*
- Gravitational acceleration: $g = 9.81$ m/s²

*The 5.0 m tunnel height was used during the working group discussion [13] because it is a common road tunnel size. The U.S. Department of Transportation Federal Highway Administration also suggests similar tunnel height [17].

It is recognized that there is an ongoing debate on the characteristic tunnel size definition:

1. the tunnel hydraulic diameter [4]; or
2. the tunnel height [5]; or
3. the height from the base of the fire to the tunnel ceiling at the fire site [1].

Tunnel height is used for this paper. If future verified and validated research indicates otherwise, future modifications may be appropriate.
Table 2 shows the relationship between the dimensionless HRR and the variable Froude number factors.

<table>
<thead>
<tr>
<th>Q (MW)</th>
<th>$Q^*$</th>
<th>$K_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt;$100</td>
<td>$&gt;$1.608</td>
<td>0.606</td>
</tr>
<tr>
<td>90</td>
<td>1.448</td>
<td>0.62</td>
</tr>
<tr>
<td>70</td>
<td>1.126</td>
<td>0.64</td>
</tr>
<tr>
<td>50</td>
<td>0.804</td>
<td>0.68</td>
</tr>
<tr>
<td>30</td>
<td>0.483</td>
<td>0.74</td>
</tr>
<tr>
<td>$&lt;$10</td>
<td>$&lt;$0.1608</td>
<td>0.87</td>
</tr>
</tbody>
</table>

The variable Froude number factor table for a 3 m by 3 m square tunnel at standard ambient condition is calculated by solving total HRR ($Q$) in Eq. (7). The results are listed side by side with NFPA 502 2017 Methodology as shown in Table 3.

<table>
<thead>
<tr>
<th>Dimensionless HRR Methodology</th>
<th>NFPA 502 2017 Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^*$ (MW)</td>
<td>Q (MW)</td>
</tr>
<tr>
<td>$&gt;$1.608</td>
<td>$&gt;$28</td>
</tr>
<tr>
<td>1.448</td>
<td>25</td>
</tr>
<tr>
<td>1.126</td>
<td>19.5</td>
</tr>
<tr>
<td>0.804</td>
<td>14</td>
</tr>
<tr>
<td>0.483</td>
<td>8.4</td>
</tr>
<tr>
<td>$&lt;$0.1608</td>
<td>$&lt;$2.8</td>
</tr>
</tbody>
</table>

In comparison, the two methods (dimensionless HRR method and NFPA 502 2017 method) exhibit different total HRR ranges with the same range of variable Froude number factors as shown in Table 3. The Critical Velocity can be calculated using the dimensionless HRR methodology which replaces the variable Froude number factor Table from NFPA 502 2017 edition with the corresponding dimensionless HRR columns in Table 3.

Figure 3 Critical Velocity Calculation Methodologies Comparison for a 3 m by 3 m Tunnel (Including Dimensionless HRR methodology)
Figure 3 shows the results comparing all five methodologies. The updated dimensionless HRR methodology eliminates the peak around 15 MW total HRR shown by the 2017 methodology. It also displays higher Critical Velocities compared to the NFPA 502 2014 methodology for small fires (lower than 40 MW). For large fires (greater than 40 MW), however, it displays identical behaviour as the NFPA 502 2014 methodology. The figure shows that both Li et al. and Wu and Bakar methodologies asymptotically reaches a maximum Critical Velocity. Consequently, both scale-model methodologies predict lower Critical Velocity values for large fires compared to NFPA 502 2014 methodology and the dimensionless HRR methodology.

The verification and validation of scaling is still an active area of discussion [18]. Additionally, the scale-model methodologies (Eqs. (4) and (6)) do not include tunnel area as an input parameter. Tunnel area is an important parameter because it is the only parameter in the NFPA 502 methodologies that accounts for tunnel blockage. The importance of the blockage effect cannot be overlooked as all real tunnel fires and scale model fires contain tunnel blockages of varying significance. Therefore, the scale-model experimental methodologies from NFPA 502 2017 Annex D references cannot be adopted without modification. As an active research topic, recent research publications have taken blockage ratio into consideration (e.g. [19], [20]). Since NFPA 502 Annex D is always seeking to improve on the equation based Critical Velocity calculation method, update to the blockage ratio effect may be implemented in the future cycles.

The NFPA 502 2017 Critical Velocity calculation methodology has limited applicability to tunnels with sizes deviating from the 5 m by 5 m typical road tunnel. To demonstrate this, three different tunnel sizes are used to compare the variability of the HRR ranges for the Froude number factors as shown in Table 4.

<table>
<thead>
<tr>
<th>$Q^*$</th>
<th>$Q_{H=3\text{m}}$ (MW)</th>
<th>$Q_{H=5\text{m}}$ (MW)</th>
<th>$Q_{H=7\text{m}}$ (MW)</th>
<th>$K_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;1.608</td>
<td>&gt;28</td>
<td>&gt;100</td>
<td>&gt;232</td>
<td>0.606</td>
</tr>
<tr>
<td>1.448</td>
<td>25</td>
<td>90</td>
<td>209</td>
<td>0.62</td>
</tr>
<tr>
<td>1.126</td>
<td>19.5</td>
<td>70</td>
<td>162</td>
<td>0.64</td>
</tr>
<tr>
<td>0.804</td>
<td>14</td>
<td>50</td>
<td>116</td>
<td>0.68</td>
</tr>
<tr>
<td>0.483</td>
<td>8.4</td>
<td>30</td>
<td>70</td>
<td>0.74</td>
</tr>
<tr>
<td>&lt;0.1608</td>
<td>&lt;2.8</td>
<td>&lt;10</td>
<td>&lt;23</td>
<td>0.87</td>
</tr>
</tbody>
</table>

A graphical representation of the relationship between the convective HRR and the variable Froude number factor are plotted in Figure 4 for the three different tunnel sizes listed in Table 4. For a 3 m by 3 m tunnel convective HRR varies between 2.8 MW to 28 MW; a 5 m by 5 m tunnel convective HRR varies between 10 MW to 100 MW; a 7 m by 7 m tunnel convective HRR varies between 23 MW to 232 MW.
A comparison between the 2017 methodology and the dimensionless HRR methodology is demonstrated in Figure 5 and Figure 6 for the 5 m by 5 m and 7 m by 7 m tunnels, respectively.

Not surprisingly, the 2017 methodology produced identical Critical Velocity results to the dimensionless HRR methodology for the 5 m by 5 m tunnel (Figure 5).

Contrary to the other two tunnel sizes presented, the 2017 methodology underpredicts the Critical Velocity when compared to the dimensionless HRR methodology and the scale-model experimental calculation methodologies for the 7 m by 7 m tunnel as shown in Figure 6. This suggests that for a tunnel size bigger than a 5 m by 5 m typical road tunnel, TVS may be undersized if it is designed based on the NFPA 502 2017 methodology.
Referring to Wu and Bakar [4] and Li et al. [5], their presented results were developed from scale-model experiments and were studied comparatively with full-scale tests. Figure 7 shows that the dimensionless HRR methodology closely match Wu and Bakar and Li et al. data. This clearly shows that the dimensionless HRR methodology better predicts the scale-model 250 mm by 250 mm tunnel experimental data than the NFPA 502 2017 methodology.

There are questions and uncertainties surrounding the comparability between scale-model data and full-scale fire test data (e.g., MTFVTP) [18] as the dimensionless HRR methodology does not address these issues. However, use of the dimensionless HRR improves on the applicability of the NFPA 502 Critical Velocity calculation methodology.
To further demonstrate the limitation of the NFPA 502 2017 methodology (also included by the NFPA 502 2023) and the improvement made by applying the dimensionless HRR methodology, all five tunnel size calculations were nondimensionalized by using Eq. (7) and Eq. (8). Both Wu and Bakar and Li et al. used a form of Eq. (8). Equation (7) was used to normalize the total HRR parameter while Eq. (8) was used to normalize the velocity parameter.

\[ V_c^* = \frac{V_c}{\sqrt{gH_t}} \]  

With both parameters normalized, the plots for each method were expected to be identical for different tunnel sizes. As shown in Figure 8, of the three methodologies plotted (NFPA 502 2014, 2017, and dimensionless HRR methods), the 2017 methodology showed variability with different tunnel sizes. Hence, the dimensionless HRR methodology removed the peaking behaviour observed in the 2017 methodology. The dimensionless HRR methodology also predicts higher Critical Velocity with small fires which seemingly resolves the issue stated by Kennedy on the 2014 methodology [11].

**CONCLUSIONS AND RECOMMENDATIONS**

This paper has presented a potential remedy to one of the limitations of the NFPA 502 2017 Critical Velocity calculation methodology included in the current NFPA 502 2023 Edition Annex D. It addresses a limitation of the 2017 methodology demonstrated mathematically in Reference [2]. The recommended approach is derived from the referenced equations (Eqs. (1), (2), and (3)) in the NFPA 502 2014 and 2017 methodologies.

Instead of the variable Froude number factor table provided in the 2017 methodology, a new table (Table 5) which varies the Froude number factor based on the dimensionless HRR is proposed by following the original research papers [3] [4] [5] referenced by NFPA 502 2017 edition.
Table 5  Variable Froude Number Factors based on Dimensionless HRR

<table>
<thead>
<tr>
<th>Q*</th>
<th>K_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;1.608</td>
<td>0.606</td>
</tr>
<tr>
<td>1.448</td>
<td>0.62</td>
</tr>
<tr>
<td>1.126</td>
<td>0.64</td>
</tr>
<tr>
<td>0.804</td>
<td>0.68</td>
</tr>
<tr>
<td>0.483</td>
<td>0.74</td>
</tr>
<tr>
<td>&lt;0.1608</td>
<td>0.87</td>
</tr>
</tbody>
</table>

To solve for dimensionless HRR (Q*), the normalizing Eq. (7) should also be included. There is an ongoing debate on the characteristic tunnel size definition. Tunnel height (H_t) was used in this paper. If future verified and validated research indicates otherwise, other modifications may be appropriate.

This paper focused on solving the particular limitation with the 2017 methodology, thus improving the applicability of the NFPA 502 2023 Edition Annex D Critical Velocity calculation methodology. The 2017 methodology can only be applied to tunnels with size similar to a 5 m by 5 m typical road tunnel. The dimensionless HRR method can be applied to other tunnel sizes as it addresses the trend observed in the 2017 methodology.

It is recognized that equation-based Critical Velocity calculation methodology is an area of active research and discussion. There exist several ongoing debates regarding the subject: from combustion chemistry to fire geometry, from tunnel aspect ratio to blockage ratio, from tunnel slope effect implementation to characteristic tunnel size definition, and from scale-modelling verification and validation to interpretation of the MTFVTP data.

As an active area of research, it is the responsibility of the engineer to survey the available calculation methodologies for solving Critical Velocity. With active research and discussions, engineers are advised to pick the appropriate methodology at the time of application for the particular TVS design.

REFERENCES


Numerical study on the influence of the ventilation strategy on life safety in a metro tunnel

Matteo Pachera, Wouter Van den Berghe, Luc Derie & Johan Dubruel
Sweco Belgium, Brussels, Belgium

ABSTRACT

The present article investigates the impact of the ventilation regime on the passengers’ life safety level in a metro tunnel equipped with a longitudinal ventilation system. Coupled analyses of smoke spread and evacuation are proposed to quantify the consequences of passengers’ exposure to smoke during the evacuation. Different scenarios are considered with different positions of the metro train along the tunnel and different positions of the fire on the train. The consequences of the exposure to untenable conditions are quantified for the different scenarios and the different ventilation conditions; the FED and the FED$_{th}$ are calculated for each passenger. The global results show that a higher ventilation regime allows to minimize the FED for the passengers, therefore, to guarantee a higher chance of evacuating safely. This is mostly caused by the presence of smoke upstream the fire which descends on the passengers when using a lower ventilation speed. On the other hand, the FED$_{th}$ is generally higher for a higher ventilation speed because the hot and cold layers are better mixed. However, the FED$_{th}$ is generally lower than the FED, thus less critical for passengers’ life safety. Based on this study, a three-dimensional model shall be used for the analysis of smoke spread including both the tunnel and the interiors of the train.

KEYWORD: metro tunnel, coupled CFD-Evacuation, ventilation strategy

INTRODUCTION

In case of a fire in a metro tunnel equipped with longitudinal ventilation there is the risk that some passengers must evacuate in smoke. This exposure to smoke if extended in time might prevent the passengers from evacuating autonomously from the tunnel. The ventilation strategy plays a fundamental role in the evolution of the tenability conditions in the tunnel. Low ventilation speeds are beneficial in maintaining a stratified smoke layer underneath which passengers can evacuate. However, smoke can spread in both directions and expose more passengers. Higher ventilation speeds, above the critical velocity, allow to confine the smoke only on one side of the fire and to better dilute it. However, the smoke loses stratification at higher speed, so passengers evacuate in an untenable environment. Different authors [1-3] already investigated this problem highlighting how the conflicting effects of stratification and dilution of smoke don’t allow to find an easy answer on the most optimal ventilation strategy.

CASE OF STUDY

The present article presents a case of study of a fire in a metro tunnel where two ventilation strategies are compared to each other. A low ventilation regime is generally proposed to maintain smoke stratification, allowing smoke spread upstream and downstream the fire. A high ventilation speed regime is proposed to confine the smoke upstream on one side of the fire and to dilute toxic smoke. There are advantages and disadvantages in both strategies, therefore the two are quantitatively compared to evaluate which strategy guarantees better conditions for passengers’ evacuation in case of fire in a tunnel.
Tunnel and train
The proposed analysis is carried out in a metro tunnel connecting two stations 700 m apart. The tunnel is bidirectional; therefore, the passengers need to reach the closest station to evacuate and there are no intermediate shafts or exits. The tunnel has a rounded section with a diameter of 8.7 m and a height of 6.6 m. Emergency walkways are installed on the sides of the tunnel, 0.8 m wide.

The tunnel is equipped with a longitudinal ventilation system that is activated in case of fire detection in the train. The ventilation system is designed to deliver a longitudinal ventilation of 2.7 m/s, but lower speeds can be reached as well. The ventilation direction is based only on the location of the train in the tunnel and not on the location of the fire on the train. Therefore, smoke is pushed towards the closest station in order to minimize the exposure of the passengers who might evacuate in smoke.

In case of fire the train should always drive to the closest station to evacuate the passengers. However, in the study it is assumed that a fire breaks out on the train preventing it from reaching the next station. The train is composed of six railcars connected with an open gangway structure that possibly exposes all passengers to smoke. As the train stands in the tunnel, different train locations are investigated between the two stations, 50 m, 150 m, 250 m, 350 m, 450 m, 550 m and 650 m. The analysis of different positions allows to compute the risk for passengers for the whole tunnel and not for only one location. The scenarios at 450 m, 550 m and 650 m are expected to give the same results as respectively the scenario at 250 m, 150 m and 50 m, because the ventilation direction is reversed. Different fire scenarios are considered also on the train, at the front in the center and at the back of the train relative to the ventilation direction.

In case of a fire at the front of the train it is assumed that most of the passengers are located downstream the fire. In case of a fire at the centre of the train it is assumed that about half of the passengers are located downstream the fire. In case of a fire at the back of the train it is assumed that most of the passengers are located upstream the fire.
Fire scenario
The fire scenario inside the train is chosen to represent a realistic worst-case scenario in a modern metro train where materials comply with the latest regulations [4-6]. The proposed curve is a medium growing fire curve with a peak HRR of 15 MW, reached after 18 minutes and 38 s. The fire is assumed to start in one railcar and to fully involve it in the burning process.

As the fire is vented with two ventilation regimes there could be a possible impact of the ventilation speed on the fire development (maximum HRR and growth rate). Different authors [1,7-8] proposed different correlations between the ventilation speed and the evolution of the fire. However, in the current study the fire breaks in the train where it affects the highest number of passengers. In the train the velocity field obtained with the two ventilation strategies is weakly affected by the velocity in the tunnel itself. Moreover, the presence of passengers in the first phases of the fire should create a blockage for the air recirculation in the train. The limited impact of ventilation on shielded fires was also shown experimentally in reference [8].

The smoke toxicity is another important parameter for the study as the amount of inhaled toxic smoke that cumulates in the blood has consequences on the possibility of self evacuating. Based on experimental data available in literature a CO yield of 0.10, a HCl yield of 0.039 and a HCN yield of 0.01 are proposed [9-11]. These values are conservative and possibly cover most of the fuels in well ventilated fires.
Passengers

In the study the train is assumed to travel at the design capacity as worst-case scenario. There are in total 800 occupants in the train which are uniformly distributed in the train, with exception for the car affected by fire. Passengers are assumed to move away from the source of the fire towards the other cars. Once on the walkway, passengers are expected to move away from the fire towards the station.

<table>
<thead>
<tr>
<th>Car 1</th>
<th>Car 2</th>
<th>Car 3</th>
<th>Car 4</th>
<th>Car 5</th>
<th>Car 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Centre</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Back</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
</tbody>
</table>

Passengers are modelled to be representative of different groups in the society: children, adults, elderly and passengers with reduced mobility (PRM). These passengers have different walking speeds which are assigned to each group [12].

<table>
<thead>
<tr>
<th>Group</th>
<th>Age [years]</th>
<th>Percentage</th>
<th>Mean [m/s]</th>
<th>Std [m/s]</th>
<th>Min [m/s]</th>
<th>Max [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRM</td>
<td>0-99</td>
<td>3.0%</td>
<td>0.56</td>
<td>0.24</td>
<td>0.36</td>
<td>0.75</td>
</tr>
<tr>
<td>Children</td>
<td>0-15</td>
<td>13.8%</td>
<td>1.00</td>
<td>0.25</td>
<td>0.50</td>
<td>1.5</td>
</tr>
<tr>
<td>Adults</td>
<td>16-55</td>
<td>65.8%</td>
<td>1.11</td>
<td>0.25</td>
<td>0.72</td>
<td>1.5</td>
</tr>
<tr>
<td>Elderly</td>
<td>56-80</td>
<td>17.4%</td>
<td>0.91</td>
<td>0.26</td>
<td>0.65</td>
<td>1.17</td>
</tr>
</tbody>
</table>

In the study the correlation proposed by Jin is used to limit the walking speed of the passengers when they walk through smoke. It is assumed that the smoke is irritant and when the extinction coefficient exceeds coefficient exceed 0.45 1/m the walking speed drops to 0.3 for all passengers’ groups [13].

Order of events

Before passengers start leaving the train and evacuate there is a premovement time which is the sum of different time components. The fire is detected by smoke detectors in each railcar, this is estimated equal to 30 s based on CFD calculation. There are additional 90 s required by the operator which receives the alarm to confirm the alarm and to open the doors. At the same time after 120 s the ventilation is also started.

Once the doors are open the passengers in the vicinity of the fire that are already in smoke (low visibility conditions) leave the train immediately. However, other passengers who are not in smoke start moving with an additional delay following a statistical distribution. A normal distribution is proposed with mean value 90 s and standard deviation of 26 s, based on reference [14].

Evaluation of the consequences

The risk for the passengers to be unable to evacuate autonomously is related to the exposure to untenable conditions during the evacuation process. In case of exposure to smoke there are different threats for the passengers. The exposure to toxic gasses and their cumulation in the blood is described by the Fractional Effective Dose, FED, which was proposed by Purser in reference [15-16]. Considering the toxic species modelled in the study the formulation of the FED is simplified as follows:

\[
FED = \left( \int_0^t 2.764 \times 10^{-5} (C_{CO}(t))^{1.036} + \frac{C_{HCN}(t)}{220} - 0.0045 + \frac{C_{HCl}(t)}{F_{FLD,HCl}} \right) e^{\frac{0.1903C_{CO2}(t)+2.0004}{7.1}} dt
\]
Tenth International Symposium on Tunnel Safety and Security, Stavanger, Norway, April 26-28, 2023

Where \( C_{CO} \) is the volume fraction of Carbon Monoxide in ppm, \( C_{HCN} \) is the volume fraction of Hydrogen cyanide in ppm, \( C_{HCl} \) is the volume fraction of Hydrogen chloride in ppm, \( C_{CO_2} \) is the volume fraction of Carbon dioxide in percentage and \( C_{O_2} \) is the volume fraction of oxygen in percentage.

Alongside the exposure to toxic gases there is also the exposure to high temperatures and levels of radiation which cause skin burns. The combined effect of the two is cumulated by the passengers and it is described by the thermal fractional effective dose, \( FED_{th} \) [17].

\[
FED_{th} = \int_{0}^{t} \left( \frac{q^{1.56}}{6.9} + \frac{T^{3.4}}{5 \times 10^7} \right) dt
\]

Where \( q \) is the radiative incident heat flux and \( T \) is the temperature. The original model of the FED assumed that incapacitation is reached once the value is higher than 1.0 [15]. However, lower values, 0.3, are sometimes suggested to account for incapacitation of weaker passengers [17].

NUMERICAL APPROACH

In order to evaluate the impact of the ventilation strategy on the passengers’ life safety the smoke spread, and the evacuation process are investigated through numerical analyses.

Analysis of the smoke spread

The evolution of the flow field inside the train and the tunnel is investigated through computational fluid dynamics (CFD). The software Fire Dynamics Simulator FDS 6.7.9 [18] is used to simulate the fire and the two ventilation systems. The numerical model includes the train with its interiors and the tunnel. The region of the train is discretized with a resolution of 0.125 m while the tunnel is discretized with a resolution of 0.25 m. This allows to properly represent the geometrical features of the train. The domain of the tunnel is also extended in order to obtain results for different train’s locations. The tunnel domain is extended 650 m upstream the train and 450 m downstream the train.

The ventilation strategy is implemented as a uniform velocity at the portal of the tunnel. However, thanks to the additional domain the flow field can develop freely before interacting with the smoke and the train. The results obtained from the CFD calculation in terms of toxic species’ concentrations, temperature, radiation intensity and visibility are elaborated and implemented in the evacuation analysis.

Analysis of the evacuation process

The analysis of the evacuation process is carried out with the software Pathfinder (2022) [19]. The software allowed to implement the different walking speeds for the different passengers and the walking speed reduction caused by reduced visibility conditions. The evacuation model was also used to trace the position in time of each occupant so the FED and \( FED_{th} \) can be calculated for each occupant. As for the CFD model also the evacuation model includes both the train and the evacuation route. As discussed above the walking speed and the premovement time are defined with a statistical distribution, therefore multiple runs (5) of the same case were executed.

ANALYSIS OF THE RESULTS

The results of the different scenarios in terms of fire and train locations are presented in this section. As the train has an open gangway and the smoke can affect all passengers, therefore, the tenability conditions are presented inside the train and inside the tunnel. The variables presented at 2 m high for each scenario are:

- Extinction coefficient
- Carbon monoxide volume fraction
- Temperature
A low visibility or high extinction coefficient doesn’t harm per se the passengers, but it negatively impacts the walking speed [13]. High concentrations of carbon monoxide, carbon dioxide and hydrogen cyanide cause incapacitation of the passengers due to asphyxia which is summarized in the FED. High temperature and radiative heat fluxes cause incapacitation of the passengers due to skin burns which is summarized in the FEDh.

Fire at the front of the train
In this section the first fire location is investigated with a fire located at the front of the train. The extinction coefficient is presented in Figure 5 for both ventilation regimes.

![Figure 5](image1.png)

**Figure 5**  Extinction coefficient [1/m] along the walkways in the tunnel (low ventilation left, high ventilation right)

The CO concentration is presented in Figure 6 for both ventilation regimes inside and outside the train.

![Figure 6](image2.png)

**Figure 6**  Extinction coefficient [1/m] along the walkways in the tunnel (low ventilation left, high ventilation right)
The temperature is presented in Figure 7 for both ventilation regimes inside and outside the train.

The results of the CFD analysis are implemented in the evacuation model in order to estimate the number of incapacitated passengers in case of an accident. With this fire location all the passengers need to evacuate downstream the fire in smoke, the distance they need to cross depends on the position of the train in the tunnel. The number of incapacitated passengers is presented in Figure 8 and Table 3. For each position of the fire the number of passengers with a FED or FED$_{th}$ higher than 1.0 are presented and in brackets those with FED or FED$_{th}$ higher than 0.3

Table 3: Summary of FED and thermal FED for a fire in the front of the train.

<table>
<thead>
<tr>
<th>Train position</th>
<th>FED</th>
<th>FED th</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0 m/s</td>
<td>2.7 m/s</td>
</tr>
<tr>
<td>50 m (650 m)</td>
<td>0 (0)</td>
<td>0 (1)</td>
</tr>
<tr>
<td>150 m (550 m)</td>
<td>0 (94)</td>
<td>0 (201)</td>
</tr>
<tr>
<td>250 m (450 m)</td>
<td>0 (299)</td>
<td>0 (394)</td>
</tr>
<tr>
<td>350 m</td>
<td>2 (538)</td>
<td>7 (579)</td>
</tr>
</tbody>
</table>
Fire in the centre of the train
In this section the first fire location is investigated with a fire located at the centre of the train. The extinction coefficient is presented in Figure 9 for both ventilation regimes.

Figure 9 Cumulative distributions of the FED (left) and thermal FED (right) for the different ventilation strategies.

The CO concentration is presented in Figure 10 for both ventilation regimes inside and outside the train.

Figure 10: Extinction coefficient [1/m] along the walkways in the tunnel (low ventilation left, high ventilation right)
Figure 11  Carbon monoxide concentration [ppm] in the train (low ventilation top left, high ventilation top right) and along the walkways in the tunnel (low ventilation bottom left, high ventilation bottom right).

The temperature is presented in Figure 11 or both ventilation regimes inside and outside the train.
The results of the CFD analysis are implemented in the evacuation model in order to estimate the number of incapacitated passengers in case of an accident. With this fire location the passengers of the first two railcars can evacuate upstream the fire, while the other three need to evacuate downstream the fire in smoke. The distance they need to cross depends on the position of the train in the tunnel. The number of incapacitated passengers is presented in Figure 12 and Table 4. For each position of the fire the number of passengers with a FED or FED\textsubscript{th} higher than 1.0 are presented and in brackets those with FED or FED\textsubscript{th} higher than 0.3.

Table 4  Summary of FED and thermal FED for a fire in the front of the train.

\begin{tabular}{|c|c|c|c|c|}
\hline
Trains position & FED & & FED \textsubscript{th} & \\
 & 1.0 m/s & 2.7 m/s & 1.0 m/s & 2.7 m/s \\
\hline
50 m (650 m) & 0 (32) & 4 (56) & 0 (0) & 0 (4) \\
150 m (550 m) & 0 (48) & 28 (134) & 0 (0) & 0 (112) \\
250 m (450 m) & 0 (100) & 35 (266) & 0 (0) & 3 (197) \\
350 m & 0 (339) & 82 (403) & 0 (0) & 27 (274) \\
\hline
\end{tabular}
Figure 13  Cumulative distributions of the FED (left) and thermal FED (right) for the different ventilation strategies.

Fire in the rear of the train
In this section the first fire location is investigated with a fire located at the rear of the train. The extinction coefficient is presented in Figure 13 for both ventilation regimes.

Figure 14  Extinction coefficient [1/m] along the walkways in the tunnel (low ventilation left, high ventilation right)

The CO concentration is presented in Figure 14 for both ventilation regimes inside and outside the train.
The temperature is presented in Figure 15 for both ventilation regimes inside and outside the train.
The results of the CFD analysis are implemented in the evacuation model in order to estimate the number of incapacitated passengers in case of an accident. With this fire location the passengers of the first four railcars can evacuate upstream the fire, while the last one need to evacuate downstream the fire in smoke. The distance they need to cross depends on the position of the train in the tunnel. The number of incapacitated passengers is presented in Figure 16 and Table 5. For each position of the fire the number of passengers with a FED or FED\textsubscript{th} higher than 1.0 are presented and in brackets those with FED or FED\textsubscript{th} higher than 0.3

Table 5  Summary of FED and thermal FED for a fire in the front of the train.

<table>
<thead>
<tr>
<th>Trains position</th>
<th>FED 1.0 m/s</th>
<th>FED 2.7 m/s</th>
<th>FED \textsubscript{th} 1.0 m/s</th>
<th>FED \textsubscript{th} 2.7 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 m (650 m)</td>
<td>145 (240)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (1)</td>
</tr>
<tr>
<td>150 m (550 m)</td>
<td>172 (260)</td>
<td>0 (0)</td>
<td>0 (6)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>250 m (450 m)</td>
<td>162 (251)</td>
<td>0 (2)</td>
<td>0 (0)</td>
<td>3 (4)</td>
</tr>
<tr>
<td>350 m</td>
<td>195 (293)</td>
<td>0 (86)</td>
<td>0 (0)</td>
<td>0 (27)</td>
</tr>
</tbody>
</table>
Discussion
The results of the CFD analyses show how the smoke is well confined downstream the train in case of high ventilation speed and how it spreads upstream the fire in case of low ventilation speed. After few minutes after the fire breaks the visibility is lost in both ventilation regimes, therefore there is not a clear layer of smoke floating above the passengers. However, in case of low ventilation speed the smoke spreads upstream the fire up to 250 m.

The velocities inside the train are generally lower compared to the velocities in the tunnel, however, once the fire reaches steady state the smoke spread in the train is different for the two ventilation regimes. The concentration of carbon monoxide in the train is affected as well by the ventilation regime. For the different fire locations on the train high CO concentrations are found closer to the origin of the fire for low ventilation regimes, while the high CO concentrations are more spread with high ventilation regime. In the tunnel the mixing of smoke and air occurs differently downstream for the two ventilation regimes. For a low ventilation regime, the CO concentration increases after 200 m downstream the fire, while for higher ventilation regimes it mixes quicker. In case of high ventilation regimes, the location of the fire also impacts the smoke destratification downstream the fire, for a fire at the front of the train the smoke layer tends to remain more compact compared to the other two fire locations. In low ventilation regimes there is a large recirculation zone of smoke upstream the fire with high CO concentrations.

The temperature is generally higher for high ventilation regimes downstream the fire. This explains why the $\text{FED}_{\text{th}}$ is generally higher with this ventilation regime. In case of low ventilation regime, the hot gasses tend to remain higher and don’t affect the passengers evacuating underneath. Also, in the zone where the smoke reverses the temperature remains limited.

The different results obtained for the different fire locations are combined in order to find which ventilation strategy allows to globally minimize the number of incapacitated passengers. This is done assuming that the fire in the three different locations on the train have the same probability.
Figure 18 Cumulative distributions of the FED (left) and thermal FED (right) for the different ventilation strategies.

Figure 17 shows that the higher ventilation speed guarantees an overall lower FED compared to the lower speed ventilation regime. The FED$_h$ is generally higher for the higher speed ventilation regime; however, the FED$_th$ is generally less critical than the FED. The results of the analysis show also that the FED cumulated in the train is not negligible for the total FED, therefore it should be included in this kind of investigations.

CONCLUSIONS

The study presented above compares the life risk for metro passengers in case of fire using two ventilation regimes. The scope of the study is to evaluate the ventilation regime that minimizes the risks for the passengers given as information the position of the train in the tunnel. Based on the results above the following conclusions can be made:

- In case of a fire in a railcar, which exposes the largest number of passengers to smoke, the impact of the ventilation speed on the HRR is negligible.
- The low ventilation regime is not capable to maintain a clean layer of fresh air under the smoke, however, it guarantees a better thermal stratification. Therefore, downstream the fire passengers evacuate is low visibility conditions in both ventilation regimes.
- The low ventilation regime creates a large smoke recirculation zone upstream the fire that can be very dangerous for the passengers because of the high concentration of toxic gasses.
- In the study both the Fractional Effective Dose and the Thermal Fractional Effective Dose are monitored. For a high-speed ventilation regime, the FED is generally lower compared to the FED obtained with a low-speed ventilation regime.
- For the low-speed ventilation regime the FED$_h$ is almost negligible because the hot gasses can remain better stratified. In the high-speed ventilation regime, the FED$_h$ is higher however it is always less critical than the FED.
- The combined impact of FED and FED$_th$ still requires further investigations, however, the results show that the FED$_h$ is less critical than the FED, therefore, the high-speed ventilation regime is considered to be safer.

REFERENCES

6. Åhnberg, N., Jönsson, A., “Design Fires in Swedish Railway Tunnels – How are Research Results Implemented and What are We Missing?”, Fourth International Conference on Fire in Vehicles, Baltimore, USA, 5-6, October, 2016
18. FDS-SMV (nist.gov)
19. Pathfinder | Thunderhead Engineering
Assessment of Jet Fan Installation Efficiency in a Shotcrete-Lined Drill & Blast Rail Tunnel

Iain Bowman, David Eckford, Sohail Alizadeh, Jay Ganeshalingam, Tommy Norris & Rebecca Zhao†
Mott MacDonald Canada Ltd, Vancouver, Canada
† Now with Goldman Sachs

ABSTRACT

An operational 1960s era single-bore, single-track, shotcrete-lined drill & blast freight rail tunnel required a new tunnel ventilation system (TVS) in order to support the expected future increase in traffic on the rail corridor. Due to confidentiality requirements, the location of the tunnel is anonymised in this paper. While the TVS is required to have the ability to maintain performance in event of fire in the tunnel, the primary function of this TVS is control of diesel locomotive emissions to provide a safe environment for train crews. The existing purge-type TVS was the critical constraint on traffic throughput and was incapable of upgrade to meet the new requirements. Following an optioneering exercise, a reversible longitudinal TVS design using jet fans installed within the tunnel was selected. Due to the corridor’s 24/7 operations with no scheduled engineering/maintenance periods, the jet fans were required to be installed with no excavation of niches for installation. Due to the constrained available space and the consequent non-standard installation, computational fluid dynamics (CFD) analysis was performed as part of the design process to develop a reasonable estimate of the jet fan installation efficiency. This was used as an input into 1-dimensional aerodynamic analysis of the TVS design performance. The design was taken through construction, installation and commissioning and the completed installation was demonstrated to meet the project requirements.

KEYWORDS: Tunnel refurbishment, system upgrade, ventilation system, jet fans, CFD, installation efficiency

INTRODUCTION

A single-bore freight rail tunnel required ventilation upgrades due to a forecast increase in traffic throughput. Due to confidentiality requirements, the location of the tunnel is anonymised in this paper. The existing TVS was predicted not to be able to support safe operation of the tunnel following the increase in traffic. An optioneering exercise determined that due to geometric and operational constraints, the only practical, constructable solution was to install a system of jet fans in the crown of the tunnel, without excavation of niches. Owing to the non-standard geometry it was not feasible to use standard good industry practice guidance such as References [1]-[4] to assess the installed thrust of the jet fans. Instead, following on from similar work as found in References [5]-[12], computational fluid dynamics (CFD) was used to assess the installed thrust. The findings from the CFD analysis were used to derive an installation efficiency for use in the 1-dimensional aerodynamic analysis of the design to quantify the required number and specifications of the jet fans to be installed in the tunnel.
PROJECT OVERVIEW

The tunnel is a 3.4km long, single-track, single-bore freight rail hard rock tunnel constructed in the 1960s and operated continuously up to the present. It was constructed primarily using the drill and blast method, with two relatively short sections of precast tunnel adjacent to the portals. The tunnel uses a final lining of unreinforced shotcrete over the rock. Figure 1 shows a view of the interior of the tunnel before the commencement of the upgrade works. The characteristic drill-and-blast regularly undulating surface of the tunnel is clearly visible, as is the finer surface roughness of the shotcrete final lining.

![Figure 1. Interior view of tunnel prior to rehabilitation works](image)

Figure 2 shows the cross-section of the tunnel, both design and as-built, with the train operational envelopes (defined as “Plate J”, “Plate K” in Figure 2) which illustrates the spatial constraints for fan installation. The figure also shows a section of a laser imaging, detection, and ranging (LIDAR) scan of the as-built tunnel with a representation of a jet fan. For scale, the vertical clearance between the fan and the largest vehicle envelope is approximately 200mm.

The difference between the design profile and the as-built profile is known as “overbreak” and is a characteristic typical of drill-and-blast tunnels.

The tunnel portals are also spatially constrained. At one portal the tracks transition rapidly onto a bridge over a body of water while at the other portal space is constrained by a road overhead and existing urban infrastructure either side of the right-of-way. These constraints also preclude the possibility of creating a second track, so the single-track alignment will remain.

When constructed in the 1960s, traffic through the tunnel was substantially less than now, and substantial future increase in traffic is anticipated by the rail owner to support increased demand. A critical limitation on traffic was the existing TVS, which was the original system installed in the tunnel when new.
The existing TVS was a purge-type system supplying air to the tunnel from a shaft at approximately mid-chainage of the tunnel. It was designed to clear (purge) diesel locomotive emissions from the tunnel to render the tunnel environment safe for the next train and its crew to enter the tunnel. The original TVS was not designed for fire emergencies. Figure 3 shows a schematic of the installation. Two unidirectional 70m³/s fans were installed at the bottom of the shaft and supplied air to the tunnel via adits. Air was purged equally to each portal. This arrangement was efficient when traffic was infrequent and sufficient time was available for the purging to complete. Due to the design, the purge air in one half of the tunnel acted against the piston effect of the train passage. The piston effect is significant due to the blockage created by the trains. The time required to reduce tunnel pollutant levels below the required safety threshold was up to 35 minutes. This duration when the tunnel is required to be empty, between exit of one train and permitted entry of a second train, is defined as the Tunnel Clearance Time (TCT).

However, as traffic on the line increased, this purge time became the limiting factor in traffic throughput and with further significant projected increases in traffic, the rail owner concluded that the TVS required upgrade or replacement. They also wished to add some resilience and capability in the event of fire in the tunnel, which was lacking in the original TVS.

NEW TVS REQUIREMENTS

The performance requirements for the new TVS were as follows:

1. Provide tunnel environmental conditions in compliance with applicable Occupational Health and Safety (OHS) requirements;
2. Provide system resiliency in event of fire to facilitate egress of occupants (train crews or maintenance staff): all TVS-related equipment to remain operational for a minimum of one hour when exposed to 250°C temperature;
3. Provide emissions clearance capability to support a Tunnel Clearance Time (TCT) of not more than 10 minutes.
TUNNEL OPERATIONS AND OCCUPANCY

Due to its function as a privately-owned freight rail tunnel, occupants are limited to staff and authorised contractors of the rail owner. All those entering the tunnel are trained and aware of the hazards and how to respond in emergency. Train crews are not more than two persons, located in the cab of the lead locomotive of the train. Maintenance crews may be larger and may access the tunnel either by foot, or by diesel-powered road-rail (“hi-rail”) vehicles. Operations on the railway are 24 hours per day, 7 days per week. Consequently, all maintenance access requires tunnel occupancy permits and track protection to be in place. Staff accessing the tunnel carry all required safety equipment and hi-rail vehicles are required to carry portable fire extinguishers on board at all times. Staff in the tunnel maintain full-time radio communications with both the staff providing track protection and with train control.

![Figure 3. Schematic of existing TVS installation; tunnel and shaft truncated for clarity](image)

The freight rail sector uses the term “consist” to describe an operational freight train. The operational traffic through the tunnel is exclusively freight rail consists, which carry a variety of bulk cargoes in open wagons. Typical consists utilise in excess of 100 wagons hauled by three diesel locomotives. The locomotives may be all located at the head end of the train or may be split, with two at the head-end and one at mid-consist. Some consists are composed of up to 170 wagons with a gross weight of up to 23000 tonnes. The length of a train varies between 1.4km to 3.8km, so some consists are longer than the tunnel. Loaded consists travel in one direction only, towards their unloading points, while empty consists travel in the opposite direction only. The crew is always located in the cabin of the lead locomotive.

Due to the tunnel having only a single track, traffic patterns are implemented depending on demand. These are termed either “fleeting” or “alternating” traffic. Fleeting traffic sends multiple consists in one direction (1); followed by multiple consists in the other direction (2). Alternating traffic sends one consist in one direction (1), followed by a second in the other direction (2), then repeats the pattern. A typical fleeting pattern is therefore 1-1-1-2-2-2-1-1-1, while a typical alternating pattern is 1-2-1-2-1-2-1-2.

The critical parameter for traffic operations is the Tunnel Clearance Time (TCT). This is the time required to reduce pollutant levels in the tunnel below the threshold required to provide safety for staff. This is defined as the time between the exit of the rear of the first train and the permitted safe
entry of a second train. (Note this is not the same as headway, which would be time between first train tunnel entry and second train tunnel entry.) The existing TVS performance supported a minimum TCT equal to 35 minutes.

FIRE SAFETY

The fire risk in the tunnel is low, and the rail operator has not experienced a fire in the tunnel in more than fifty years of operations. Nonetheless a fire hazard exists, due to the usage of diesel trains for operations, diesel hi-rail vehicles for regular maintenance, and occasional maintenance hot works within the tunnel. A drawback of the original TVS was that it was never designed for operations in a tunnel fire scenario. The rail operator required that the new TVS be designed to be resilient in event of fire. They did not require it to be designed to provide critical velocity in event of fire, citing the low occupancy and multiple operational safety measures in place for staff accessing the tunnel. They did require the system, including the new backbone services (electrical power supply and distribution, control and monitoring systems), to be designed to operate in a temperature of 250°C for a minimum of one hour, such that it could be used to assist in a fire emergency response if required.

TVS OPTIONEERING

An initial phase examined a variety of conceptual designs that could improve the ventilation of the tunnel. These are summarised in Table 1. Four criteria were examined as shown in the table. Six options were examined and compared with the existing TVS. (Note that the existing TVS satisfied the OHS criteria for the current 35 minutes TCT but could not do so for the required reduced TCT.) Three options were eliminated due to lack of constructability, while two more were eliminated as they failed to achieve at least one of the performance criteria. The only option that satisfied all the criteria was a design using jet fans installed in the existing available space between the train vehicle envelope and the tunnel structure.

<table>
<thead>
<tr>
<th>Design Option</th>
<th>Constructable?</th>
<th>Meet OHS Requirements?</th>
<th>Improve TCT?</th>
<th>Achieve TCT ≤ 10 minutes?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing TVS</td>
<td>n/a</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Install larger fans in current TVS</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Not assessed</td>
</tr>
<tr>
<td>Saccardo nozzles</td>
<td>No</td>
<td>Not assessed</td>
<td>Not assessed</td>
<td>Not assessed</td>
</tr>
<tr>
<td>Axial fans at portals</td>
<td>No</td>
<td>Not assessed</td>
<td>Not assessed</td>
<td>Not assessed</td>
</tr>
<tr>
<td>Jet fans in niches</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Jet fans without niches</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Constructability was a critical criterion in assessment of the options since due to the nature of rail operations within the tunnel there were no conventional “engineering hours” available.

The jet fans installed without niches option was selected as the only practical design option. The next phase was a more detailed performance assessment to quantify the overall thrust required to meet the performance requirements, and consequently to assess the required fan selection and eventual number of jet fans that would be required.

DESIGN OF NEW TVS

The new TVS design was constrained by several requirements as described above. To satisfy the requirements the design incorporated these features:

1. Fully reversible system to support bi-directional train operations;
2. Fans installed individually at specific tunnel chainages due to limited space available (Figure 2);
3. Spacing of the fans is approximately equal longitudinal spacing but with some variation due to the variability of the overbreak, due to the drill and blast method, in the tunnel crown (see Figure 4); exactly equal spacing could not be implemented;
4. Fan length 3861mm including silencers;
5. Maximum fan outside diameter 860mm due to limited clearance to train envelope;
6. Minimum fan clearance to largest train envelope 200mm;
7. Fan clearance to tunnel crown variable depending on fan station and amount of overbreak, minimum less than 200mm, maximum 1000mm, average 300-400mm;
8. Number of fans – dependent on nominal thrust of fan selection that would satisfy the maximum diameter requirement;
9. Support frame design is bespoke, with each fan location unique to satisfy the specific spatial requirements due to the variability of the overbreak (Figure 1);

10. The ventilation fans are operated in three stages during the passage of each train through the tunnel;
   (i) When the front of the train enters the tunnel, the jet fans are started and operated against the direction of train travel, in order to ensure a flow of clean air over the front cab,
   (ii) When the front of the train leaves the tunnel, the jet fans are reversed so as to operate in the direction of train travel, to gain maximum benefit from the piston effect within the tunnel,
   (iii) When the rear of the train leaves the tunnel, the jet fans continue to run (in the direction of train travel) until the pollutant concentrations drop below the required threshold levels, and then the jet fans switch off, until the arrival of the next train.

Train location is used to determine direction of operation, with train location obtained from the railway signalling system.

Figure 4. Example of jet fan installation in the tunnel
(Tunnel stationing in kilometres+metres e.g. 0km+580.0m)

**DESIGN PERFORMANCE REQUIREMENTS**

Primary performance requirements were specified for the occupational health and safety of staff entering the tunnel as discussed above, primarily consisting of train crews. The pollutants of interest are CO, NO, and NO₂. Daily exposure time for the train crew is less than fifteen minutes, as crews typically only do one transit of the tunnel per shift. Emissions criteria were derived from the ACGIH TLVs and BEIs Guide [13]. A TLV is the permitted Threshold Limit Value for a particular pollutant. The TLV-Time Weighted Average (TLV-TWA) is a threshold limit value for an 8 hour exposure. The
TLV—Short Term Exposure Limit (TLV-STEL) is most appropriate for the exposure, being a time-weighted average concentration of pollutant over a 15 minute period. However, no TLV-STEL value is given for CO, NO, or NO$_2$. Per ACGIH, “Excursions in worker exposure levels may exceed 3 times the TLV–TWA for no more than a total of 30 minutes during a workday, and under no circumstances should they exceed 5 times the TLV-TWA, provided that the TLV-TWA is not exceeded.” Consequently, for the pollutants of interest, the selected criteria were agreed with the rail owner to be five times the TLV-TWA i.e. 5*(TLV-TWA).

The second key performance criterion was the time required to clear the tunnel of emissions. This is the Tunnel Clearance Time (TCT), as discussed above. The TCT for the original TVS was 35 minutes. The new TVS would be required to reduce this to not more than 10 minutes.

The design requirements for each criterion are summarised in Table 2. Peak values obtained via analysis were compared against these values.

<table>
<thead>
<tr>
<th>Design Criterion</th>
<th>Design Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum CO concentration</td>
<td>≤125ppm</td>
</tr>
<tr>
<td>Maximum NO concentration</td>
<td>≤125ppm</td>
</tr>
<tr>
<td>Maximum NO$_2$ concentration</td>
<td>≤1.0ppm</td>
</tr>
<tr>
<td>Maximum Tunnel Clearance Time</td>
<td>≤10 minutes</td>
</tr>
</tbody>
</table>

**DESIGN PERFORMANCE ASSESSMENT**

Id aerothermodynamic computational analysis using the MottTunnels software was used to analyse the design performance. The objectives of the analysis were to predict variations in pollutant concentration along the tunnel for a range of different train operating patterns, and then to determine the fan performance necessary to maintain concentration levels below the limits defined in Table 2, and to achieve a TCT value no greater than 10 minutes.

Most of the analysis model required a relatively simple set-up in terms of configuration and input parameters, to define the tunnel, ambient weather conditions, trains, and fans, but two key aspects required careful attention:

a) Tunnel wall geometry – As shown in Figure 1 above, the tunnel walls have unevenness at several levels of scale: a large scale undulation due to the drill and blast construction method, a roughness due to the sprayed concrete surface, and a smaller roughness due to the material properties. Since the 1D model can have only single values of area, perimeter, and roughness height, it was necessary to derive suitable values which would provide appropriate values of overall tunnel resistance. The effective tunnel area was taken to be the mean minimum value of area along the undulating tunnel wall profile. The effective tunnel perimeter was taken to be the mean of the maximum and minimum values of perimeter along the length of the tunnel. Based on the range of tunnel wall profile dimensions and following sensitivity analysis, a value of 25mm was assumed for the effective wall roughness height.

b) Jet fan installation efficiency – Per Reference [1], the installation efficiency of a jet fan is defined as the relationship between the achieved installed thrust and the factory-measured nominal thrust, represented as a percentage of the nominal thrust. Nominal thrust is assessed using methodology as specified in a recognised test standard such as AMCA 250 [2] or ISO 13350 [3]. In this project, due to the irregular wall profile, it was not possible to derive a value for installation efficiency from the standard reference sources (e.g. [1]). Instead, a CFD model was built, incorporating a jet fan in a representative length of tunnel, to derive a value from simulations. This modelling work is described later in this paper. The CFD simulations to derive a value for jet fan installation efficiency were carried out both for the case with no train in the tunnel, and for the case with a
train present underneath the jet fan, since the high blockage ratio has a significant impact on dispersion of the jet plume. However, only a single value of efficiency was possible in the 1D model at the level of detail applied for this study. After review, the value for operation in the open tunnel was used, since the most important phase determining the clearance of pollutants is after the train cab has left the exit portal.

Once the 1D aerodynamic model had been constructed, simulations were run for the different train operating patterns. Pollutants were modelled as scalar values emitted at defined rates dependent on engine power and the specification and age of each locomotive. Pollutant concentrations were monitored at key tunnel locations including moving points adjacent to the cab of each loco, and at both portals. A series of physical tests had previously been carried out on trains passing through the tunnel, including comparative measurements of pollutant concentrations both inside and outside the cabs: as a result, for this study the pollutant concentrations inside the cab were assumed to be 17% of the concentrations in the tunnel outside the cab.

Figure 5 shows a plot of NO₂ concentrations at each portal as a function of time for a sample train operating pattern (note that this shows tunnel concentrations and not the concentrations experienced by drivers in the cabs).

![Figure 5. Portal pollutant NO₂ concentration for a sample train operation pattern](image)

**CFD ANALYSIS**

**Tunnel - Jet Fan Configuration**

The CFD work assessed the installation efficiency for the installed jet fan in tunnel arrangement, to be used in the 1D analyses.

CFD simulations were undertaken using a domain representing a typical 170m long repeatable length of the tunnel. This represented the approximate distance separating the jet fans in the tunnel. The undulating wall of the tunnel was represented using an average pitch of 0.15m and an average amplitude of 3.5m [Figure 6]. The freight trains were modelled in simplified block representation for two different sections, Plate J & Plate K [Figure 2], running the simulated length of the tunnel. The larger Plate K train creates increased blockage and has a narrower clearance to the jet fans. The positioning of the sections representing the train blockage relative to the tunnel and jet fan is shown in Figure 7. The jet fan was placed with its inlet end 54.5m from the upstream end of the CFD model.

All CFD modelling was undertaken using the ANSYS suite of software including SpaceClaim for geometry modelling, Fluent-Mesh for generation of the computational domain and Fluent-Solver for undertaking all the CFD computations. The realisable k-ε turbulence model was employed.
Specific Modelling Components

Jet Fan Sub-Model
The jet fans were represented using a fan sub-model which accounted for both circumferential and axial components of momentum. The model also accounted for the radial variation of the circumferential velocity at the section of the fan impeller.

The fan sub-model required the specification of a step increase in pressure across the impeller to represent the energy added to the airflow by the fan thrust. In order to correctly calibrate the jet fan in the computational model with the nominal thrust stated by the fan manufacturer, a CFD test model was constructed with the fan placed in a domain free of nearby influences of any tunnel walls. The specified pressure increase was adjusted to correlate with the nominal thrust specification of the fan manufacturer. Additionally, the test model was used to derive the pressure variation with upstream flow velocity, to represent the fan offloading effect encountered when the jet fans are installed in tunnels. The relationship was subsequently used in the different scenarios of the jet fan in tunnel simulations.

Computational Mesh
The unstructured grid, shown in Figure 8, was generated with an inflation layer of computational cells following the contour of the wall. The layered mesh reduced the potential for numerical errors associated with the near wall flows, increasing the accuracy of the wall shear force prediction. The near-wall model was used to represent the impact of the wall boundary layer, with the first mesh layer
away from the wall suitably sized to yield a suitable compromise between the magnitude of the y+ parameter and computational mesh structure and size. Generally, average y+ were about 100 in magnitude, however peak values particularly in the regions where the jet efflux brushed against the tunnel ceiling (i.e. Cases 2, 3, & 4 below) was of the order of a few hundred in magnitude.

![Figure 8. CFD model mesh refinement for a jet fan installed close to the tunnel ceiling](image)

**Train**

The two different train sections were represented in a simplified block model format. As with the tunnel walls, the computational domain was generated with an inflation mesh later on the surfaces of the train, ensuring accuracy of shear stress prediction on the train surfaces. For Plate K section geometry, which encroached more on the jet fan space, the cell sizing was suitably adjusted to ensure a sufficient number of computational cells were captured in the gap between the jet fan casing and the train top. The first cell layer on the train surface was also sized to ensure appropriate y+ levels for turbulent flow boundary layer prediction in the log-law layer of the wall.

**Jet Fan Thrust**

In preliminary design, the jet fans were specified to have 250N nominal thrust. This was the thrust used in the CFD analysis. In final design, this was revised to a 500N nominal thrust due to design development. It was found that this jet fan selection would fit in the tunnel, allowing reduction in the number of installations required.

The thrust of a jet fan is given by Newton’s Second law, that the sum of forces acting on a body or system is equal to the body or system rate of change of momentum. For a jet fan in a test environment this is relatively easily expressed in terms of the momentum of the jet efflux at the fan exit, according to the following, given that the air is accelerated from a quiescent condition. This is the factory nominal thrust of the jet fan $T_{nom}$.

$$T_{nom} = (\rho \cdot A_{fan} \cdot V_j) \cdot V_j = \rho \cdot A_{fan} \cdot V_j^2$$

(1)

For a fan in a tunnel environment the installed thrust $T_i$ (i.e., the thrust that is transmitted to the tunnel air) is lower than $T_{nom}$, owing to blade off-loading (i.e., offloading thrust loss). Moreover, there is increased wall friction due to eccentrically located fans. The force-momentum balance for a fan in tunnel can be expressed in terms of the following.
\[ \Sigma \text{Force} = \Delta \text{Momentum} \quad (2) \]

\[ T_{\text{nom}} - T_{\text{offloading}} - F_{\text{friction}} - \Delta P_{\text{in/out}} \cdot A_{\text{tunnel}} = \Delta \text{Momentum}_{\text{tunnel}} \quad (3) \]

**Installation Efficiency**

The factory nominal thrust of a jet fan is generally not achievable in a tunnel environment owing to (i) fan offloading due to tunnel air velocity, (ii) eccentric placement of the fan and (iii) fan niche inclination angle. In this design there are no niches so the latter is not a factor. As described in Reference [1], the relationship between the nominal thrust and installed thrust of a jet fan in a tunnel may be represented as shown below, with reference to coefficients (i) \( k_1 \) for fan offloading, and (ii) \( k_2 \) for the proximity of the fan to the tunnel walls (“eccentric placement”).

\[ T_i = T_{\text{nom}} \cdot k_1 \cdot k_2 \quad (4) \]

In a tunnel environment, the different terms in Equation (3) above can be evaluated in a CFD calculation. From a knowledge of derating of the fan, \( k_1 \) is calculated for the tunnel flow predicted in CFD. \( k_2 \) may in turn be evaluated from the increase in tunnel friction force due to eccentricity, compared to a case of a centrally located fan. The combination \( k_1 \cdot k_2 \) represents an efficiency parameter per Reference [1] for the jet fan in its installed environment, yielding \( T_i \) for a given \( T_{\text{nom}} \).

Note that \( k_1 \) is calculated dynamically in the MottTunnels 1d software and so \( k_2 \) is the parameter that is input into the software to account for the installation geometry effects.

**CFD Modelling Cases**

The following four cases were modelled to estimate the performance of the selected jet fan under various tunnel speeds. For all cases, a section of the tunnel is modelled as described above.

a) Case 1: This is a baseline case of an empty tunnel section without train and a fan installed at the centre of the tunnel for comparison purposes.

b) Case 2: An empty tunnel section without a train and a fan installed per the design, close to the crown of the tunnel.

c) Case 3: A tunnel section including a Plate J train, with a simplified block representation of a Plate J train (as shown in Figure 7). The train is assumed to run the whole length of the section.

d) Case 4: A tunnel section including a Plate K train, with a simplified block representation of a Plate K train (as shown in Figure 7). The train is assumed to run the whole length of the section.

**CFD Modelling Results**

Case 1 is a baseline case undertaken for comparison purposes with the jet fan centrally placed in the tunnel. The velocity contours for this case are shown in Figure 9. When the fan is at the middle of the tunnel, it can be seen that the effect of the walls on the jet is minimised hence the spread of the jet is larger and much longer than in the other cases. The jet disperses downstream of the fan to establish a substantially uniform velocity profile, although the effect of the wavy tunnel wall profile can be seen throughout the length of the tunnel, producing a thick shear layer. In general, the thrust can be seen to be transferred to the bulk tunnel flow more efficiently. Installed thrust is higher than for the other cases analysed.
Figure 9. Case 1, Velocity contours through empty tunnel mid-plane

Figure 10 for Case 2 clearly demonstrates the Coanda effect acting to attach the jet to the tunnel wall ceiling when the jet fan is positioned close to the tunnel crown. The jet remains attached travelling along the ceiling in the tunnel. This effect diminishes the spread of the jet efflux within the tunnel. Therefore, the transfer of thrust to the bulk tunnel flow is inefficient. Installed thrust is lower than for Case 1. Case 2 is key to the assessment of the TCT parameter.

Figure 10. Case 2, Velocity contours and vector plots through empty tunnel mid-plane

For cases 3 and 4 with the Plate J and Plate K trains placed in the tunnel, the velocity contours are shown in Figure 11 and Figure 12 respectively. In this situation, the airflow pattern is more complex, with the airflow constrained to flow in the annulus around the train, particularly at a high level. Limiting the jet fan flow area in the space between the train and tunnel walls results in increased wall friction and reduces the efficiency of thrust transfer to the bulk tunnel flow. Installed thrust is lower than for both Case 1 and Case 2.

Figure 11. Case 3, Velocity contours through tunnel mid-plane with smaller section Plate J train
CFD Analysis Findings

The wall friction increases significantly to almost double its value, from the baseline Case 1 to Case 2, with the jet fan in its eccentric position and the jet exit flow attaching to the ceiling. The cases with train elevate the increase in friction.

As wall friction increases, the jet fan thrust conversion to the useful tunnel bulk flow reduces. The baseline Case 1 shows the highest level of tunnel bulk velocity and Case 2 values are higher than Cases 3 & 4 with the train.

The installed thrust evaluated from Equation (4) is highest for the central position fan, and Cases 3 & 4 with train have lower installed thrust compared to Case 2 with the fan in tunnel crown location with empty tunnel. When the fan was moved from the central to the tunnel ceiling position a significant drop in $k_2$ of about 19% owing to increased wall friction was observed. A further decrease of about 8% was seen for the cases with train compared to the empty tunnel case with the fan in the same position, owing to increased friction.

The combined $k_1,k_2$ parameter, a measure of installed thrust compared to the nominal thrust (i.e. Installation Efficiency) was observed to be low for Cases 2, 3 & 4 (~ 65% - 74%), due to the design constraints that limited the options for aerodynamic optimisation.

### Table 3. Key Jet Fan Design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Thrust (N), $T_{nom}$</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Blade Offloading (N)</td>
<td>25.5</td>
<td>21.7</td>
<td>24.1</td>
<td>25.7</td>
</tr>
<tr>
<td>Thrust at Fan Outlet (N)</td>
<td>224.5</td>
<td>228.3</td>
<td>225.9</td>
<td>224.3</td>
</tr>
<tr>
<td>Wall Friction (N)</td>
<td>45.1</td>
<td>88.4</td>
<td>105.2</td>
<td>107.7</td>
</tr>
<tr>
<td>Offloading Coeff, $k_1$</td>
<td>89.8%</td>
<td>91.3%</td>
<td>90.4%</td>
<td>89.7%</td>
</tr>
<tr>
<td>Eccentricity Coeff, $k_2$</td>
<td>100.0%</td>
<td>81.0%</td>
<td>73.4%</td>
<td>72.1%</td>
</tr>
<tr>
<td>Alternative $k_2$</td>
<td>-</td>
<td>61.3%</td>
<td>53.4%</td>
<td>52.0%</td>
</tr>
<tr>
<td>$k_1 \cdot k_2 \ (\approx T_i/T_{nom})$</td>
<td>89.8%</td>
<td>74.0%</td>
<td>66.3%</td>
<td>64.7%</td>
</tr>
<tr>
<td>Installed Thrust (N), $T_i$</td>
<td>224.5</td>
<td>185.0</td>
<td>165.8</td>
<td>161.7</td>
</tr>
</tbody>
</table>

The “alternative $k_2$” in Table 3 represents the effect of eccentric installation as a function of the absolute wall friction, rather than following the guidance in Reference [1], which assumes $k_2$ would be relative to the 100% value used for installation at the centre of the tunnel cross-section. In the analysis, this “alternative $k_2$” was used conservatively for Cases 2, 3 and 4, instead of the Reference [1] value. This was due to the very close proximity of the fans to the tunnel crown where the absolute wall friction becomes a key factor in assessing the installed fan thrust.
For the final design, as a conservative value, $k_2$ was set to 50% and the jet fan specification was revised to 500N nominal thrust in forward direction, with a minimum of 95% of that figure in reverse direction, with a total of 16 jet fans installed. This was done to minimise the number of fans requiring to be installed following discussions with the rail owner.

**VERIFICATION & VALIDATION**

All engineering analysis possesses uncertainty in the results. Estimating the degree of uncertainty in numerical modelling of fluid mechanics problems is non-trivial but an understanding of the probable uncertainty is essential to verification of the results. Freitas [14] presented an overview of the issue and guidance for addressing sources of numerical uncertainty. The AIAA [15] has provided guidance for good practice in managing numerical uncertainty in CFD. Vendors of commercial software also conduct verification of their tools, as do agencies with a special interest in safety, e.g. the US Nuclear Regulatory Commission [16]. The accuracy of 1-dimensional numerical tools has been validated via full scale tests, for example those conducted in the Montreal Metro for the Subway Environmental Software (SES) tool [17]. Design validation via full scale testing introduces further sources of uncertainty associated with the testing itself, including test methodology, test equipment, environmental effects, and the full scale installation itself.

These uncertainties are typically accounted for in tunnel ventilation design by the use of design margins above the required minimum performance criteria. In this case, the primary performance criterion, the design TCT was selected to be 8 minutes, compared with the performance target of 10 minutes.

For the problem in this paper, purely numerical uncertainties related to choices for mesh sizing, solver, and turbulence model, etc are assumed to be minimised to within normal good industry practice acceptable levels by using and verifying good industry practice as cited above. Other sources of analysis uncertainty arise from the practical necessity of (i) simplifying the tunnel roughness and wall profile and the train itself, (ii) modelling only a representative length of the tunnel, (iii) simplifying the representation of the operational jet fan. Verification was undertaken by an iterative process involving multiple levels of check and review to provide assurance the analysis was complete and accurate to the desired degree.

Validation of the design was completed by airflow testing carried out during system commissioning, prior to cutover from the existing TVS to the new TVS. Uncertainties in the testing include measurement uncertainties arising from the limits of anemometer accuracy, uncertainty in the cross-sectional area calculation, variability in environmental conditions at time of testing, etc.

As part of the system testing and commissioning, tunnel air flowrates were measured with the fans running in both forward and reverse directions. Tunnel airspeeds were measured at four locations along the tunnel, with twelve measurements at each location, using hot-wire anemometers on a metal grid fixed to a hi-rail vehicle. Tunnel flowrates were then calculated using the effective areas at each measurement location. Figure 13 shows one of the installed jet fans during test and commissioning.

Table 4 shows a summary of the measured flowrates, in comparison with the values expected under the test conditions (which included some wind-induced flow).

<table>
<thead>
<tr>
<th>Flow direction</th>
<th>Expected flowrate m$^3$/s</th>
<th>Measured flowrate m$^3$/s</th>
<th>Measured / Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward</td>
<td>122</td>
<td>104</td>
<td>85%</td>
</tr>
<tr>
<td>Reverse</td>
<td>119</td>
<td>82</td>
<td>69%</td>
</tr>
</tbody>
</table>

These values of expected flowrate were based on fans intended to provide a nominal TCT of 8 minutes, giving a design margin above the required TCT = 10 minutes. Further 1-dimensional
simulations were carried out with adjustments to be consistent with the measured flowrates, and these showed that the required TCT of 10 minutes was still achieved, for both fleeting and alternating train operations.

As noted above, for final design a conservative value for installation efficiency of 50% was used in the 1d design analysis. Airflow testing was executed in the tunnel with no locomotive or train present, so the design value of 50% was substantially less than the 61% figure for an empty tunnel (Case 2 in Table 3).

The installed system exhibited some unexpected behaviour during commissioning. Specifically, two phenomena were observed: (i) overall lower than predicted airflow, and (ii) significantly lower flow in reverse direction. The latter behaviour was associated with issues with the fans, as it was found that some of the fans were stalling in reverse, necessitating \textit{in situ} adjustment of the fan blade angles. The former behaviour was likely due to physical effects which could not be represented in full detail in the analysis, such as (i) the complex actual tunnel profile (necessarily simplified in the CFD analysis and in the 1d analysis), (ii) the irregular spacing of the fans along the length of the tunnel (due to variation in the available overbreak), (iii) variations in the clearance between fan and tunnel crown at each installation location, etc. However detailed diagnostic assessment of the root causes of the variations was not undertaken, as the rail owner was satisfied that the design requirement for TCT $\leq$ 10 minutes had been achieved and wanted to cut over to the new system immediately.

CONCLUSIONS

Detailed computational assessment of jet fan efficiency for fans installed in a rail freight tunnel was completed due to the unusual and non-standard installation geometry required. The assessment demonstrated that actual effective energy transfer to the tunnel air was significantly less in this project than the standard guidance would predict. The assessment confirmed that, for this particular design, standard industry guidance was not sufficient to accurately represent the performance of the installed fans when using 1d aerodynamic analysis to assess the required specification and number of fans to meet the project performance criteria. The value of utilising design margins to account for
uncertainties in both engineering analysis and full-scale physical testing, especially in atypical installations, was demonstrated in the outcomes of the commissioning process.

REFERENCES

1. Woods Jetfoil & Large JM Aerofoil Fans for Tunnel Ventilation, JM/JET1, January, 1999
13. Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs), American Conference of Governmental Industrial Hygienists (ACGIH), 2020 Edition
Medical Knowledge as Prerequisite for Establishing Criteria for Design, Management and Emergency Preparedness in Road Traffic Tunnels

Geir Sverre Braut¹, Harald Søiland², Haavard Søiland¹ & Ove Njå²
¹Stavanger University Hospital, Stavanger, Norway
²University of Stavanger, Stavanger, Norway

ABSTRACT

The article aims to give an overview of the lacunes between medical knowledge and how current medical knowledge is applied in connection with tunnel accidents. There is abundant knowledge related to the medical effects of exposure to different types of chemicals. However, we lack evidence on the connection between exposure to chemical compounds in tunnel fires and subsequent health effects. Not least, we lack evidence on long term health effects of acute exposure to gases from tunnel fires.

KEYWORD: Criteria, design, management, emergency preparedness, road traffic tunnels

INTRODUCTION

Exposure to toxic fire smoke and gases [1] cause injuries and deaths in fires. The traditional terms of assessing fire safety of humans in engineering of, for example tunnels are connected with the outcome of two parallel timelines. These are the time from ignition of the fire to the development of incapacitating conditions (ASET) and the time required for tunnel users to reach a place of safety (RSET) [2, 3]. When occupants become immersed in smoke, behavioural, sensory and physiological effects occur. Toxic fires effluents are responsible for the majority of fire deaths and an increasingly large majority of fire injuries [1]. According to Lönnermark’s opinion [4], there must be cascading accident if HGV fires in tunnels shall be fatal.

Until now, updated and evidence based medical knowledge has not been systematically used when establishing criteria for design, management or emergency plans related to road traffic tunnels.

Tunnels are exposed to fire risk, but how shall we as a society approach frequency, variation in numbers and the extent and consequences of fires? How shall we express uncertainties and predictions for various purposes leading to decisions? Can we say that there exist valid models, and how do these models express human exposure? Very often quantitative models are referred to because they express risk and performance so precisely. But who do we foul then; the society, experts, or naïve subjects such as road-users?

Tijms states: “Though the primary goal of stochastic modelling is to provide insights and not numbers, numerical answers are often indispensable for gaining system knowledge” [5]. The interpretation of numbers is worthless if we do not know the models and the data material behind it. We do have a knowledge-based view on tunnel safety and that is why it is so important to reflect upon the medical knowledge in tunnel safety work. How can we relate knowledge about toxicology and fire risk?
Nævestad et al.’s [6] data material from Norway shows that on average there are 24 tunnel fires per year (statistics from 2008 – 2015, through 1134 km tunnels). Annual frequency varies from 17 to 30 fires, and in general the fire occurred rarely in HGVs > 3.5 tons. The regional fire distributions were as follows:

- **Region East** – 17 fires, of which 5 in the Opera tunnel, 5 in the Oslofjord tunnel and 2 in the Tåsen tunnel and the last 5 occurred in different tunnels (total 8 tunnels)
- **Region South** – 4 fires, all in different tunnels
- **Region West** – 24 fires, of which 3 in the Mastrafjord tunnel, 2 in the Bømlafjord tunnel, 2 in the Gudvanga tunnel, and the last 17 fires in different tunnels (total 20 tunnels).
- **Region Middle** – 11 fires, of which 4 in the Hitra tunnel, 2 in the Stavsjøfjell tunnel, 3 in the Eiksund tunnel and the 3 last fires in different tunnels (total 6 tunnels).
- **Region North** – 7 fires, all in different tunnels.

In total there were fires in 51 tunnels during the 8-year period. Njå [7] analysed and modelled fire frequency in Norwegian tunnels based on a set of parameters (length, AADT, slope etc.). The models may be used as input to risk analyses for various tunnels. Heavy fire loads were reported in the two fires in the Gudvanga tunnel, Brattl tunnel, Follo tunnel, Skatestraum tunnel and in two fires in the Oslofjord tunnel. The truck driver was killed in the incident in the Follo tunnel. In the other major events noone were killed. Of the total number of fires mentioned above 5 persons have been killed, but not as a consequence of smoke intoxication. In order to check the data reliability we collected more information on the most serious incidents [8]:

- In 2009 a person was killed in a head on collision between a private car and a truck in the Stavsjøfjell tunnel (Friday night – private car came over in the truck driver’s lane). Driver of the private car was killed – male in the 20-ies. Fire in the private car was quickly extinguished.
- In 2010 a person was killed in an accident between an HGV and a private car in the Hordvik tunnel. The driver of the private car was killed. Both vehicles were ignited but the fires were quickly extinguished.
- A foreign driver of an HGV was killed in a collision with the Follo tunnel entrance in 2010. The driver was found between the tunnel wall and the HGV, and he died from smoke intoxication and physical injuries from the collision.
- In 2011 an HGV in the Oslofjord tunnel caught fire that resulted in major smoke injuries for several road-users. The statistics show minor injuries, which is not true [9].
- Two persons were killed in 2011 in a head on collision between a bus and a private car. The incident happened on the outside of the Vassenda tunnel. Some smoke development in one of the vehicles, but no fire. We raise questions concerning the relevance of this event.
- The rear wheels of an HGV trailer caught fire in 2012 in the Mastrafjord tunnel. Two persons were lightly smoke intoxicated (Haugesund news), while the accident report describes serious person injuries.
- A head on collision between a private car and an HGV in the Storesand tunnel killed the driver of the private car. The HGV caught fire.
- In 2013 a motorcyclist was killed in a collision with a truck in the Naustdal tunnel. A minor fire occurred, but it was extinguished quickly.
- In 2013 the Gudvanga tunnel fire occurred, in which many were injured from smoke intoxication, and several serious injuries. A research institute investigated the human exposure and behaviour of the road-users in the fire [10].
- The second fire in the Gudvanga tunnel happened in 2015 and it implied five intoxicated persons.

1 7 if the incident outside Vassenda tunnel is included.
Nævestad describes the Oslofjord-, Byfjord-, Bømlofjord-, Eiksund- and Hitra tunnel as the most fire exposed tunnels in Norway. However, if we restrict to fully developed fires, the situation is a bit different. The Byfjord tunnel has not had any fires in the period 2008 – 2015. Nævestad et al. [6] look holistically upon near fires and fires, in which the criterion for their observation is that the tunnel was closed. Near fire incidents are in principle smoke development, but it does not have to be something else than an operator at the road traffic management centre became suspicious about smoke development. Furthermore, there are neither efforts to analyse the connection between the frequencies of near fires and fires, nor the physical and chemical parametric conditions leading to fires and near fires. Thus, it is difficult to conclude that the statistics on near fires is a good indicator of assessing the risk of fire in HGVs. We are in an area with large uncertainties.

Table 1 presents an overview of events in which smoke exposed road users have been involved. These events are collected from investigations performed by the Accident Investigation Board Norway, either as the subject of their investigations or information referred to (secondary information). The two tunnel fires with fatalities are gathered from public media articles and subsequent discussions.

<table>
<thead>
<tr>
<th>Year</th>
<th>Tunnel</th>
<th>Vehicles involved</th>
<th>Smoke exposed road-users</th>
<th>Injured from toxic exposure</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Seljestad tunnel</td>
<td>6 vehicles</td>
<td>9</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>2006</td>
<td>Seljestad tunnel</td>
<td>Bus</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2011</td>
<td>Oslofjord tunnel</td>
<td>HGV</td>
<td>34</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>2012</td>
<td>Eidsvoll tunnel</td>
<td>Car</td>
<td>0</td>
<td>0</td>
<td>1*</td>
</tr>
<tr>
<td>2012</td>
<td>Mastra fjord tunnel</td>
<td>HGV</td>
<td>At least 3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>2013</td>
<td>Gudvanga tunnel</td>
<td>HGV</td>
<td>67</td>
<td>28</td>
<td>0</td>
</tr>
<tr>
<td>2013</td>
<td>Brattli tunnel</td>
<td>HGV</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2015</td>
<td>Gudvanga tunnel</td>
<td>Bus</td>
<td>5</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>2015</td>
<td>Gudvanga tunnel</td>
<td>HGV</td>
<td>17</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>2016</td>
<td>Måbø tunnel</td>
<td>HGV</td>
<td>?</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2017</td>
<td>Fjærland tunnel</td>
<td>HGV</td>
<td>13</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>2018</td>
<td>Nakkagjeld</td>
<td>Bus/HGV</td>
<td>17</td>
<td>5</td>
<td>1*</td>
</tr>
<tr>
<td>2019</td>
<td>Gudvanga tunnel</td>
<td>HGV</td>
<td>33</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

*The persons killed is due to the mechanical forces in the accident, not the fire smoke exposure

To some degree general criteria laid down in legislation and industrial standards are based upon current medical knowledge. The extent to which this knowledge is based upon systematically collected information from scientific medical literature, remains unclear. Typical for legislative processes and elaboration of industrial standards is to invite professional experts to give their soundings into the work, without an explicit requirement related to the demonstration of how this knowledge is collected and systematised.

When planning specific tunnels, the use of medical experts in developing the design and plans for management has been scarce or mainly absent. To some extent medical experts seem to be invited to take part in the emergency and rescue planning related to different tunnel projects. Still there exist no generally agreed standards on how this participation should be taken care of.

**MATERIAL AND CONDITIONING - METHODOLOGY**

The first aim of the study presented in this paper was to identify current medical knowledge that could be used for improving design, management, and emergency preparedness in road traffic tunnels. The second aim was to define a possible gap between available medical knowledge and the kind of medical knowledge that appears to be useful in such activities. The study builds upon previously unpublished research related to knowledge on smoke gas exposure and health effects in road tunnel fires [11].
The study was organised to retrieve and analyse the medical knowledge relevant for road traffic safety of tunnels. We did not reflect on which tunnel project phases, but in general how and why could and should medical knowledge play a role in a relatively technology and engineering-based domain. We chose systematic review as the approach, in which aggregated knowledge from the literature is used to answer our major issues. Our main concern was to elaborate on why the medical disciplines have not obtained a stronger role in tunnel safety, in spite of the knowledge and competence this scientific field possess. We were not interested in organisational and historical barriers, but rather looking at the relevance of approaches and level of expertise the medical disciplines might offer the tunnel safety industry.

Further, a document study of reports from investigation of tunnel accidents were performed to give an overview over medical challenges connected to the investigated accidents. This material was analysed by specialists in community and forensic medicine and related to the current knowledge as described in the systematic review, to identify possible knowledge gaps.

Figure 1: Steps in the systemic review process [12]

Literature from relevant medical fields, mainly toxicology, trauma care, thermoregulation and respiratory diseases were approached through a systematic review [11, 12], shown in figure 1. In this way, we established an overview of current scientific knowledge.

We collected articles from acknowledged data bases. Our inclusion criteria were determined as; Scientific quality (peer reviewed works); Language (Scandinavian, English and German); Toxic gases that might occur in tunnels. The exclusion criteria then became all the literature not meeting the inclusion criteria, but examples such as; Toxins that were not gases; Environmental pollution; Wildland fires; Fire fighters’ long term challenges related to toxic exposure in their working environment; Coal mines; Tobacco smoke and addictions. We retrieved many articles that were in the outskirt and thus needed specific assessments. The process is depicted in figure 2.
RESULTS

There are many risk influencing factors in tunnel safety work, comprising exposure to toxic gases. In general, those can be divided into two categories:

- **Health effects from a hazardous situation occur onwards fire ignition to evacuation.** This includes incapacitation and lethal conditions. Incapacitation influences evacuation performance and relates to reduced vision, reduced cognitive abilities, physical paralysis, etc.

- **Health effects after evacuation is completed.** Lethal conditions are also in this category relevant, but mainly it relates to acute and chronical long-term injuries.

The articles appear to be repetitive. That is they focus on a limited set of well known toxic agents. The quality criteria normal in biomedical science seem not to be adhered to, as mostly the clinical studies are observational and retrospective. Not least, studies concerning a comprehensive, standardized, initial clinical investigation of those exposed to tunnel fires seem to lack, as do also studies following exposed individuals over a longer period of time. There are few “controlled” studies in the data material. Some of the articles are rather old (1970s–1980s).

**Toxicology related to road tunnel fires**

The literature’s coverage of smoke and fire gases with regards to fire in vehicles was of major interest. We looked for documented insights, but also knowledge gaps. We focused on zoot particles and local and systemic effects of gases.
Zoot particles:
These are described as critical by their ability to attach to and irritate the mucosa in the respiratory system. Such particles are also suspected carcinogenic agents.

Gases as surface irritants:
The most profiled gases studied due to their possible effects on skin and mucosae are:

- Phosgene (COCl₂) is well known as a chemical weapon, able to severely damage the respiratory tract and lungs, not least due to its ability to induce pulmonary oedema.
- Hydrochloric acid (HCl) may lead to skin lesions due to its acid effects, and it may also irritate the mucosa of the respiratory tract.
- Sulphurous acid (H₂SO₃) and sulphuric acid (H₂SO₄) are both extremely irritating to skin and the mucosa in the airways, and may destroy tissue due to its ability to decompose lipids and proteins.
- Ammonia (NH₃) and formaldehyde/formalin (HCHO) are also irritating agents, and especially formaldehyde is able to decompose living tissue.

Gases with systemic effects:
The most profiled gases studied due to their possible systemic effects are:

- Carbon monoxide (CO) are highly lethal due to its ability to block the oxygen transportation capacity of haemoglobin.
- Carbon dioxide (CO₂) are lethal when it occurs in concentrations able to reduce partial pressure of oxygen, and it may also irritate the mucosa in the respiratory tract, possibly inducing pulmonary oedema.
- Cyanide (CN⁻) is able to inhibit an enzyme needed for production of ATP across the cell membrane, thus blocking the aerobic cellular respiration, which rapidly may lead to death.

Electric cars:
Fires in electric cars give a couple more challenges to consider:

- Hydrofluoric acid (HF) is an irritating agent and has a high ability to penetrate and decompose tissue.
- Metal oxides have compound effects, which are related to type of agent, but currently high emphasis is laid upon the study of nanoparticles released from fires affecting metal oxides.

Organ specific, acute health effects after exposure of gases from tunnel fires
Descriptions of phenomena related to acute health effects dominate the literature. Most of the works provide details about anatomic and pathophysiological processes after exposure to fire combustion products. We were not able to identify any relevant studies encompassing exposure data.

Very few works are based on fires in tunnels, which means that the experiences reported must be contextualised and applied on tunnel fires by the reader. The following is a presentation of major systems in humans that suffer damages in tunnel fires.

Lungs
Nanoparticles (<1µm) are considered damaging to tissue. When these particles reach the alveoli in the lungs, they appear to increase airway resistance, in addition to being irritating agents. They are suspected to interfere with the production of surfactant, which may result in reduced transportation across the membrane of the alveoli [13]. Systemic cascade reactions might also threaten the health situation, cfr. figure 3.

The temperature of the smoke being inhaled, might induce damages to the throat, especially the larynx, that might inhibit the airflow down to the lungs [14]. Surface irritating gases as described
above may induce chemical damage to the airways, which in turn may trig pathophysiological cascading reactions, cfr. figure 3. Exposure to smoke with elevated temperature as well as exposure to irritating gases leads to local damage, which rapidly may induce local inflammation turning into cell damage and even systemic responses, cfr. figure 3.

Figure 3  Systematic presentation of major pathophysiological effects of gases irritating the airways. 1. Inflammation, that may lead to 2. blocked airways and 3. failure in cell functions. In addition, activation of white blood cells may lead to an uncontrolled «storm» of biochemical and unspecific immunological reactions, which may add up to lung oedema and even systemic effects. Figure modified after Toon et al. [13].

Fire in electrical batteries generates several heavy metal oxides. One of the most important is cobalt oxide (CoO), which reduces the lung capacity, by creating CoO oxidants and free radicals which is reported to damage cilia in the airways [15]. Burning batteries may also release nickel oxide that may lead to oxidative stress reactions, which may ad on to the mechanisms described in figure 3.

Central nervous system
The nerve cells in the brain are very sensitive to lack of oxygen. Thus, CO poisoning will damage the brain quite soon, because of its ability to block the transportation capacity of oxygen by hemoglobin. Early symptoms may be reduced cognitive capacity and headache already from a concentration of CO in air from 0.01 to 0.1 vol%. Concentrations from 0.5 to 1 vol% may be life threatening after 5 to 10 minutes. Concentrations at this level may be found in tunnel fires after short time [16]. Another aspect to consider is that if the concentration of CO bound to hemoglobin (COHb) is high, it may be an indication of other toxic gases also being present, e.g. cyanide [17].

Cardiovascular system
The heart is also sensitive to carbon monoxide inhalation and will most probably become evident on patients with known or unknown cardiovascular diseases [16, 18].
Long term effects after acute exposure of gases from tunnel fires

Published scientific studies that specifically are concerning long term effects after exposure of toxic gasses from tunnel fires were not identified. Studies from other settings indicate that exposure to a high level of COHb, inducing unconsciousness, may lead to neurological deficiencies after a latency period from 2 to 40 days after the acute exposure [19-21]. Continuing symptom, lasting more than one year after exposure, is well known [16, 22, 23].

In addition to these effects, psychological disturbances as fatigue and depression, are reported [9, 24, 25].

Norwegian monitoring practice of health effects from toxic gases in tunnel fires

There is no national programme for monitoring long term health effects of toxic gas exposure in tunnel fires. Every single exposed person will be followed up according to clinical procedures, but not as part of an established policy. We were not able to identify other, nationally organised, monitoring programmes related to long term health effects of toxic gas exposure in tunnel fires. When designing such a programme, it appears sound to focus particularly on effects on airways, central nervous system and cardiovascular system. Based on existing literature, a programme based on three levels may be suggested.

Level 1: Acute phase, by prehospital services, ensuring acute interventions focusing airways and circulation.

Level 2: Acute phase, by hospital, ensuring stabilisation of vital functions and observation of possible systemic and topical pathophysiological responses.

Level 3: Long term observation, by general practitioner, ensuring discovery of possible long term effects and follow up of relevant rehabilitation in cooperation with hospital and community rehabilitation services.

The programme must specifically define what to be monitored and how to respond on findings at every level.

![Figure 4](image)

**Figure 4**  Simplified illustration of which exposures to be monitored and what to monitor at the first two levels. ECMO: Extra corporal membrane oxygenation. pO2: partial pressure of blood oxygen. SaO2: saturation of blood oxygen. pCO2: partial pressure of blood CO2. HbCO: amount of CO bound to haemoglogin [11].
DISCUSSION

The accident history in Norway has not given any fatalities due to smoke inhalation from tunnel fires. The safety and risk perception amongst the regulators and tunnel owners might be influenced in a way that neglects these issues. There are professionals that trust ventilation technology to provide sufficient smoke control. Few incidents might reduce the safety attention. Some describes this phenomenon as safety drift factors, and it should be an issue for tunnel safety personnel. A well-designed safety management system is needed in which proactive perspectives are recommended.

There is a limited set of relevant publications based upon medical research directly related to tunnels in general and road traffic tunnels in particular [11]. We therefore must be prepared to include findings from research in other relevant systems and contexts, e.g., related to aviation, railways, petroleum installations, ships, and buildings. The validity of knowledge from other contexts therefore will be a core element in future discussion and involvement of medical knowledge in tunnel safety work.

Furthermore, we will couple our findings from this study with current knowledge as implicitly emerging from today’s governing requirements in legislation and industrial standards, hopefully, being able to point at issues that should be further approached aiming to improve current requirements. The theoretical basis is systems theory [26], where we will focus on how medical knowledge can modulate already established safety constraints for tunnel systems in general and for specific tunnels in particular.

![Figure 5 Involvement of medical discipline in tunnel safety.](image-url)
As no practical efforts of medicine involvements are experienced in the literature nor based on our work with tunnel safety, we address a simple safety control structure based on the planning and operation of road tunnels. We know that these processes should be broken further into more detailed critical processes, but for now we are most interested in how the medical competence could be involved and contribute to the design and operations of road tunnels. Figure 5 shows that the medical component must be integrated in the regulator’s as well as the tunnel owner’s understandings – their process models. This means that the medical competencies need to be addressed in the assessment of evidence and literature applied in the updating of regulations, for example the N500 on road tunnels [27]. In normal operations of road traffic management, the medical competence is needed for identifying monitoring issues and prediction of toxins. In figure 5 it is related to the process models of the tunnel owner’s work because we claim that it is vital to acknowledge lack of competencies in their tunnel safety work. Designing safety control structures that integrate medical constraints needs further studies.

We claim that censor functions, such as physical censors and various types of safety measuring tools will benefit from medical knowledge as well as future updating of regulations and safety systems and contingency plans.

For example, the self-rescue principle will both require knowledge about the morbidity in the population as well as the level of toxins in various accident scenarios. Monitoring morbidity in the population is a national concern, where data might be useful for the design of evacuation systems. There are many vulnerable groups in the population that might be exposed, not least persons suffering from cardiovascular and pulmonary diseases, as ischemic cardiac diseases (with heart failure, angina pectoris), chronic obstructive pulmonary disease (with asthma or emphysema). As these diseases are more prevailing among older adults than younger adults, senior citizens in general should be regarded as a potentially more vulnerable group than younger adults. Children and youths are also to be particularly considered because their organs are still developing, and due to a greater respiratory volume per body mass unit compared to adults. Pregnant women and their unborn child should also be regarded as a group needing particular consideration.

Levels for incapacitation and lethality are important to understand and use as part of the safety control systems in normal operations. The road traffic and vehicles represent toxins, and medical knowledge can be utilized to assess traffic flow and how these could be managed. So far, no, or very few efforts have been made to influence this situation. There are international standards on lethality from fires [28, 29], but these are rarely seen in the tunnel fire safety work.

The literature review showed that there are major knowledge gaps of the health-related delayed injuries from smoke gas exposure. Brain injuries are an obvious phenomenon, because of lack of oxygen in fires. The respiratory system is also vulnerable and KOLS and lung cancer is possible outcomes. The increasing electrical car population can imply increasing cobalt oxide that has a paralyzing effect on the heart. Increased knowledge on health status in the population will also provide input for the tunnel safety systems, especially in emergencies. We need more retrospective and prospective studies. «Long-covid» has been identified as delayed effects from Covid-19 pandemics, which might also influence human resistance against smoke and associated toxin combinations.

Fires create a large number of gases not counted for, which might damage most organ systems in human bodies. The local irritating gases damages pulmonary systems as well as skin. The systemic toxic gases might influence all cells in the body, such as CO, CN- og CO2, of which brain disease and cardiac arrest is critical.

Hu et al. [30] show that the CO level in tunnels are much higher than it should be, based on the monitored air temperature from the car fire. There is a need to further integrate CO-censors in the tunnel safety systems. Ambulances should also be equipped with on scene measuring the blood
saturation of oxygen and the level of CO adhered to hemoglobin. This could enable the health personnel on site to identify patients needing hyperbaric treatment. This type of specific triage on site possibly could save lives, as well as limiting health deterioration. New energy carriers, such as batteries and ammonia will change the toxins related to fires, which is also an argument for bringing medical knowledge in the tunnel safety work.

The regulations on dangerous goods transport do not approach toxicology and transport through tunnels. This is a major concern both with respect to lack of knowledge amongst the tunnel safety actors, as well as the safety control systems at the tunnel infrastructures. We need a classification system encompassing various goods, vehicle types and combinations of goods and vehicle materials. This would be relevant for risk analyses and further into the performance assessments of the emergency preparedness and response systems. A proper medical knowledge-based assessment is needed to validate safety measures and emergency procedures of tunnel fire incidents. This work could also provide new and better censors for CO, cyanide, heavy metals, hydro fluoric acid etc. as input to the ambulance service in case of accident scenarios. Improving communication chains will influence the ability of the pre- and in hospital preparations.

Correct treatment then can be administered quicker as it may be started by prehospital staff or the prehospital personnel can inform the hospital so that it can be prepared to start treatment as soon as the patients arrive, e.g., by making “Cyanokit” or hydroxocobalamin available, as this may not be readily accessible, neither in prehospital units, nor at admission department in the hospital. It may for example be collected from the pharmacy or even another hospital. Such preparative processes may reduce consequences of an accident.

CONCLUSIONS

This article provides ideas to the possibilities of combining safety management thinking based on systems theory and medical knowledge about toxicology from incidents in tunnels. However, the starting points from defining standardised fire scenarios must be altered to ask questions about which toxicology situation must be regarded design criteria for the evacuation systems in road tunnels. This fact also necessitates a discussion about safe shelters or escape rooms, which must be within necessary egress time. The medical knowledge and statistical knowledge of the human morbidity with respect to critical diseases for tunnel fire smoke exposure in a population (for example Norway), must be considered and being part of the safety management process of road tunnels. Today, such assessments are lacking because of the fragmented conditions within the tunnelling industry. Tunnel owners need to adapt to a safety management practise based on systems thinking [26].

The medical perspective can also provide better information of toxicology and which toxins the various tunnel owners need to be aware of and integrate in their emergency preparedness assessments. This will be an asset for the contingency plans developed for each of the tunnels and it will provide the ambulance services with necessary information to increase their actual performances in crisis situations. Njå & Kuran [9] found critical voices amongst their interview candidates from the Oslofjord tunnel fire in 2011 with respect to the medical treatments provided, that included experiences with both the acute health services as well as the long term follow up treatments.

The study reported in this paper also point at developing new censors that will give a better picture of the criticality of the emerging fire scenarios. Ventilation control is an extremely difficult task as a crisis management measure. Any improvements in vital conditions for road users must be reflected as long as the self-rescue principle is prevailing.

REFERENCES

Tunnel safety: how about the safety of maintenance workers in tunnel service corridors?

Nils Rosmuller, Johan van der Graaf & Joost Ebus
NIPV, Netherlands Institute for Public Safety Arnhem, The Netherlands

ABSTRACT

In The Netherlands, there is an extensive set of safety requirements which applies to tunnel safety. These regulations and requirements are mainly concerned with the safety of road users and people working in the tunnels, and in some cases with the safety of emergency services such as the fire brigade. Scenario analysis and quantitative risk assessments (QRA’s) are used to examine tunnel safety. However, one specific hazard that concerns the safety of maintenance workers in the service corridor of the tunnel is not included in the Dutch set of regulations. These service corridors run parallel to the traffic tubes and are hundreds of metres or even kilometres long. Despite the lack of specific safety guidelines for maintenance workers in service tunnels, there are some general guidelines such as the occupational risk assessment and evaluation that provides some basis for the occupational safety of tunnel service workers. However, as for the tunnel service corridor itself (the construction), there are no safety guidelines, nor risk assessment tools and safety measures.

In this project, we have developed a safety framework for maintenance personnel in the service corridors of tunnels, assessed their safety risks and developed safety improvement measures. In order to understand the safety hazards of maintenance personnel in case of an incident in tunnel service corridors, we studied Dutch tunnel safety regulation and building directives, as well as occupational and labour safety laws. We studied scientific literature to find out how this service corridor worker safety issue is being dealt with. In addition, we studied comparable tunnel systems including sub-surface pipeline corridors and mining activities. Using event trees, we developed incident scenarios. Using our own knowledge regarding tunnel safety fire propagation and suppression and incident management we also created a safety framework, including safety measures. We specified the requirements and conditions that need to be met for the evacuation of maintenance workers in tunnel service corridors. We validated the framework (conditions, requirements and scenario’s) and safety measures in plenary sessions with tunnel personnel, maintenance workers and fire brigades.

The service corridor is not an area primarily meant to be used by humans. However, the Dutch Labour Law is applicable and normative for the (evacuation) safety of maintenance workers. The employer needs to specify the safety risks in an occupational risk assessment and evaluation (RI&E) and take according safety measures. Neither the tunnel operator nor the maintenance organisations have developed relevant incident scenarios for existing tunnels to assess the risks for service corridor workers. The relevant incident scenarios in tunnel service corridors are ‘fire in the corridor’ and ‘victim in corridor’ (not fire, but situations in which the victims needs assistance to be evacuated such as broken leg or service workers who became unwell). Based on these scenario’s we discovered serious safety issues for rescuing maintenance workers. To deal with these safety issues, we developed a set of measures which can be used to increase the safety of service corridor workers.

KEYWORD: tunnel service corridor, maintenance workers’ safety, fire, emergency, evacuation
DESCRIPTION OF THE TUNNEL SERVICE CORRIDOR

Road tunnels are defined by the EU-directive [1] as enclosed infrastructure with a minimal length of 500 metres and meant to facilitate road traffic. In The Netherlands, the minimum length is reduced to 250 metres. The Netherlands have developed many tunnel safety requirements and even a tunnel safety law [2] to guarantee the safety of road users, tunnel operators and emergency services. Next to the traffic tubes, service corridors are constructed. These corridors are long and small and contain the various kinds of piping, electricity cables, etcetera, necessary to operate the tunnel (see figure 1). In The Netherlands, the service corridor is often combined with the escape route for road users between the two traffic tubes.

Figure 1 Example of a tunnel service corridor.

In service corridors, people are rarely present. In case there are, they are maintenance workers or tunnel personnel. In case of an incident in the service corridor, escape is only possible using the exits of the service corridor. In general, these exists are situated at the entrance and end of the road tunnel and near service buildings/technical spaces, and often in the middle of the tunnel to support the traffic operations in the tunnel tubes. This means that the distance between exits can be 1 kilometre or more,
which can be problematic with respect to both the egress time for maintenance workers and the possibilities for emergency responders to reach the victim(s) of an incident in the service corridor.

The Netherlands have specified several requirements for service corridors:
- Construction: concrete and inflammable/ fire resistant construction materials have to be used.
- Installations: lighting and alarm systems have to be installed and inflammable/ fire resistant cables and piping material have to be used.
- Organisational: there are procedures to close the tunnel (for traffic), maintenance personnel gets instructions, incidents are registered and there are good housekeeping rules.

In The Netherlands, a tunnel is designed using pre-specified (standardized) tunnel safety measures. A strict safety analysis is conducted, including a Quantitative Risk Analysis (QRA). To this end, a pre-specified QRA-method is employed. The result of such a QRA is a ‘road user fatality rate’. This fatality rate should be less than the legally established $0.1/N^2$ per kilometre tunnel tube per year for $N > 10$, in which $N$ is the number of road user fatalities per incident.

Such a norm and QRA do not exist for maintenance workers in tunnel service corridors. In fact, for the service corridor, hardly any official safety assessment guidelines are available. Although the ‘Dutch tunnel knowledge platform’ has published a thorough report that describes and explains Dutch tunnel safety, the service corridor is mentioned only once in the 64 pages document, and only in combination with the tunnel corridor in the middle, not discussing the specific maintenance workers’ safety [3].

EXAMPLES OF TUNNEL SERVICE CORRIDOR FIRES IN THE NETHERLANDS

Traffic incidents in road tunnels often occur during maintenance work, as can be concluded from the data concerning road workers incidents or construction workers incidents in ‘Storybuilder’ [4]. Storybuilder is the database of the Dutch institute for health and environmental research (RIVM) and contains about 31,000 occupational incidents in the Netherlands in the period 1998-2014. These incidents have been reported to the Dutch Occupational Inspection Maintenance Workers and concern cases such as falls, being hit by heavy objects, get electrocuted, become unwell or cause a fire. Obviously, such accidents may also occur in service corridors and technical spaces belonging to the tunnel. Below, four of these incidents are briefly discussed. Rijkswaterstaat (RWS), the Dutch road tunnel provider for the national roadway tunnels, states that in their 60 year tunnel operation history no or hardly any incidents occurred in the service corridors (fire in the Schiphol tunnel service corridor).

Fire in the Westerschelde tunnel, 2018 (road)
On September 2, 2018, a fire broke out in a technical room of the Westerschelde tunnel. The cause of the fire was machine insulation material that had melted due to overheating. Although, the size of the fire was limited, the Westerschelde tunnel had to be closed for a short time.

Fire in the IJ tunnel, 2018 (road)
On August 11, 2018, a fire raged in the technical room of the emergency power supply of the IJ tunnel / Piet Heintunnel. A control box had caught fire for an unknown reason. The fire led to a temporary closure of the tunnel in both directions.

Fire in the Schiphol tunnel, 2017 (road)
On 27 March 2017, a fire raged in a service corridor of the Schiphol tunnel, where the electricity box for the tunnel lighting burned down. A fire in the service electricity cables in the corridor caused heavy smoke. The fire affected the cable bed above, resulting in the failure of various systems. The fire was confined to the immediate vicinity of the cabinet. The moment the fire started, there were no maintenance workers in the service corridors and no one was injured. However, the tunnel had to be
closed for several days because several tunnels safety systems were destroyed: 200 cables had burnt down, resulting in malfunctioning of the lighting and camera systems in the tunnels [5].

**Fire in the Schiphol tunnel, 2001 (railway)**

On 11 July 2001 there was a fire in a switch room (technical room) in the Schiphol tunnel, caused by maintenance work. The fire was investigated by the Transport Safety Council. After it was formally confirmed that the overhead lines were de-energized, the fire brigade started to extinguish the fire. This took more than 1.5 hours. One of the council’s recommendations to the companies involved was to improve their emergency organizations in such a way that a) the fire brigade would immediately have all the necessary equipment at their disposal, and b) the necessary information can be provided.

In the knowledge that tunnel service corridors incidents happen, it is important to identify how the safety of service corridor personnel is guaranteed. To this end, we examined the legal aspects that deal with the safety of tunnel service corridor workers; these are discussed in the following section.

**LEGAL ASPECTS**

Despite the existing European tunnel directive, tunnel safety regulations still vary quite a lot between EU membership countries. The directive only stipulates a minimum required safety level, but not the way to guarantee such a level, nor the way to assess it. Service corridor safety is simply not a topic in the EU-directive. In The Netherlands, several safety regulations regarding tunnel service corridors exist. Some of them originate from the building code 2012 [6], Tunnel safety regulations [2] and Labor safety law [7]. The building code and the tunnel safety law guarantee a minimum safety level for the road tunnel. However, they do not cover the safety of people working in the tunnel service corridor. The Labour Law prescribes some safety guidelines for people working in service corridors or rooms with installations. The employer of the service corridor workers has to assess the risks for his or her employees (risk analysis) per service corridor. The safety risks have to be described, as well as the safety measures to reduce these risks.

The three regulations (building code, Tunnel safety law and Labor law) are related to each other. The Tunnel safety law prescribes that a tunnel may only be operated in case it meets the building code requirements. The Labour law also states that the building needs to comply with the building code requirements. However, the latter is not sufficient for those cases that are not specified in the building code, such as egressing from a technical space with installations/ such as the service corridor.

To conclude, the tunnel service corridor is not specified in the tunnel safety law, nor do egress requirements exist for installations room in the building code. In addition, the Labour law requirements are no part of the permit application process for operating a tunnel. As a result, the service corridor may comply with building code directives, but may not be able to guarantee safe working conditions (e.g. escape routes). This may lead to necessary limitations while working in the tunnel or the service corridor, or in the operation of the tunnel itself, such as using personal protection equipment (PPE) or closing the traffic tunnel for vehicles during maintenance work in the service corridor.

To avoid such drastic measures, it is necessary to assess the occupational risks in tunnel service corridors. To guide such occupational risk assessments, we have developed a framework that can be applied to each separate road tunnel. Incident scenarios in the service corridors play a major role in this occupational risk assessment.

**INCIDENT SCENARIOS AND INTERVENTIONS TO REDUCE THE CONSEQUENCES**

Above, we described the importance of an occupational safety risk assessment for tunnel service corridors. Credible incident scenarios play a major role in labor safety assessment. This is also the case in service corridors. Based upon service corridor work activities, working with electricity, and the importance of safety measures (self-rescue and fire and rescue service help), we focused at two
credible scenarios in tunnel service corridors. The first is a scenario in which a person is not able to move, for example because of a stroke or broken leg, and needs to be rescued by emergency services. We call this scenario: ‘victim in tunnel service corridor’. The second scenario is a fire in a tunnel service corridor, caused for example by hot working activities or short circuiting. We call this scenario ‘fire in service tunnel corridor’.

We do not have statistical data that provide a solid basis for assessing the incident frequency of both scenarios. We assume these scenarios to be credible, because they happen often in other maintenance work. Therefore we focus at the consequences for the service corridor workers and those interventions that reduce their risks. To reduce these consequences, it is important to assess the possible courses of action of the victim and emergency services in each scenario, the goals of these actions, the requirements and conditions to reach the goals and the necessary safety measures. Figure 2 visualizes this. We used the ‘event tree methodology’ to model the goals, conditions, and safety measures.

As for both scenario’s, we formulated the goals.

**Victim in tunnel service corridor**
For the ‘victim in the service corridor’ scenario we defined three key activities and accompanying goals which need to be fulfilled to safeguard the tunnel service corridor worker(s):

- Quick recognition/discovery of the victim
- Quick alerting of personnel/the emergency response
- Quick evacuation of the victim

**Fire in tunnel service corridor**
For the ‘fire in the service corridor’ scenario, we defined five key activities and corresponding goals which need to be fulfilled to safeguard the tunnel service corridor worker(s):

- Timely discovery of the fire
- Alerting of personnel/ the emergency response in time
- Immediate fire suppression
- Safe egress/escape
Safe deployment of the fire service

Below, we will only elaborate on the scenario ‘fire in tunnel service corridor’. We chose this fire-scenario for elaboration in this paper, because it is a bit more complex than the ‘victim-scenario’: it encompasses more intervention strategies, more stakeholders and more safety measures.

FIRE IN TUNNEL SERVICE CORRIDOR: SAFETY MEASURES

Our way of reasoning to identify suitable safety measures encompasses three steps [8]:

1) To define the goal that needs to be met with an intervention
2) To define the requirement that needs to be fulfilled to reach the goal in an efficient way
3) To define the safety measures that meet the requirements

Regarding the fire scenario, we identified five major goals:

1) The fire is detected early (by maintenance workers or sensors)
2) The maintenance worker/the tunnel operator is alerted on time
3) The maintenance worker can extinguish the (small) fire (RWS procedure is that service workers do not extinguish, even small, fire)
4) The maintenance worker can escape from the service corridor
5) The fire and rescue service are able to extinguish the fire

Each of these 5 goals is elaborated on below.

Detection of a fire and alerting (internal / external) (goal 1 and 2)

We decided to combine the goals ‘early detection of a fire’ and ‘alerting (internal/external)’ in one scheme. This scheme is shown in figure 3. It has been developed top-down, from the goal to the requirements and the safety measures. However, it should be read from bottom to top. Having the safety measures and fulfilling several requirements, it may be possible to detect a fire early and to alert the maintenance worker en tunnel operator. Following the alarm procedure (PAC-procedure; PAC means private alarm centre), a fire alarm needs to be independently confirmed before the alarm is communicated to the (public) alarm centre (emergency centre).
Figure 3  Timely detection and alarm

The scheme comes down to the following key aspects. Timely alarming is the goal. In order to guarantee this, the fire should be noticed, and its location specified and communicated (the requirements). To fulfil the requirements three main safety measures are suitable:

1) Fire detection system and automatic fire alarm
2) Education and training of tunnel service corridor personnel
3) Location determination system

The maintenance worker is able to extinguish the fire (goal 3)

Figure 4 shows the accessory scheme. Again, it has been developed from top to bottom, but should be read from bottom to top. Having the safety measures and fulfilling several requirements, it may be possible to directly extinguish the fire or evacuate.
The scheme comes down to the following key insights. In order to guarantee immediate fire extinguishing activities by maintenance personnel caused by early alarming, the fire should be noticed. In case the fire originated from ordinary maintenance activities (no hot working activities), the only safe action is to evacuate (see goal 4). In case the fire originated from hot working activities (e.g. welding), a fire watch should be stand-by (requirements). To fulfil the requirement two safety measures are suitable:

1) A hot working procedure including a fire watch and smoke or fire action plan
2) Education and training of the tunnel service corridor personnel

**Evacuate (goal 4)**

The requirements for evacuating are that a) the fire and its location are known, b) two or more escape routes are available and 3) the maintenance workers are able to choose their escape route. An additional requirement of the escape routes is that they are safe. This means that the emergency exists are located at max 500 meters from each other (which means a maximum of 250 meters walking distance), based upon the 2012 Building Decree [6]. However, this implicates a minimum escape velocity (in tunnels for road users this is 1m/s [9]) and a maximum air velocity in the service corridor, which should be less that the escape velocity to prevent toxic fumes from catching up with the evacuating maintenance worker(s). The air speed in the service corridor, caused by mechanical or
natural ventilation, should not negatively affect the spread of smoke. The ventilation can also affect the speed of the fire development and hence the smoke production. This can also be the case if a so-called ‘chimney effect’ occurs, due to height differences and openings, e.g. when doors are opened.

Figure 5  Tunnel service corridor worker safe escape.

The fire and rescue service is able to extinguish the fire (goal 5)
In case the maintenance workers are not able to extinguish the fire, the fire and rescue service could try to quench the fire. We deliberately use the word ‘could’, because fighting a fire in the service corridors brings with it serious safety risks for the fire (wo)men.

The FRS-actions depend upon several conditions which need to be assessed before a fire crew will enter the service corridor, such as the fire characteristics (not too big), the location of the fire (known and not too far away from the entrance), supporting safety measures (ventilation) and of course the interests at stake (rescue personnel or ‘just’ guarantee the tunnel integrity).

The scheme below describes the conditions that ensure safe and effective action of the fire brigade, as well as the safety of the other emergency services and the necessary safety measures.
Figure 6  Safe fire and rescue service intervention.

The scheme shows the following safety measures (from left to right at the bottom):

Fire limitation
- Limit the available flammable materials in the service corridor

Safety working conditions for emergency personnel
- Emergency response procedure for the tunnel service corridor
- Switch off procedure for electricity cables and apparatus in the service corridor
- More than one service corridor entrance

The location of the fire is known, and fire extinguishing agents are available
- System for fire extinguisher agent logistics
- Fire detection system
- Location determination system
- Prepared emergency service: emergency planning, education and training

APPLYING THE TUNNEL SERVICE CORRIDOR SAFETY FRAMEWORK: CASE STUDY

We have applied our schemes to two Dutch road tunnels, The Leidse Rijn tunnel (Utrecht) and the Koning Willem Alexandertunnel. This meant that first we studied documents concerning the tunnel service corridor design (received from the tunnel operator) and the maintenance labour assessment (received from the tunnel maintenance contractor). Not surprisingly (because this was the reason for starting our research), the safety of the tunnel service personnel is hardly discussed. However, there are some documents that mention safety risks for the service corridor workers, although these do not address the escape possibilities for the service workers, nor the activities of the fire and rescue service.
As we now have the labour assessment framework discussed above, with the goals, requirements and safety measures, we are able to assess the safety of the service corridor personnel. To better understand the labour safety documents, we spoke to tunnel labour safety officers, maintenance workers and the fire service. In addition, we visited the tunnels and used our framework, i.e. the set of safety measures, to assess the tunnel service corridor safety. The four most important observations were:

- Safety systems to facilitate alerting, communication and pinpointing the incidents’ locations were not in all tunnel service corridors available. This means that it might take a while after the start of an incident before assistance could arrive. Moreover, when the incident type and location are unknown, emergency workers have a rather limited situational awareness.
- Victims in the tunnel are difficult to rescue: the escape routes are long (kilometres), and accordingly, victims cannot easily be reached by emergency responders. In addition, these routes are small and have a rather low ceiling. This means that maintenance workers helping each other to reach the exit (e.g. by carrying or dragging an injured colleague) have a very difficult job to do.
- Systems to horizontally transport victims from the incident scene to the tunnel exits are absent. Such equipment could help both the maintenance workers as well as the emergency services to rescue victims.
- In case of fire, the accessibility of the fire scene is hampered because of the long distances. This means that the fire crew has to walk hundred to thousands of metres, wearing their breathing apparatus and fire hose. This is an enormous exhausting operation that takes a long time and might even result in hardly any time at the fire scene itself, because breathing apparatus run out of oxygen.

We learned from the two applications that our framework and schemes are useful, but require substantial know-how of fire development and fire suppression. Tunnel labor safety experts need to be assisted while working with the schemes. To this end we have developed comprehensive tables with safety measures [8]. These tables guide safety experts to the goals, the requirements and safety measures. They also indicate:

- to what scenario the safety measure is applicable
- what type of safety measures it concerns: construction, installations procedure
- to what extent (qualitatively assessed by us) the safety measures contribute to reaching the top goals (detection, alerting, evacuating, extinguishing the fire by the maintenance workers, and/or the fire suppression by the fire and rescue service)
- what the consequence are if the safety measure is not implemented
- to what regulations (articles in the law or directives) the safety measure are related to.

To illustrate the above, we have added a screen-view of a part of the comprehensive safety measures table, see figure 7 below.
Additionally, we learned from both case studies that there is a sort of natural sequence that is followed by the tunnel safety experts in employing the safety measures. We schematized this sequence or way of reasoning below (figure 8). First, the question is asked whether or not the service corridors meet the requirements in the relevant laws. In case they do not, safety measures need to be taken, e.g. regarding the construction, installation or organisation. In case the corridor meets the lawful requirements, it is important to assess whether the corridor facilitates the safe escape of service corridor workers. In case it does not, safety measures need to be taken, e.g. regarding the construction, installation or organisation. In case the corridor facilitates a safe escape, it is necessary to assess whether the corridor facilitates a safe fire service and rescue intervention. In case it does not, safety measures need to be taken, e.g. concerning the construction, installation or organisation. In case it does, an occupational safety risk assessment report should be made. In this report (RI&E) tunnel service corridor safety risks are assessed, for which the scenario’s and safety measures that we developed are very useful.

The tunnel labour safety experts indicated that such insights are very valuable, and they supported both the framework as well as the comprehensive tables with safety measures. Rijkswaterstaat (RWS) intends to apply the framework to all their tunnels. In addition, RWS takes its part of the responsibility for the maintenance workers safety (the part that belongs to the service corridor design): escape routes, horizontal transportation facilities, alarm systems, detection and service workers position determination.
CONCLUSIONS

In the laws and regulations that apply to a service corridor of a road tunnel, a distinction is made between building regulations, tunnel regulations and working conditions regulations. The regulations for safe escape from the 2012 Building Decree do not apply to a service corridor. However, some other regulations of the 2012 Building Decree could affect a safe escape. The occupational health and safety regulations are normative for the safety provisions for maintenance workers in service corridors. The Building Decree and the tunnel regulations provide a certain basic level of safety, but are both not aimed at the safety of incidentally present maintenance workers. The Occupational health and safety regulations are complementary to the regulations of the Building Decree, whereby the Occupational health and safety regulations set requirements for a workplace. The employer has to provide a description of each shift in an object RI&E analysis, the risks and the mitigating measures.

The topic 'safe escape' in the incident scenarios 'fire in the service corridor' and 'victim in the service corridor' are presently insufficiently safeguarded in the object RI&E analyses in the current safety policy of Rijkswaterstaat. This also applies to the 'safe operation of emergency services' in the corridor. The incident scenarios 'fire in service corridor' and 'victim in service corridor' have been identified as the scenarios requiring immediate escape.

We specified the scenario’s in actions/goals, requirements and safety measures. In particular, a limited number of emergency exits means that escaping involves long walking distances and long distances for emergency responders to reach the accident scene. Promising safety measures in the tunnel service corridor design to improve the maintenance workers’ safety are more emergency exits, leading to shorter walking distances, horizontal transportation facilities, alarm systems, detection and position...
determination. The comprehensive tables in combination with a short safety introduction course will facilitate tunnel safety experts to assess the tunnel service corridor workers’ safety.

REFERENCES


Study on the maximum temperature rise beneath the ceiling considering the effect of bifurcated plume flow in longitudinally ventilated tunnel fires

Ganyu Wang\textsuperscript{1,2,3}, Jiangdong Li\textsuperscript{1,2,3}, Tianhang Zhang\textsuperscript{1,4}, Xiaoqi Zhang\textsuperscript{1}, Jiajun Weng\textsuperscript{1}, Ke Wu\textsuperscript{1,2,3}
\textsuperscript{1} Key Laboratory of Offshore Geotechnics and Material of Zhejiang Province, Zhejiang University, Hangzhou, China
\textsuperscript{2} Center of Balance Architecture, Zhejiang University, Hangzhou, Zhejiang, China
\textsuperscript{3} The Engineering Research Center of Oceanic Sensing Technology and Equipment, Ministry of Education, Zhejiang University, Hangzhou, China
\textsuperscript{4} Research Centre for Fire Safety Engineering, Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong

ABSTRACT

Evaluation of the temperature profile induced by fire is of great significance to assess the tunnel fire risk and damage. In this work, the effect of plume bifurcation on the air entrainment process is analyzed theoretically, quantified with a set of numerical simulations, and validated by full-scale tunnel fire test data. Results show that the high ventilation-induced plume bifurcation will lead to two hitting points distributed symmetrically along the centre line, increase the air entrainment path, and thus, decrease the maximum temperature. Finally, a semiempirical model is proposed to evaluate the maximum temperature rise with different fire heat release rates and ventilation conditions considering the smoke plume multi-dimensional movement characteristics. This study provides a new vision to understand the plume behaviors in tunnel fire scenario and extends the applicability of classical tunnel fire dynamic theory.

KEYWORDS: tunnel fire dynamics, fire behaviour, mass transfer, smoke bifurcation flow

INTRODUCTION

Tunnel is a typical semi-closed space that poses a significant risk in case of a fire, which can lead to enormous economic losses and casualties due to the rapid accumulation of heat. The high-temperature smoke generated by the fire source will not only threaten the trapped people inside \cite{1}, but also cause thermal damage to the tunnel structure, potentially leading to tunnel collapse and permanent structural damage \cite{2}. Therefore, the maximum temperature rise distribution in tunnel fire becomes an essential parameter for assessing the risk of fire thermal environment and a hot issue in the field of disaster prevention worldwide.

The ceiling temperature distribution prediction in the tunnel fire has drawn increasing attention over the past few years, which is closely correlated with the development of the fire plume \cite{3}. Since the 1950s, the buoyant plume model based on the assumption of axisymmetric plume was proposed \cite{4,5}. Heskestad \cite{6} and Zukoski \cite{7} simplified the temperature profile through the plume horizontal sections as Gaussian distribution and self-similarity to derive the empirical formula of temperature rise on the centreline of the plume. Specifically, the temperature rise, denoted by $\Delta T$, is proportional to the ratio of the heat release rate $\dot{Q}^{2/3}$ of the fire source to the plume height $z^{5/3}$. McCaffrey\cite{8} divided the typical structure of fire plume under unrestricted fire scenarios into continuous flame zone, intermittent flame zone and buoyancy plume zone from bottom to top, and further described the plume temperature distribution characteristics in sections according to the value of $z/\dot{Q}^{2/5}$. On this...
basis, many scholars have carried out extensive research on the radiant heat flow and temperature rise around the open-air fire, but the research on thermal environment of tunnel fires under boundary restriction remains relatively limited.

Alpert [9] firstly proposed a prediction model to evaluate the maximum smoke temperature rise of ceiling jet, which is applied to specific scenarios where the distances between the fire source and the sidewalls are greater than 1.8 times of ceiling height, see Eq. (1).

$$\Delta T_{\text{max}} = 16.9 \frac{Q^{2/3}}{H_{\text{ef}}^{5/3}}$$

(1)

where $\Delta T_{\text{max}}$ is the maximum smoke temperature rise beneath the ceiling in $K$; $Q$ is the heat release rate in $kW$ and $H_{\text{ef}}$ is the effective tunnel height in m, i.e., the distance from the fire surface to the tunnel ceiling. Obviously, the narrow and long structure of the tunnel cannot meet the requirements of the Alpert model, which only considers the process of ceiling jet and ignores the accumulation effect of smoke layer beneath the tunnel ceiling. In fact, the restriction of the tunnel sidewall will limit the air entrainment of the thermal plume and accumulate heat under the ceiling. The empirical equations similar to Eq. (1) were proposed by Li [10] and Ji [11] which can be applied to the restricted environment in tunnels, with larger constants of 17.5 and 17.9 respectively.

It is worth mentioning that longitudinal ventilation, as a widespread method to control tunnel smoke spread, will significantly affect the fire plume characteristics[12]. Kurioka et al. [13] developed a set of empirical formulas to predict the maximum temperature of smoke layer under ventilation conditions through a series of small-scale experiments and full-scale tests, as follows:

$$\frac{\Delta T_{\text{max}}}{T_a} = \gamma \left( \frac{Q^{2/3}}{Fr^{1/3}} \right)$$

(2)

where $Q^*$ is the dimensionless heat release rate, which is expressed as $Q^* = \dot{Q}/(\rho_a c_p T_a g^{1/2} H_{\text{ef}}^{5/2})$; $Fr$ is the Froude number, which represents $V^2/(g \cdot H_{\text{ef}})$; $\rho_a$ is ambient density in $kg/m^3$, $c_p$ is the specific heat capacity in $kJ/(kg \cdot K)$, $T_a$ is the ambient temperature in $K$, and $g$ is the gravitational acceleration constant in $m/s^2$. $\gamma$ and $\varepsilon$ are constants determined by the following equation:

$$\begin{cases} Q^{2/3}/Fr^{1/3} < 1.35, & \gamma = 1.77, \ \varepsilon = 1.2 \\ Q^{2/3}/Fr^{1/3} \geq 1.35, & \gamma = 2.54, \ \varepsilon = 0 \end{cases}$$

(3)

However, it can be found from Eq. (2) that when the longitudinal ventilation velocity approaches zero, $Q^{2/3}/Fr^{1/3}$ is much greater than 1.35, then $\Delta T_{\text{max}}$ will remain constant regardless of the fire heat release rate, which is obviously inconsistent with the actual fire scenarios. Considering the failure of above model at low ventilation velocity, Li et al. [10] analyzed the maximum smoke temperature below the ceiling based on the axisymmetric fire plume theory and weak plume hypothesis:

$$\Delta T_{\text{max}} = \begin{cases} 17.5 \frac{Q^{2/3}}{H_{\text{ef}}^{5/3}}, & V' \leq 0.19 \\ \frac{Q}{\sqrt{V b_{fo}/H_{\text{ef}}^{2/3}}}, & V' > 0.19 \end{cases}$$

(4)

with $V' = \frac{V}{w^*}$, $w^* = \left( \frac{\dot{Q} g}{b_{fo} \rho_a c_p T_0} \right)^{1/3}$.

where $b_{fo}$ is the radius of fire source in m, $V$ is the ventilation velocity in $m/s$, $V'$ is the dimensionless longitudinal ventilation velocity, $w^*$ is the characteristic plume velocity, $\dot{Q}$ is the convection heat release rate in $kW$, which can be considered as 70% of the total heat release rate. Besides, Li et al. [3] further pointed out that the upper limit of the maximum temperature of the tunnel ceiling is 1350 °C by summarizing a large number of scale model experimental data.
Yao et al. [14] proposed to divide the maximum gas temperature rise model into three regions on the basis of Li et al.’s model using the $V’$ of 0.19 and 0.42 as the dividing point, so as to apply to the fire scenarios with higher longitudinal ventilation velocities.

$$\Delta T_{\text{max}} = \begin{cases} 
19.5 \frac{\dot{Q}^{2/3}}{H_{\text{ef}}^{5/3}}, & V' \leq 0.19 \\
19.5 \frac{\dot{Q}^{2/3}}{H_{\text{ef}}^{5/3}} (5.26V')^{-1}, & 0.19 < V' < 0.42 \\
19.5 \frac{\dot{Q}^{2/3}}{H_{\text{ef}}^{5/3}} (5.26V')^{-5/6}, & V' \geq 0.42
\end{cases}$$

(5)

The “top-hat profiles” model, which assumes the parameters, i.e., temperature, density, and velocity are constants across the horizontal sections, was widely adopted in previous research works [15]. Based on this simplification, the maximum temperature point is distributed in the centre line of the tunnel ceiling. However, Li et al. [16] found that the temperature of the plume impingement zone would drop suddenly when the ventilation velocity increased to a certain value. Further, it can be observed that a central low-temperature region appears before the plume flow hits the ceiling. Recent research has shown that the smoke will separate into two sub-streams under high ventilation velocities [17–19], namely, plume bifurcation. When the bifurcated plume occurs, two sub-streams will hit the ceiling at different positions, respectively, and the maximum temperature point is no longer in the centre line. Therefore, the existing prediction methods for the maximum ceiling temperature, which rely heavily on the temperature data measured along the centre of the tunnel ceiling, will be invalid. A deep understanding of the maximum temperature rise beneath the ceiling considering the effect of bifurcated plume flow is still lacking.

In this work, the intriguing phenomenon of plume bifurcation, and its consequential impacts on the plume entrainment is investigated both experimentally and numerically. The heat and mass transfer process for a bifurcated fire plume is analyzed and compared with the classical plume theory. Finally, an empirical formula is proposed to predict the maximum ceiling temperature, accounting for the effect of the bifurcated plume flow, and further validated by large-scale tunnel fire test. These new findings can deepen the understanding of tunnel fire phenomena, and provide scientific guidelines for the design of tunnel firefighting system.

THEORETICAL ANALYSIS/MODEL

Maximum ceiling temperature

Previous studies have shown that the maximum ceiling smoke temperature is typically located at the impingement point [10,20]. When a fire occurs in a natural ventilation condition, the fire plume will impinge on the tunnel ceiling vertically and form an axisymmetric ceiling jet [21]. However, longitudinal ventilation will disrupt the upstream and downstream airflow movement, leading to an asymmetric flow. As depicted in Fig. 1, there is an increasing tendency of the flame tilting to the downstream with a significant increase of the longitudinal airflow entrained from the upstream. When the ventilation velocity is low, the fire plume still remains typical single-stream pattern, then hitting the ceiling centreline to form a stable ceiling-jet (Fig. 1a). Once the ventilation velocity reaches a certain value, a special phenomenon of plume bifurcation will be triggered [22]. It can be observed from Fig. 1b that two sub-streams will hit the ceiling at separate positions, respectively, and the maximum temperature point is no longer situated on the centreline, but symmetrically distributed on both sides along the central axis of the tunnel. During this bifurcation process, the maximum ceiling temperature rise is determined by the combined effect of longitudinal ventilation entrainment and the cumulative heat release generated by fire.
To analyze the relationship between the basic characteristic parameters of the bifurcation plume, a novel bifurcated plume model was introduced by modifying the classical "top-hat" plume model (Fig. 2a), as shown in Fig. 2b, to adapt to the strong longitudinal ventilation environment in the tunnel. It is assumed that the temperature of the bifurcated flow has a similar distribution at any height, displaying a top-hat profile distribution[10]. Consequently, the maximum ceiling temperature of the tunnel is considered as the maximum temperature of the bifurcated plume section at the tunnel height, and the corresponding location of maximum temperature is the midpoint of the two bifurcated plume sections. These assumptions facilitate the prediction of the most vulnerable position of the ceiling under tunnel fire accidents, by defining $L_{OM,x}$ as the horizontal distance between the position of the plume hitting points and the fire source centre, and $d$ as the transverse distance between the two hitting points. The two characteristic angles, $\theta_v$ and $\theta_h$, are also used to describe the degree of plume deflection in the vertical and horizontal directions. $\theta_v$ is the plume deflection angle from vertical, representing the included angle between the central axis perpendicular to the fire source surface and the inclined path of plume flow. While the plume deflection angle from horizontal, $\theta_h$, is defined here as half of the angle formed by the positions where the two sub-streams hit the ceiling and the vertical projection point $O'$ of fire source centre on the tunnel ceiling.

$$\tan \theta_v = \frac{L_{OM,x}}{H_{ef}}$$

(6)

$$\tan \theta_h = \frac{d}{2L_{OM,x}}$$

(7)

Zukoski et al.[23] obtained the empirical formula of plume mass flow in buoyancy plume zone by conducting a large number of model experiments as follows:

$$\dot{m}_p(z) = 0.071 \dot{Q}_c^{1/3} z^{5/3}$$

(8)
where \( z \) is the height in the vertical direction in m, \( \dot{Q}_c \) is the convection heat release rate in kW. The radiative component of the total HRR is considered as 30% [24], while the convection heat release rate is 70% of the total heat release rate. The convection heat release rate \( \dot{Q}_c \) can be expressed as:

\[
\dot{Q}_c = c_p \dot{m}_p(z) \Delta T_{ave}(z)
\]  

Substituting Eq. (8) into Eq. (9), the average temperature of the fire plume can be obtained as follows:

\[
\Delta T_{ave}(z) = \frac{\dot{Q}_c^{2/3}}{c_p \dot{m}_p(z)} = 11.05 \frac{\dot{Q}_c^{2/3}}{z^{5/3}}
\]  

Considering that there is a proportional relationship between the plume centre temperature and the average smoke temperature, combined with Eq. (10), the maximum smoke temperature rise of the plume can be written as:

\[
\Delta T_{max}(z) = C_T \Delta T_{ave}(z) = 11.05 C_T \frac{\dot{Q}_c^{2/3}}{z^{5/3}} = \alpha \frac{\dot{Q}_c^{2/3}}{z^{5/3}}
\]  

where \( C_T \) is the temperature correction coefficient, i.e., the ratio of the maximum temperature rise to the average temperature rise, \( \alpha \) is the coefficient related to the specific fire scenario, which can be determined experimentally.

It is assumed that the maximum smoke temperature rise in the longitudinal ventilated tunnel fires is almost equal to that in the natural ventilation tunnel [14]. As shown in Fig. 2(a), we can substitute the length of the plume inclined path \( L_{OM} \) into Eq. (11) to obtain the expression of the maximum ceiling temperature of the single-stream plume, as follow:

\[
L_{OM} = \frac{H_{ef}}{\cos \theta_v}
\]

\[
\frac{\Delta T_{max}(L_{OM})}{\Delta T_{max}(H_{ef})} = \left( \frac{H_{ef}}{L_{OM}} \right)^{5/3} = \cos \theta_v^{5/3}
\]  

where \( \theta_v \) is the plume deflection angle, and its empirical formula is given in ref [25]:

\[
\cos \theta_v = \begin{cases} 
1, & V' \leq 0.19 \\
(5.26V')^{-3/5}, & V' > 0.19
\end{cases}
\]  

Combining Eq. (13) and Eq. (14), the maximum ceiling temperature under low longitudinal ventilation can be written as:

\[
\Delta T_{max} = \begin{cases} 
\alpha \frac{\dot{Q}_c^{2/3}}{H_{ef}^{5/3}}, & V' \leq 0.19 \\
\alpha \frac{\dot{Q}_c^{2/3}}{H_{ef}^{5/3}}(5.26V')^{-1}, & V' > 0.19
\end{cases}
\]

As mentioned, the plume morphology will change from single-stream to double-stream with strong ventilation conditions. Considering the effect of re-distribution of mass and energy caused by the bifurcated plume, we assume that the air entrainment behaviors are considered to be the same for bifurcated plume and single plume under the ideal symmetry conditions, then the mass flow rate, and enthalpy for each single plume could be expressed as:

\[
\dot{m}_{p,b}(z) = 0.5 \times \dot{m}_p(z) = 0.0355 \dot{Q}_c^{1/3} z^{5/3}
\]

\[
\dot{Q}_{c,b} = 0.5 \dot{Q}_c
\]
Thus, the maximum temperature at different heights of each bifurcated plume is:

\[
\Delta T_{\text{max},b}(z) = C_T \frac{Q_{c,s}^{2/3}}{c_p m_{p,s}(z)} = 17.57 C_T \frac{Q^{2/3}}{z^{5/3}} = \beta \frac{Q^{2/3}}{z^{5/3}}
\]  

(18)

Obviously, the maximum temperature rise of bifurcated plume is still proportional to the 2/3 power of the total heat release rate \( \dot{Q} \) and inversely proportional to the 5/3 power of the height \( z \), which shares the same formula structure with single ones. Then the bifurcated plume flow path will also be transformed as follows:

\[
L_{\text{OM}} = H_{ef} \left( 1 + \tan \theta_v^2 + \tan \theta_v^2 \tan \theta_h^2 \right)^{1/2}
\]

(19)

Therefore, the maximum ceiling temperature under strong ventilation can be written as:

\[
\frac{\Delta T_{\text{max}}(L_{\text{OM}})}{\Delta T_{\text{max}}(H_{ef})} = \left( \frac{H_{ef}}{L} \right)^{5/3} = \left( 1 + \tan \theta_v^2 + \tan \theta_v^2 \tan \theta_h^2 \right)^{-5/6}
\]

(20)

\[
\Delta T_{\text{max}} = \beta \frac{Q^{2/3}}{H_{ef}^{5/3}} \left( 1 + \tan \theta_v^2 + \tan \theta_v^2 \tan \theta_h^2 \right)^{-5/6}
\]

(21)

### Plume deflection angle

The characteristic angles of plume, including the vertical deflection angle \( \theta_v \) and the horizontal deflection angle \( \theta_h \), serve as crucial indexes in identifying the location of the maximum ceiling temperature. According to the dimensional analysis[26,27], the governing factors for the projected length plume along the x-direction \( L_{\text{OM},x} \) in a longitudinally ventilated tunnel are the characteristic parameters of tunnel section \( W \) and \( H \) in m, fire source radius \( b_{fo} \) in m, heat release rate \( Q \) in kW, longitudinal ventilation velocity \( V \) in m·s\(^{-1}\), air density \( \rho_a \) in kg·m\(^{-3}\), ambient temperature \( T_a \) in K, the thermal capacity of air \( C_p \) in kJ·kg\(^{-1}\)·K\(^{-1}\), and gravitational acceleration \( g \) in m·s\(^{-2}\). Therefore, all parameters affecting plume development can be mathematically expressed as the following equation:

\[
f(L_{\text{OM},x}, W, H, b_{fo}, Q, V, T_a, \rho_a, C_p, g) = 0
\]

(22)

Based on the relevant criteria of similarity theory, Eq. (22) can be transformed as follows:

\[
f(L_{\text{OM},x} = \frac{Q}{\rho_a H^2 V^3}, \frac{C_p T_a}{V^2}, \frac{gH}{V}, \frac{b_{fo}}{V}, \frac{W}{H}) = 0
\]

(23)

\[
L_{\text{OM},x} = \frac{Q}{\rho_a C_p T_a g^{1/2} H^{5/2} V^{5/2}} = \frac{Q}{\rho_a C_p T_a g^{1/2} H^{5/2} V^{5/2}} = \frac{Q}{(gH)^{1/2}} = f(A_R \cdot \beta_s V^*^3)
\]

(24)

where, \( Q^* = \frac{Q}{\rho_a C_p T_a g^{1/2} H^{5/2}} \) is the dimensionless heat release rate, represents the buoyancy effect; \( V^* = \frac{V}{(gH)^{1/2}} \) is the dimensionless ventilation velocity, represents the inertial force action of longitudinal ventilation; \( A_R = \frac{W}{H} \) is tunnel section coefficient, i.e., the ratio of tunnel width to height; \( \beta_s = \frac{b_{fo}}{W} \) represents the blocking effect of fire plume on incoming flow.

A new dimensionless ventilation velocity \( V' \) is defined as [25]:

\[
V' = V' \left( \frac{A_R \cdot \beta_s}{Q^*} \right)^{1/3} = V' \left( \frac{gQ}{b_{fo} \rho_a C_p T_a} \right)^{1/3}
\]

(25)

Then the above expression can be written as:
\[ \tan \theta_v = \frac{L_{OMX}}{H} = f(V'^{-3}) = \lambda (AR)^m (V')^n \] (26)

Where, \( \lambda, m, \) and \( n \) are the coefficients that can be obtained by fitting the results of numerical simulation. Therefore, the plume vertical deflection angle \( \theta_v \), which reflects the degree of plume inclination during the rising stage, can be well correlated with the aspect ratio \( AR \) and the dimensionless ventilation velocity \( V' \). The above relationship has also been verified by previous studies on tunnel flame and plume deflection angle [25,28]. Considering that the bifurcation behavior of plume is also attributed by the coupling effect of buoyancy of hot smoke, inertia force of longitudinal airflow, and the constraints of tunnel section. Given the similar influence mechanism on the plume morphology, it can be inferred that the plume horizontal deflection angle \( \theta_h \) can also establish a good relationship with the aspect ratio of tunnel section \( AR \) and the dimensionless ventilation velocity \( V' \) [19].

EXPERIMENTAL AND NUMERICAL METHOD

Tunnel fire test
A series of full-scale fire tests were conducted in WangZhai Tunnel in Zhejiang with longitudinal ventilation system. As shown in Fig.3, WangZhai Tunnel is a two-lane single tube tunnel with a cross-section of \( 4.5 \times 9 \) \( m^2 \) and a slope of 2.8%. The total length of the tunnel is 2.24 km, and two groups of fans are set at the entrance and exit of the tunnel, with an interval of 200 m, respectively. The fire test was performed in the section with a length of 200 m between the two fan groups.

Fig. 3. Plane view of the Wangzhai Tunnel.

The layout of the experiment configuration is shown in Fig. 4a. Two CCD cameras were used to capture the morphological characteristics of the plume from the front and side view respectively. Additionally, a laser-sheet with an output wavelength of 523 nm was applied to assist the smoke flow imaging. Two groups of anemometers were positioned upstream and downstream from the fire source to monitor the real-time velocity of air flow. The measurement accuracy, range, and sampling interval are 0.01 m/s, 0-40 m/s, and 1 s respectively. The average value of velocity measured by three points on the monitoring surface represents the airflow velocity of the tunnel cross-section. The temperature measurement system consists of two sets of K-type thermocouples and one set of fiber temperature detectors under the tunnel ceiling, as illustrated in Fig. 4b. The optical fiber is equipped with a temperature detector every 0.4m along the longitudinal direction of the entire tunnel section. Meantime, two groups of longitudinal thermocouples were respectively arranged 5 cm beneath the tunnel ceiling at the tunnel centreline and side wall with a total of 28 measuring points. The thermocouples were placed 3 m in the near fire field and 6 m in the far fire field. The electrical signals collected by the data acquisition device were then transmitted to the data storage device for subsequent analysis.
Diesel pool fires were adopted as the fire source and each experimental fuel pan was 1 m (L) × 1 m (W) × 0.2 m (H). The fuel depth was 2 cm, which was sufficient to generate a steady heat release rate \[29\]. During the fire test, the fuel pan was set on a fireproof board, and the real-time mass variety of the fuel was recorded with four weighing sensors, as shown in Fig. 4c. The mass data were recorded at one-second intervals, then the heat release rate of the fire source can be calculated by the mass loss rate as follows:

\[
\dot{Q} = \eta \dot{m} \Delta H
\]  

where \(\dot{Q}\) is the heat release rate in kJ/g; \(\eta\) is the combustion efficiency, which is 0.75 for the square oil pan[30]; \(\dot{m}\) is the mass loss rate of the fuel pan in g/s; \(\Delta H\) is the combustion heat in MJ/kg, adopted as 43 MJ/kg for diesel. Therefore, two different pool fires of 1.34 and 1.91 MW were set by controlling the number of oil basins. It is worth mentioning that the ventilation condition will not lead to significant differences in the heat release rate of the same pool fire, and the fluctuation range of its statistical value will not exceed 10% as shown in Fig. 5a.

Four operation models of the vent groups were considered to validate the ceiling temperature distribution under varying ventilation conditions. To eliminate the impact of environmental wind on the smoke flow motion caused by tunnel slope, the tests were conducted with the fan closed, resulting in an observed airflow velocity of approximately 1.13 m/s. On this basis, different longitudinal ventilation velocities ranging from 0.5 to 2.5 m/s can be achieved by regulating the number of fans opened. The velocity distribution under different test conditions is shown in Fig. 5b, which reveals a relatively uniform distribution with a fluctuation range of no more than ±0.2 m/s. Details of the fire test condition are given in Table 1, eight sets of experiments were conducted under different fire power and ventilation conditions.
Fig. 5. (a) Heat release rate, and (b) ventilation velocity in the full-scale tunnel fire test

Table 1. The fire test conditions.

<table>
<thead>
<tr>
<th>No.</th>
<th>Numbers of fuel pans</th>
<th>HRR (MW)</th>
<th>Fans model</th>
<th>u (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.34</td>
<td>One reverse fan</td>
<td>0.50</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1.34</td>
<td>No fan</td>
<td>1.13</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1.34</td>
<td>One fan</td>
<td>1.97</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1.34</td>
<td>Three fans</td>
<td>2.45</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>1.91</td>
<td>One reverse fan</td>
<td>0.50</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>1.91</td>
<td>No fan</td>
<td>1.13</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1.91</td>
<td>One fan</td>
<td>1.97</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>1.91</td>
<td>Three fans</td>
<td>2.45</td>
</tr>
</tbody>
</table>

CFD simulation

Fire dynamics simulator (FDS) software is adopted to simulate the tunnel fire scenarios in this work. The large eddy simulation (LES) and the mixture fraction-based combustion model (MFCM) are employed to solve the turbulence mixture and combustion processes respectively [31]. The computational domain is the same as the full-scale tunnel. Considering that the tunnel width will affect the transverse flow pattern [32] and the temperature distribution near the fire source [33], a 200 m long, 4.5 m high model tunnel is established with different tunnel widths (4.95 m, 14.85 m, 21.6 m, 35.1 m, and 41.85 m), and tunnel aspect ratios varying from 1.1 to 9.3, as shown in Fig. 6. The dimension of fire source is $1.0 \times 1.0 \text{ m}^2$, which is located at the centreline of tunnel, and the distances from the fire source to the tunnel inlet and outlet are 60 m and 140 m respectively. The combustion reaction for methane is selected from material properties in the database with a soot yield of 0.01.

Fig. 6. Diagram of the numerical model (a) 3D view, and (b) cross-section view.

In all simulations, the ambient air temperature, ambient pressure, and humidity are set at 20°C, 101.325 kPa, and 40%, respectively. The tunnel entrance is set as "SUPPLY" with a fixed ventilation
velocity to simulate the longitudinal ventilation airflow, while the tunnel exit is set as "OPEN". The solid boundaries of the tunnel are endowed with the thermal and physical properties of concrete, whose density, thermal conductivity, and specific heat are 2280 kg/m$^3$, 1.8 W/(m-K), and 1.04 kJ/(kg-K), respectively [34]. The arrangement of various measuring points and slices of the model is illustrated in Fig.6a. A sequence of thermocouples is arranged longitudinally 0.25 m below the tunnel ceiling along the tunnel to capture the maximum ceiling temperature. The transverse interval of thermocouples is 0.25 m, while the longitudinal intervals are 0.25 m within a range of 50 m around the fire source, and 0.5 m within 100 m of the far-fire field.

In order to optimize the grid computing efficiency in FDS simulation, a non-uniform mesh system is applied to the FDS computational domain, i.e., the whole tunnel domain is divided into three continuous subdomains. A refine grid of 0.125 m is used to capture changes in the flow field near the fire source, while relatively coarse numerical grids of 0.25 are used upstream and downstream of the fire source. The simulated conditions are summarized in Table 2. Totally, 480 numerical simulations are conducted for the tunnel considering six different section aspect ratios, four different fire source powers, and the longitudinal ventilation velocity in the range of 0.2 m/s~4 m/s. The fire heat release rates are designed based on common fire scenarios in road tunnels, including car fire (3~5 MW), van fire (10 MW), and truck or bus fire (20 MW) [35]. The grid dependent study and the validation could be found in ref [22].

### Table 2. Calculation domain information.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>AR</th>
<th>Calculation domain L (m) × w (m) × h (m)</th>
<th>Heat release rate (MW)</th>
<th>Ventilation velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test No.</td>
<td>AR</td>
<td>Calculation domain L (m) × w (m) × h (m)</td>
<td>Heat release rate (MW)</td>
<td>Ventilation velocity (m/s)</td>
</tr>
<tr>
<td>A1 – A80</td>
<td>1.1</td>
<td>200×4.95×4.5</td>
<td>3, 5, 10, 20</td>
<td>0.2 - 4.0</td>
</tr>
<tr>
<td>B1 – B80</td>
<td>2</td>
<td>200×9×4.5</td>
<td>3, 5, 10, 20</td>
<td>0.2 - 4.0</td>
</tr>
<tr>
<td>C1 – C80</td>
<td>3.3</td>
<td>200×14.85×4.5</td>
<td>3, 5, 10, 20</td>
<td>0.2 - 4.0</td>
</tr>
<tr>
<td>D1 – D80</td>
<td>4.8</td>
<td>200×21.6×4.5</td>
<td>3, 5, 10, 20</td>
<td>0.2 - 4.0</td>
</tr>
<tr>
<td>E1 – E80</td>
<td>7.8</td>
<td>200×35.1×4.5</td>
<td>3, 5, 10, 20</td>
<td>0.2 - 4.0</td>
</tr>
<tr>
<td>F1 – F80</td>
<td>9.3</td>
<td>200×41.85×4.5</td>
<td>3, 5, 10, 20</td>
<td>0.2 - 4.0</td>
</tr>
</tbody>
</table>

The simulation time is set as 360 s to ensure that the smoke movement reached a relatively stable state, and the temperature evolution of each measuring point along the longitudinal direction is summarized in Fig.7. It can be observed that the fire reaches a quasi-steady stage after 60 s, after which the small pulsations of temperature measuring point are caused by the puffing flame and turbulent smoke flow. The temperature fluctuation range in the near fire source area is less than 10%, and that in the far fire source area is even less than 5%. Therefore, the time average value from 300 s to 360 s is selected to represent steady-state value for subsequent analysis.

![Fig. 7. Time varying process of temperature at different positions downstream of the fire source at the centre line.](image)
RESULTS AND DISCUSSION

Characteristics of inclined plumes
As the longitudinal ventilation velocity increases, the plume morphology gradually changes due to the different interactions between the air flow and the fire plume. It evolves from complete merging to intermittent merging, and ultimately triggers the plume bifurcation, resulting in different maximum smoke temperature rises under the tunnel ceiling. Fig. 8 shows the temperature field under different plume morphologies, including a typical single-stream plume under low ventilation and a bifurcated-stream plume under strong ventilation. It can be seen that the plume bifurcation occurs only when the ventilation velocity reaches a certain value. Unlike the traditional fire scenario, in which the maximum ceiling temperature is always located in the middle of the tunnel (Fig. 8a), the bifurcated flow will produce two hitting points on the tunnel ceiling, resulting in two maximum temperature distribution points symmetrically distributed on both sides of the tunnel (Fig. 8b). Then we can determine the hitting points according to the position of the maximum ceiling temperature.

Fig. 8. The temperature field beneath the tunnel ceiling under (a) 1.8 m/s and (b) 3 m/s, where the HRR and tunnel aspect ratio are fixed as 5 MW and 4.8, respectively.

Considering the plume bifurcation is strongly correlated with the ventilation velocity, the mechanism of plume bifurcation can be better shown by Fig. 9. As fresh air flow from the upstream of the tunnel is blocked by the plume, airflow faces difficulty in passing through the plume to reach the downstream. Therefore, a so-called local velocity of the airflow around the plume $u_{loc}$ accelerates the exchange of mass and energy between fresh air and the plume boundary, dominating the transverse spread of the plume. As illustrated in Fig. 9a, the longitudinal ventilation velocity and the corresponding local velocity of the airflow $u_{loc}$ are relatively small and not enough to affect the plume morphology dominated by buoyancy, thus maintaining a single plume state. However, When the shear rate at the edge of the plume induced by $u_{loc}$ surpasses that of the core, the greater buoyancy, lowest density, and faster rising speed of the plume core lead to the formation of a pair of counter rotating vortices (CVP), which is equivalent to a drag force, as depicted in Fig. 9b. If the drag force is large enough to tear the plume into two sub-streams, a stable bifurcation occurs [22].

Fig. 9. The mechanism of (a) typical single-stream plume and (b) bifurcated two-stream plume.

To further verify the phenomenon and influence of plume bifurcation, the plume morphology and the corresponding ceiling temperature distribution were recorded and analysed. Fig. 10 demonstrates the
fire test phenomenon of Wangzhai tunnel. It can be observed that when the longitudinal ventilation velocity is 0.5 m/s, the plume generates a standard ceiling jet after hitting the tunnel ceiling, resulting in a single hitting point beneath the ceiling. Simultaneously, the fire plume in the tunnel hardly deflects longitudinally and forms a quasi-stable smoke layer spreading to the upstream and downstream of the tunnel. However, when the ventilation velocity reaches 1.15 m/s, excessive airflow not only causes the fire plume to incline longitudinal, but also induces the plume to bifurcate laterally, producing two independent sub-streams that diverge from each other in a V-shape. As velocity increase from 1.15 to 2.45 m/s, the phenomenon of plume bifurcation becomes more obvious, and the longitudinal deflection angle to the downstream of the tunnel will also increase from 55° to 70°.

All data of the full-scale tunnel fire test are summarized in Table 3.

<table>
<thead>
<tr>
<th>No.</th>
<th>HRR (MW)</th>
<th>u (m/s)</th>
<th>( \theta_p ) (°)</th>
<th>( \theta_h ) (°)</th>
<th>( T_{max,c} ) (°C)</th>
<th>Plume status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.34</td>
<td>0.5</td>
<td>32</td>
<td>0</td>
<td>159.57</td>
<td>Single-plume</td>
</tr>
<tr>
<td>2</td>
<td>1.34</td>
<td>1.15</td>
<td>55</td>
<td>15</td>
<td>141.51</td>
<td>Bifurcated plume</td>
</tr>
<tr>
<td>3</td>
<td>1.34</td>
<td>1.97</td>
<td>65</td>
<td>10</td>
<td>57.45</td>
<td>Bifurcated plume</td>
</tr>
<tr>
<td>4</td>
<td>1.34</td>
<td>2.45</td>
<td>70</td>
<td>9</td>
<td>50.76</td>
<td>Bifurcated plume</td>
</tr>
<tr>
<td>5</td>
<td>1.91</td>
<td>0.50</td>
<td>30</td>
<td>0</td>
<td>163.27</td>
<td>Single-plume</td>
</tr>
<tr>
<td>6</td>
<td>1.91</td>
<td>1.15</td>
<td>52</td>
<td>17</td>
<td>146.63</td>
<td>Bifurcated plume</td>
</tr>
<tr>
<td>7</td>
<td>1.91</td>
<td>1.97</td>
<td>65</td>
<td>12</td>
<td>60.74</td>
<td>Bifurcated plume</td>
</tr>
<tr>
<td>8</td>
<td>1.91</td>
<td>2.45</td>
<td>68</td>
<td>10</td>
<td>53.81</td>
<td>Bifurcated plume</td>
</tr>
</tbody>
</table>

**Fig. 10.** Plume morphology with 1.34 MW (a) cross section view, (b) side view.

**The position of maximum ceiling temperature**

As mentioned above, the position of maximum ceiling temperature changes with increasing ventilation velocity since the ventilation condition dominates the plume morphology. Fig. 11 shows the correlation of the inclined length \( L_{OM,X} \) along the longitudinal direction and the bifurcation length \( d \) along the transverse direction of the typical plume, as well as the vertical and horizontal deflection angle of the plume, denoted as \( \frac{L_{OM,X}}{W_{ef}} \) and \( \frac{d}{2L_{OM,X}} \) respectively.
Fig. 11. The correlation of (a) the inclined length along the x-direction \(L_{OM,X}\) and the bifurcation length \(d\), and (b) the vertical deflection angle and horizontal deflection angle with the dimensionless ventilation velocity \(V'\).

Three stages of plume development with ventilation velocity can be identified: 1) when \(V' \leq 0.19\), the entrained air velocity in the tunnel is relatively low, resulting in almost no deflection of the plume. At this time, the temperature field on both sides shows a symmetrical distribution, and the maximum temperature point is directly above the fire source. 2) when \(0.19 < V' \leq 0.33\), the velocity of airflow entrained from the upstream increases significantly, which leads to an increasing tendency of the inclination degree of fire plume. At this stage, with the increase of the longitudinal ventilation velocity, the plume gradually extends along the transverse direction, but still no obvious bifurcation phenomenon can be observed. Consequently, the plume will have a stable single hitting point downstream of the tunnel. 3) when \(V' > 0.33\), the plume bifurcation is triggered. The bifurcated flow will hit the ceiling at different positions, respectively, resulting in the observation of two temperature peaks symmetrically distributed on both sides along the central axis of the tunnel.

In order to determine the location of the maximum ceiling temperature at different stages of plume development, and quantify the influence of various factors, the vertical and horizontal plume deflection angle \(\theta_v\) and \(\theta_h\) are introduced as plume characteristic parameters. According to the dimensional analysis method, the plume deflection angle has a good exponential relationship with the aspect ratio of tunnel section \(AR\) and the dimensionless ventilation velocity \(V'\), which can be expressed in the following functional form:

\[
tan(\theta) = \lambda(AR)^m(V')^n
\]  

where, \(\theta\) represents the different directions of plume deflection, \(\lambda\), \(m\), and \(n\) are the correction coefficients related to the corresponding fire scenario.

The variation of vertical plume deflection angle \(\theta_v\) and horizontal plume deflection angle \(\theta_h\) with the dimensionless ventilation velocity \(V'\) is presented in Fig. 12. It is evident that the plume angles in the vertical and horizontal directions occur during the plume rising stage at dimensionless ventilation velocity of 0.19 and 0.33, respectively. Furthermore, the vertical plume deflection angle increases with the ventilation velocity, while the horizontal plume deflection angle displays a decreasing trend with the increase of the ventilation velocity.

It should be noted that the vertical plume deflection angle \(\theta_v\) is insensitive to the change of aspect ratio, which means that the plume hitting point beneath the ceiling is basically fixed in tunnels with different aspect ratios, as shown in Fig. 12a. However, the horizontal plume deflection angle \(\theta_h\) is affected by the aspect ratio to a certain extent, especially when \(AR\) is small, the transverse spread of the plume is significantly restrained, resulting in a smaller bifurcation region than that in the ideal condition without sidewall constraints, as illustrated in Fig. 12b. In this scenario, the degree of plume
Tenth International Symposium on Tunnel Safety and Security, Stavanger, Norway, April 26-28, 2023

bifurcation development can be directly determined by the tunnel width, i.e., \( W = r_{p,sc} = r_{p,no_sc} \), where \( r_{p,sc} \) and \( r_{p,no_sc} \) refer to the size of plume bifurcation region with and without sidewall constraints, respectively.

With the increase of the aspect ratio of the tunnel section, the fire source located in the centreline of the tunnel gradually moved away from the sidewall, providing sufficient space to develop the plume. As a result, the influence of the tunnel side wall on smoke entrainment is gradually weakened. The plume bifurcation development is no longer limited by the sidewall until \( AR \) increases to 3.3, at which point it is approximately equal to the open boundary condition, i.e., \( r_{p,sc} = r_{p,no_sc} < W \). After this point, the plume deflection angle in the horizontal direction \( \theta_h \) remains constant. Based on the fitting results, the relationship between the two deflection angles \( \theta_v \) and \( \theta_h \) of the plume bifurcation and dimensionless ventilation velocity \( V' \) can be obtained as follows:

\[
\begin{align*}
tan\theta_v &= 3.5 \cdot V^{0.9} \quad (29) \\
tan\theta_h &= \begin{cases} 
0.082 (AR)^{0.6} \cdot V'^{-0.7} & \text{when } r_{p,no_sc} > W \\
0.168 \cdot V'^{-0.7} & \text{when } r_{p,no_sc} < W 
\end{cases} \quad (30)
\end{align*}
\]

where \( V' = V/(\frac{g Q}{b_{D_f} \rho_a C_p T_a})^{1/3} \), \( AR = \frac{W}{H} \), which is the aspect ratio of tunnel section.

Moreover, the longitudinal and transverse offset distance of the maximum temperature position under the ceiling relative to the fire source point is defined as \( L_v \) and \( L_t \) respectively, which can be obtained from the following formula:

\[
\begin{align*}
L_v &= H \cdot tan\theta_v = \begin{cases} 
0, & \text{when } V' \leq 0.19 \\
H \cdot 3.5V'^{0.9}, & \text{when } V' > 0.19 
\end{cases} \quad (31) \\
L_t &= L_v \cdot tan\theta_h = \begin{cases} 
0.287 \cdot W^{0.6} \cdot H^{0.4} \cdot V'^{0.2}, & \text{when } r_{p,no_sc} > W, V' \geq 0.33 \\
0.588H \cdot V'^{0.2}, & \text{when } r_{p,no_sc} < W, V' \geq 0.33 
\end{cases} \quad (32)
\end{align*}
\]

Maximum temperature of smoke layer beneath the ceiling

It is noteworthy that previous studies have focused on determining the maximum ceiling temperature distribution by assuming that the peak point appears in the middle of the tunnel ceiling. On this premise, many classic prediction models of maximum ceiling temperature are derived based on the model form of Alpert, as indicated in Eq. (33). Table 4 lists the coefficients under different conditions.
experimental conditions, which range from 16.9 to 20.96. There is no doubt that the coefficient $\alpha$ is closely associated with the ratio of tunnel width to height.

$$\Delta T_{\text{max}} = \alpha \frac{\dot{Q}^{2/3}}{H_{\text{ef}}^{5/3}}$$

(33)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$W/H$</td>
<td>$&gt; 3.6$</td>
<td>1 to 1.15</td>
<td>2</td>
<td>2.27</td>
<td>0.8</td>
<td>0.78</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>16.9</td>
<td>17.5</td>
<td>17.5</td>
<td>17.9</td>
<td>19.5</td>
<td>20.96</td>
</tr>
</tbody>
</table>

Table 4. The comparison of coefficient under different aspect ratios of tunnel.

In addition, since the bifurcation phenomenon only occurs under high ventilation condition, the new correlation to predict maximum temperature can be further divided into two regions for the transition point $V' = 0.33$: 1) the low-ventilation region with $V' \leq 0.33$, where the plume is single-stream, and the maximum temperature can be well predicted by previous models according to the specific fire scenario. 2) the high-ventilation region with $V' > 0.33$, in which the bifurcated plume occurs, and the maximum temperature is lower than the prediction of classical models. On this basis, the improved model on the maximum ceiling smoke temperature caused by bifurcated flow can be developed effectively. We can comprehensively predict the maximum ceiling temperature rise by determining the hitting points of the bifurcated flow through Eq. (29) and Eq. (30), as follows:

$$\Delta T_{\text{max}} = \begin{cases} 
\alpha \frac{\dot{Q}^{2/3}}{H_{\text{ef}}^{5/3}}, & V' \leq 0.19 \\
\alpha \frac{\dot{Q}^{2/3}}{H_{\text{ef}}^{5/3}}(5.26V')^{-1}, & 0.19 < V' \leq 0.33 \\
\beta \frac{\dot{Q}^{2/3}}{H_{\text{ef}}^{5/3}}(1 + 12.25V'^{9/5} + 0.082V'V'^{2/5})^{-5/6}, & V' > 0.33
\end{cases}$$

(34)

where $\alpha$, $\beta$, and $\gamma$ are the coefficients related to the tunnel aspect ratio, which can be obtained by fitting the results of numerical simulation. The empirical formula of $\gamma$ is:

$$\gamma = \begin{cases} 
\frac{W}{H}^{6/5}, & \text{when } r_{p,\text{no,sc}} > W \\
4.19, & \text{when } r_{p,\text{no,sc}} < W
\end{cases}$$

(35)

Fig. 13 depicts the relationship between the maximum ceiling temperature rise $\Delta T_{\text{max}}$ and the tunnel aspect ratio $AR$. The slope values in Fig. 13a, and b represent $\alpha$ in Eq. (34), and the slope values in Fig. 13c represent the coefficient $\beta$. As shown, $\alpha$ and $\beta$ exhibit opposite trends with the increase of $AR$ when $AR < 3.3$, and keep constant for a larger $AR$. The correction coefficient $\alpha$ in the range of 0-0.33 decreases with $AR$ due to increased air resistance and smoke accumulation effects in tunnel with a smaller $AR$. When $V' > 0.33$, bifurcation of plume flow leads to stronger air entrainment and lower ceiling temperature rise in smaller-$AR$ tunnels, resulting in an increasing coefficient $\beta$ with $AR$.

Therefore, the relationship between the coefficients $\alpha$, $\beta$ and $AR$ can be fitted with a piecewise function, as shown in Eqs. (36) and (37), respectively. Then the maximum ceiling temperature rise in a tunnel fire can be evaluated according to Eqs. (34)-(37).

$$\alpha = \begin{cases} 
20\left(\frac{W}{H}\right)^{-0.23}, & \text{when } r_{p,\text{no,sc}} > W \\
15.2, & \text{when } r_{p,\text{no,sc}} < W
\end{cases}$$

(36)
$$\beta = \begin{cases} 20 \left( \frac{W}{H} \right)^{0.13}, & \text{when } r_{p, n o, sc} > W \\ 23.4, & \text{when } r_{p, n o, sc} < W \end{cases}$$

Additionally, the relatively good agreement between the full-scale test data and correlations based on numerical simulation data indicates that the maximum ceiling temperature, as measured at the central axis of the tunnel ceiling under the low ventilation, is reliably obtained. However, when the bifurcated effect induced by strong airflow is further considered, the measured results are significantly lower than the actual maximum ceiling temperature due to environmental conditions. This discrepancy is particularly pronounced under conditions of a higher heat release rate of the fire source, with prediction errors exceeding 30% in some cases.

![Fig. 13. The relationship between the maximum ceiling temperature rise $\Delta T_{max}$ and the tunnel aspect ratio $AR$](image)

**CONCLUSIONS**

In this work, eight groups of full-scale tunnel fire tests and a series of numerical simulations are conducted to investigate a special plume phenomenon, namely, the plume bifurcation, and its effect on the maximum ceiling temperature rise. The theoretical analysis shows that the high ventilation-induced plume bifurcation will lead to two sub-streams hitting the ceiling symmetrically along the centre line. The air entrainment path is longer than that of traditional two-dimensional assumption.
The relationship between hitting points, represented by the inclined length ($L_{OM}$) and the bifurcation length ($d$) is quantified with the fire heat release rate and ventilation condition. The bifurcation length ($d$) is 0 when $V' \leq 0.33$, representing a single plume; and rapidly increase, and then slowly decrease with $V' > 0.33$, representing the variation of bifurcation angle with the ventilation condition. The vertical deflection angle $\theta_v$ and horizontal deflection angle $\theta_h$ are then fitted based on the relative relationship between the plume width and the tunnel width. Finally, by combining the smoke plume model of classical fire dynamics, a novel piecewise function is proposed considering the effect of the plume bifurcation. The new equation can well predict the temperature profile under different fire heat release rates, tunnel aspect ratios, and ventilation conditions, especially for strong-ventilated tunnel fire scenarios.

This study reveals the plume bifurcation phenomenon, quantifies the criterion to trigger it, and corrects its impacts on the temperature profile, thus covering the sci-tech gap on the multi-dimensional smoke spread phenomena of the traditional tunnel fire dynamic theory.

REFERENCES


Bonding behaviour of CFRP composite strengthened tunnel structure under fire exposure

Yi Shen\textsuperscript{1,2*}, Shi-qi Dou\textsuperscript{2}, Cheng Yang\textsuperscript{2}, Long Zhou\textsuperscript{2}, Hui Wang\textsuperscript{3}, He-hua Zhu\textsuperscript{1,2} & Zhi-guo Yan\textsuperscript{1,2}

\textsuperscript{1} State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
\textsuperscript{2} Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
\textsuperscript{3} School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China

ABSTRACT

In order to improve the safety and durability of the structure, a growing number of shield tunnels with structural damage of metro lines have been reinforced by carbon fiber reinforced polymers (CFRP). After a long-term operation, there is a great concern with the fire resistance of the epoxy bonded CFRP strengthened tunnel structure. In this study, a series of experimental studies were conducted on specimens of the epoxy resin and the CFRP composite-concrete to investigate the residual bond behavior of interfaces of CFRP strengthened shield tunnel subject to elevated temperature. The experimental specimens were for both the tension and the shear test. The influences of the different levels of the exposure temperature were considered and contained seven groups for 20, 50, 100, 200, 250, 300, and 400 °C in a controlled condition. Based on fitting and regression on the experimental results of the CFRP composite-concrete interfacial bond performance, the interfacial constitutive relationships for both tensile and shear properties were established. Combined with the experimental results, a numerical model of the reinforced shield tunnel structure, including tunnel lining segments, longitudinal joints, and CFRP composites, was also established to analyze the temperature distribution and mechanical behaviors of the debonding of CFRP under four fire scenarios. The numerical results suggest that the CFRP-strengthened shield tunnel may face a challenge when a large fire occurs and sustains for a considerable duration. As bonding interface extends with the heating, the cohesive elements start to fail gradually from the joint to the segment span, and the complete failure of the interface is mainly due to the complete failure of the interface shear performance. The significance of the shear properties of the CFRP-strengthened tunnel bonding interface precedes that of the tensile properties.

KEYWORD: tunnel structure, elevated temperatures, carbon fiber reinforced polymer (CFRP), experimental study, numerical analysis

1 INTRODUCTION

The shield tunnel is the main structure type in soft clay areas worldwide and is generally designed for one hundred years. In view of long operation in the surrounding variational environment, the tunnel structure faces great challenges from external disturbances and internal deterioration [1]. The reinforced concrete segments may generally have crept cracks, and the joints between segments may deform to induce leakage. Such defects accumulate over a long period, and the assembled tunnel rings will be subjected to large deformation over the design criterion twice or more [2]. In order to improve the safety and durability of the structure, a growing number of shield tunnels with structural damage of metro lines have been reinforced by steel plates or carbon fiber reinforced polymers (CFRP) after a long-term operation [3]. As a significant factor affecting the safety of the tunnel, fire not only induces
the destruction of the shield tunnel lining structure but also reduces the structure's bearing capacity, even leading to unexpected structural failure. CFRPs are combustibles and are similar to wood in that they burn when exposed to fire [4]. Failure modes triggered by fire effects and the associated fire safety measures are extremely difficult to capture as they depend on periodic maintenance. This explains the need for research on strengthened segmental tunnel structures in fire. Therefore, it is of great significance to analyse the thermo-mechanical behaviours of the composite system consisting of shield tunnel lining and reinforced structure in fire scenarios.

Strengthened tunnel structure has already been proven to improve the bearing capacity and the structural stiffness to restrain the overall convergence and potential subsequent deformations. These strengthened techniques also have been widely used in retrofitting shield tunnels [5]. Liu et al. [6] carried out a full-scale test of a segmental tunnel ring strengthened by epoxy-bonded steel rings. However, debonding of the steel plates and the high self-weight promote the development of fiber strengthened methods. Jiang et al. [7] estimated the reinforcing effect of fiber-reinforced steel grids embedded in polymer cement mortar shotcrete on degraded tunnels by laboratory direct shear and bending tests. Yang et al. [8] applied the carbon fiber reinforced composite onto the inner surface of the tunnel segmental joint and verified the strengthened effect under the sagging moment. As the unit weight of the composite is relatively light, this strengthened technique is also very efficient during installation. Full-scale tests with consideration for secondary loading were conducted on the ultimate bearing capacity of linings strengthened by the new method [9]. When utilizing the proposed strengthened method, the strengthened linings' failure indicates that the adhesive's bonding capacity is of great importance. Liu et al. [10] also reported a comprehensive parametric study of the influence of several mechanical properties based on a numerical model. Li et al. [11] analysed the mechanical behaviour of the concrete linings retrofitted by carbon fiber reinforced polymer sheet, and the strengthened effects were thoroughly evaluated. The failure of the tested specimens or structures strengthened by epoxy-bonded carbon fiber reinforced composite was dominated by the bonding strength and composite stiffness. Therefore, for the fire safety assessment, the residual strengths of CFRP reinforcements and interfaces after elevated temperature exposure are significantly notable [12]. To date, this problem has received scant attention in the research literature.

There is a great concern with the fire resistance of the epoxy-bonded CFRP-concrete structure. For the fire design of CFRP-strengthened concrete members, the methods presented in the design code [13] do not consider the contribution of the CFRP strengthened on the flexural behaviour of these elements under fire conditions. For reinforced concrete (RC) structures, the influence of temperature on the mechanical properties of bonding adhesives used in CFRP-strengthened systems has been addressed in a number of studies [14]. Firmino et al. [15] conducted an experimental study about the bond between concrete and CFRP-strengthened systems at elevated temperatures in both steady and transient conditions. The bond between the CFRP and the concrete loses its bond strength ranging from 85°C to 110°C [16]. By numerical methods, Arruda et al. [17] simulated the bond effect between concrete and CFRP-strengthened systems at elevated temperatures. The loss of structural effectiveness of insulated CFRP-strengthened RC beams simultaneously subjected to a service load and the standard fire can also be predicted by the finite element method [18]. As determined in the experimental and numerical campaigns, the consistent reductions of stiffness and allowable stress of the CFRP with increasing temperature inevitably weaken the strengthened systems. The fire resistance tests conducted by Azevedo et al. [4] highlighted that the susceptibility of CFRP strengthened slab lost its effectiveness after 24 minutes’ exposure to fire without any protection. As for the experimental results from Yu and Kodur [19], the CFRP strips and rods lose 50% of their initial strength at 305 °C and 330 °C, respectively. Wang et al. [12] conducted a comparative study on the residual bond performance of epoxy bonded carbon fiber-reinforced polymer (CFRP) reinforcement to concrete interfaces exposed to different levels of elevated temperatures. It was found that the initial stiffness and ultimate deformability of the strengthened concrete specimens dropped remarkably when the temperature approached 400 °C. The test results indicated that the degradation of comprehensive bonding strength plays an important role in dominating the failure modes and performance degradation of CFRP-strengthened concrete members. On the other hand, according to these previous studies, concerning the research efforts to describe the bond behaviour of CFRP in elevated
temperatures, the test data, and numerical results are still too scarce to predict the mechanical behaviours of RC segmental rings reinforced by the CFRP. Therefore, the influence of temperature on the mechanical properties of carbon fiber reinforced composite strengthened systems for tunnel structures has been addressed only in a very limited number of studies [20].

Large fires are proved to directly and seriously influence the tunnel structure [21]. Several post-fire results were provided in previous research. Serafini et al. [22] conducted a mesoscale experiment and employed a numerical approach to determine the bearing capacity of steel fiber reinforced concrete tunnel linings after fire exposure. Yan et al. not only [23] investigated the vertical load capacities of tunnel segments but also [24] tunnel segmental joints for post-fire scenarios. Maluk et al. [25] used cylinder specimens of fiber reinforced concrete used in the tunnel to assess the residual compressive and splitting tensile strength at different depths after cooling. Alhawat et al. [26] even conducted the prototype fire exposure testing of two unloaded tunnel rings to replicate the RABT fire curve, which includes the cooling phase. Although extensive research has been carried out on the tunnel structure, few studies exist with the characterization of the mechanical properties of retrofitted shield tunnels. However, the aforementioned studies with CFRP-reinforced concrete members have verified their vulnerability after fire exposure. The potential failure of the tunnel structure may occur due to adverse conditions in the retrofitting sections. Further studies are clearly needed to fill this gap in current knowledge, and the findings should make an important contribution to the field of fire safety assessment on tunnel structure.

This paper aims to conduct a comparative study on the mechanical performance of the epoxy-bonded carbon fiber reinforced composite to tunnel lining after elevated temperature exposure through experimental tests and numerical analysis. The focus will also be placed on the fire safety assessment of the CFRP tunnel segments according to the exposure temperature. Section 2 describes experiments on the shear and tension properties of the interface between the concrete cube and the CFRP composite exposed to elevated temperatures. Section 3 elaborates on the failure modes and the critical temperature of the interface. According to the rules of the tensile strength and shear strength of the interface with the temperature, the constitutive relation of the interface exposed to elevated temperatures was also established. Section 4 analyses the debonding mechanism of CFRC-reinforced tunnel rings based on the thermal and mechanical results calculated by the numerical method.

2 EXPERIMENTAL STUDIES

2.1 Materials and specimen preparation
The experimental specimens were divided into two parts: (i) epoxy resin specimens and (ii) CFRP reinforcement specimens for tension and shear test were prepared. Each part of the specimens considered the effects of the different levels of the exposure temperature and contained seven groups. Each group consisted of three identical replicates. The tensile and shear epoxy specimens were dumbbell-shaped and strip-shaped, respectively, as depicted in Figure 1. The elastic modulus, tensile, and shear strength of epoxy resin were 1.5 GPa, 30 MPa, and 10 MPa, respectively. As shown in Figure 2, the CFRP composite profile is formed by welding three thin-walled steel tubes, which are then clad with carbon fiber reinforced polymers and filled with the high-strength mortar (standard compressive strength was 38.5 MPa). The sectional dimension of the composite was 160×40 mm². The elastic modulus and tensile strength of carbon fiber were 240 GPa and 3400 MPa, respectively. The elastic modulus and strength of steel were 206 GPa and 235 MPa, respectively. As illustrated in Figures 3 and 4, the tensile and shear specimens were all epoxy-bonded with the CFRP-composite and the 100 mm concrete cube (standard compressive strength was 32.4 MPa). All the concrete cubes were cast from the same batch of concrete in the laboratory and were cured in a well-controlled condition with a temperature of 20°C and a relative humidity of 95% for 28 days.
2.2 Heating and loading setup

Two independent test steps, including exposure to elevated temperature and the consequent mechanical loading, were adopted in this study. It should be noted that such a test scenario may not totally replicate the actual conditions of CFRP-strengthened tunnel segments exposed to fire, for which the heating and loading are simultaneously imposed to create a more severe condition. However, according to the previous related study [12], the post-fire performance of the structure members still can reflect the fire survivability to some extent and, in particular, can be used to compare the mechanical properties of different cases during a fire.
Epoxy resin and CFRP reinforcement specimens were all exposed to different levels of temperatures, i.e., 20, 50, 100, 200, 250, 300, and 400 °C, in a controlled furnace shown in Figures 3 and 4. All the surfaces of the specimens were exposed to elevated temperatures. The heating time of epoxy resin and CFRP reinforcement specimens were 1.5 h and 2.5 h, respectively. Afterward, the specimens were naturally cooled down and loaded by a servo-electric universal testing machine. For the CFRP reinforcement specimens, before loading, a proper stiffness angle iron was fixed on both sides of the composites to place the linear variable differential transducers to measure the displacement. The tests were conducted in a load control mode with a 3 kN/min loading rate, and every loading level was set for 3 kN.

3 TEST RESULTS AND DISCUSSIONS

3.1 Residual mechanical behaviours of epoxy resin

The epoxy resin was quite vulnerable to the influence of the heating constant elevated temperature process. When the temperature exceeded 200°C, the epoxy resin specimen surface began to carbonize. Moreover, flue gas was discharged from the furnace, indicating that the adhesive began to soften and volatilize. When the temperature exceeded 250°C, the head of the specimen deformed contortedly after cooling down. The failure mode of the tensile and shear specimens was mainly parallel fracture in the middle of the dumbbell, and the crack was relatively flat. When the temperature exceeded 300°C, the specimen was utterly carbonized and lost its strength.

Mechanical properties vs. temperatures of the epoxy resin specimens are shown in Figure 5. The tensile strength of the epoxy resin increases first and then decreases with the increase in temperature. The variation of shear strength with temperature shares the same tendency. The maximum tensile strength and shear strength at 150°C were 25.40 MPa and 18.87 MPa, respectively. As shown in Figure 5(c), the tensile and shear stiffness increase first and then decrease. The peak value at 150°C was 2650 N/mm and 224 N/mm, respectively. To sum up, the tensile and shear properties of the epoxy resin are firstly strengthened and then weakened with the increase in temperature. The possible explanation is that when the temperature rises to a specific value, the solidified constituent improves the mechanical properties of the epoxy resin.
3.2 Apparent phenomenon of bonding interface in heating

As for the CFRP composite-concrete specimens, the carbon fibers and epoxy resin are thermal sensitive in elevated temperatures. When the temperature exceeded 200°C, the epoxy resin started to volatilize, which was consistent with the experimental phenomenon of the epoxy resin specimen. When the temperature exceeded 250°C, the cracks between the CFRP and the steel pipe indicated that the bond property of the composite started to degrade. When the temperature exceeded 300°C, the exposed surface of the bond interface turned to deconstruct. When the temperature exceeded 400°C, a lot of flue gas and epoxy liquid flowed out of the furnace during the heating process. The composite was almost completely cracked between the steel pipe and the CFRP, and a relatively obvious carbonization phenomenon occurred. Hence, there is a failure temperature between 300°C and 400°C for the bond performance of the composite-concrete interface. The appearances of tensile and shear specimens are shown in Figure 6 (c) and Figure 7 (d), respectively.

Figure 5  Mechanical properties vs temperatures of the epoxy resin specimens: (a) Strength; (b) Displacement; (c) Stiffness.

Figure 6  Failure modes of tensile test for the CFRP composite-Concrete specimens: (a) I; (b) II; (c) III.
3.3 Tensile properties of CFRP bonding interface

There are three failure modes of tensile test specimens, as shown in Figure 6. Type I refers to the fracture failure of the concrete surface. This type mainly occurs at lower temperatures (20°C, 50°C, 100°C), and the tensile strength of concrete is the dominant factor. Type II refers to the interface fracture failure between concrete and CFRP. This type mainly occurs at higher temperatures (200°C, 250°C, 300°C), and the tensile strength of the interface of CFRP-concrete is decisive. As described in Section 3.2, Type III is a total carbonized failure mode. Both Type I and Type II are brittle failures with almost no plasticity. It can be indicated that the tensile bond performance of the interface of the CFRP composite-concrete is seriously influenced by the elevated temperature, which exceeded 200°C.

As shown in Figure 8, the tensile displacement of the CFRP composite-concrete specimen almost linearly increases with the load at various temperature conditions. With the Type I failure mode at lower temperatures (20°C, 50°C, 100°C, 200°C), the failure load and the tensile stiffness are quite close considering the variance of the concrete strength. With the Type II failure mode at higher temperatures (250°C, 300°C), the failure load and tensile stiffness drop sharply compared with specimens at lower temperatures. To determine the constitutive relationship between tensile stress σ and deformation δ based on the right triangle model proposed by Neubauer and Rostasy [28], nonlinear regression analysis was done according to the data shown in Figure 8. The piece-wise function of tensile stress σ (MPa) and deformation δ (mm) varied with temperature T (°C) is expressed in Eq. (1):

\[
\left\{ \begin{array}{l}
\alpha_\sigma(T) = 1.00 + 7.00 \times 10^{-3} \frac{T}{250} - 6.44 \times 10^{-1} \left( \frac{T}{250} \right)^2 & 20°C \leq T \leq 250°C \\
\alpha_\sigma(T) = 0 & T \geq 250°C \\
\beta_\delta(T) = 1.04 - 4.00 \times 10^{-3} \frac{T}{250} - 3.08 \times 10^{-1} \left( \frac{T}{250} \right)^2 & 20°C \leq T \leq 250°C \\
\beta_\delta(T) = 3.25 \times 10^{-4} & T \geq 250°C \\
\sigma = \frac{\sigma_0(T)}{\beta_\delta(T)} \delta_0 \quad & \delta \leq \beta_\delta(T) \delta_0 \\
\sigma = 0 \quad & \delta > \beta_\delta(T) \delta_0
\end{array} \right.
\]

where \(\alpha_\sigma(T)\) and \(\beta_\delta(T)\) are nondimensionalized regression factors of the tensile stress and the displacement, respectively. \(\sigma_0\) and \(\delta_0\) are the tensile stress (MPa) and the displacement (mm) at ambient temperature.
3.4 Shear properties of CFRP bonding interface

There are four failure modes of shear test specimens, as shown in Figure 7. As the tensile tests, Type I refers to the fracture failure of the concrete surface. This type mainly occurs at lower temperatures (20°C, 50°C), and the tensile strength of concrete is the dominant factor. Type II refers to serious cracking between carbon fibers and steel tubes on the surface of CRFP composite. This type mainly occurs at higher temperatures (100°C and 200°C). Type III refers to the stripping failure along the interface between concrete and CFRP composite after the cracking of carbon fibers and the steel tube. When the temperature reaches 250°C and 300°C, Type III failure mainly occurs. As the previous description in Section 3.2, Type IV is also a total carbonized failure mode. Type I, II, and III are all brittle failures with almost no plasticity.

Loading vs. displacement curves in different temperatures in shear tests are shown in Figure 9. The shear displacement of the CFRP composite-concrete almost increases linearly with the load in various temperature conditions. The slope of the load-displacement curve decreases with the increase in temperature, which indicates that the shear stiffness of the interface between concrete and composite cavity almost decreases with the increase in temperature (except 300°C). The shear stiffness of the interface peaks at the ambient temperature and reaches the minimum value at 250°C. Taken together, these results suggest an association between failure mode and stiffness. It should be noted that the shear bond performance of the interface of the CFRP composite is more complex than the tensile bond performance due to the shear strength of the interface of carbon fibers and the steel tube is largely reduced by elevated temperatures. There was a rather disappointing result that needs to be mentioned. For the case at the temperature of 50°C, cracks appeared in the CFRP composite-concrete interface on one side, resulting in a sudden increase of the shear displacement. Finally, the surface of the concrete specimen on the other side disengaged from the epoxy. As a result, the failure load at the interface was significantly larger than that at other temperature conditions. Therefore, the test results under this condition are not considered when establishing the interface bond constitutive relationship between the segment and composite cavity after high temperature. To determine the constitutive relationship between shear stress $\tau$ and deformation $s$ based on the right triangle model proposed by Neubauer and Rostasy [27], nonlinear regression analysis was done according to the data shown in Figure 9. The piece-wise function of shear stress $\tau$ (MPa) and deformation $s$ (mm) varied with temperature $T$ (°C) is expressed in Eq. (2):
where \( \alpha_r(T) \) and \( \beta_r(T) \) are nondimensionalized regression factors of the shear stress and the displacement, respectively. \( \tau_0 \) and \( s_0 \) are the shear stress (MPa) and the displacement (mm) at ambient temperature.

\[
\begin{align*}
\alpha_r(T) &= 0.96 + 5.23 \times 10^{-1} \frac{T}{250} - 9.69 \times 10^{-1} \left( \frac{T}{250} \right)^2 & 20^\circC \leq T \leq 325^\circC \\
\alpha_r(T) &= 0 & T \geq 325^\circC \\
\beta_r(T) &= 9.03 \times 10^{-1} + 7.95 \times 10^{-1} \frac{T}{250} + 5.19 \left( \frac{T}{250} \right)^2 & 20^\circC \leq T \leq 250^\circC \\
\beta_r(T) &= 29.84 - \frac{22.95}{250} T & 250^\circC \leq T \leq 325^\circC \\
\beta_r(T) &= 5 \times 10^{-3} & T \geq 325^\circC
\end{align*}
\]  (2)

\[
\begin{align*}
\tau &= \frac{\alpha_r(T) \tau_0}{\beta_r(T) s_0} \quad \text{if } s \leq \beta_r(T) s_0 \\
\tau &= 0 \quad \text{if } s > \beta_r(T) s_0
\end{align*}
\]

Figure 9 Loading vs. displacement curves in different temperatures in shear tests.

4 CASE STUDY

4.1 Model description

A numerical approach was adopted to allow a deeper insight into the debonding mechanism of CFRP-reinforced shield tunnel in fire effects. The shield tunnel structure of Shanghai Metro Line was chosen in this case study. The stratum obtained in this paper referred to the geological condition of a certain section of Shanghai rail transit with an average buried depth of 15.6 m, where the groundwater level was 0.5 m below the filled soil layer. Soil springs with a compressive stiffness of 5 kN/m³ for the soft clay were placed around the tunnel.

The layout of the CFRP-reinforced assembled tunnel structure is presented in Figure 10. The tunnel ring consisted of one key segment (F), two adjacent segments (L1 and L2), two standard segments (B1 and B2), and one counter key segment (D). The external diameter of the tunnel lining is 6.2 m, and the inner diameter is 5.5 m. The ring width and thickness are 1.20 m and 0.35 m, respectively. The segment concrete and the CFRP composite types were selected as the experimental study. To simulate the heating and loading process more feasibly, the main reinforcement and the bolt grade were adopted as the practical engineering: the yield strength was 400 MPa and 480 MPa, respectively.
The thermomechanical behavior of the CFRP strengthened shield tunnel, subjected to four different fire scenarios, is investigated. In these scenarios, the air temperature inside the tunnel is considered to follow four standard temperature histories, respectively, which are the ISO834 curve, the HC curve, the HCinc curve, and the RABT ZTV curve [27] as show in Figure 10 (b). Heat transferred from the hot air to the shield tunnel by means of radiation and convection, with the transfer coefficient following [28]. The heating duration was set as 120 minutes, which is the minimum requirement for fire resistance time of underground structures, following [29].

Figure 10  (a) Geometrical dimensions of the CFRP strengthened shield tunnel and (b) the thermal boundary condition following four standard temperature histories.

The following assumptions were made in the development of the numerical model. All materials were assumed to be continuous and isotropic. The post-fire residual properties of concrete and reinforcing steel were influenced by maximum temperatures experienced during the fire, the time allowed for recovery after the fire, as well as the method of cooling used for quenching the fire. According to Section 3, post-fire models were chosen because of the expected difficulty in obtaining the temperature-loading data during heating. On the other hand, the models were selected based on the suffered envelope temperature. Thermal properties of materials, i.e., thermal conductivity, heat capacity, and thermal expansion, have been assumed to be completely reversible. The effect of the decrease in heat capacity due to loss of moisture and residual thermal expansion or shrinkage was neglected for simplicity. For the concrete and steel, the thermal and mechanical properties with temperature adopted in the numerical analysis are referred from Eurocode 2 [13], as previously used by other related studies [28-31] on the tunnel structure in the fire. The basic thermal properties of CFRP were referred from previous research [4].

The thermo-mechanical analysis is sequentially-coupled, and the coupling between the two simulations is internally managed by FEM codes. The finite element discretization is kept constant while the element type changes, i.e., thermal and structural elements, are required for thermal and mechanical analysis, respectively. Following this procedure, non-linear transient thermal-mechanical coupled numerical analysis requires considerable effort in structural analysis. In the thermal analysis, a two-node heat transfer element DC1D2 was used for steel bars and bolts, and the plain heat transfer element DC2D4 was used for concrete. In the analysis model, a two-node truss element T2D2 was used for steel bars, a beam element B21 was used for bolts, and the plain strain element (CPE4R) was used for concrete. The cohesive element COH2D4 based on quads damage for traction separation laws [33] was adopted, and the constitutive model was implemented from the experimental results in Sections 3.3 and 3.4. To sort out the critical temperature for the materials and interfaces, the temperature distribution of the CFRP composite, epoxy, tunnel lining, bolt, and steel bar was analysed. For the thermal resistance of CFRP, spalling was not considered in the simulation.
4.2 Temperature field
From the cloud graph in Figure 11(a), we can see that the temperature distribution of the CFRP-tunnel lining profile is entirely consistent regardless of the thermal resistance between the different surfaces. Evolution of the temperature at the outermost surface of CFRP follows a similar development of the heating curves, whereas exhibits a hysteresis in time, see the comparison of Fig. 10(b) and Fig. 11(b). This is attributed to the heat transfer from the heated air to the structural surface in the form of convection and radiation [28]. For the temperature result of the epoxy layer under the influence of the HC curve, HCinc curve, ISO834 curve, and RABT curve, as shown in Figure 12, the upper limit temperature of the interface located at the CFRP surface is 359°C, 459°C, 298°C, and 212°C, respectively. The lower limit temperature located at the concrete segment is 206°C, 258°C, 158 °C, and 143°C, respectively. As for the lower limit temperature, the descending phase of the RABT curve does not induce the cooling-down of the interface located at the concrete segment, which may continue to maintain the temperature after 120 min. In terms of the heating condition of the HC curve and HCinc curve, the temperature of the interface located at the CFRP surface exceeds 300°C at about 80 min and 50 min, respectively. As far as the critical temperature in the experimental study in Section 3 is concerned, under the ISO834 curve and the RABT curve, the CFRP is accessible to avoid the carbonated in two hours’ heating time. Concerning the Type I fracture failure of the concrete surface in Figures 6 and 7, the heating time should be controlled within 20 minutes. The CFRP composite, of course, resists the thermal effects. However, the bonding failure may bring about a serious accident as the original structure has already been in a dangerous state.

![Figure 11](image1)

**Figure 11** Temperature field distributions: (a) Layered temperature distribution for HCinc at 120 min; (b) Temperature development of CFRP heating surface.

![Figure 22](image2)

**Figure 22** Temperature variation of epoxy: (a) Located at the CFRP surface; (b) Located at the concrete segment.

4.3 Mechanical behaviour of the debonding of CFRP
According to the constitutive model of CFRP composite bonding in the tensile or shear state in elevated temperatures, the cohesive element will gradually soften while the temperature rises. In order to analyse the stress state of the bonding element, the normal stress (tension stress is positive and pressure stress is negative) and shear stress (counterclockwise stress along the ring direction is...
positive and clockwise is negative) of the bonding element are selected as the main output results for analysis. Stress variations of cohesive elements vs. time in the HC heating curve are shown in Figure 13. The stress of the cohesive element at each position was redistributed during the heating process. The difference between the cohesive elements in the mid-span and the joints was significant. The cohesive elements in the mid-span of each segment were under compression, and the shear stress was kept in a low state. With respect to the B1-D joint of B Block, the cohesive elements at the joint reached a relatively high tensile stress for nearly 1 MPa. Nevertheless, the cohesive elements at the other joints were all in compression or with quite low tensile stress. The shear stress at the joint basically increases until the heating time reaches 20 min and then decreases to a relatively low level. As regards the normal stress, except the cohesive elements at the joint are in tension, the cohesive elements at other positions are in compression during the fire. On the other hand, the shear stress of the cohesive elements at the joint is greater than that at other locations. In addition, taking the stress and deformation characteristics of the CFRP-tunnel lining system as a whole, another critical concern is the failure state of the bonding surface. According to the results in Figure 13, compared with the cohesive elements in the middle of the segment span, the cohesive elements at the joint are in a more adverse stress state as cohesive elements gradually soften with the temperature rising.

![Figure 33 Stress variations of cohesive elements vs time in the HC heating curve (NS: Normal stress; SS: Shear stress): (a) F Block; (b) L Block; (c) B Block; (d) D Block.](image)

The cohesive elements at the joint reach the initial damage criterion before these at other locations. As shown in Figure 13 (c), the bonding of the L1-B1 joint and the B1-D joint gradually entered the failure stage with a continual reduction of the shear stress of cohesive elements and was finally in the complete failure state with no shear stress after heating for 120 minutes. This indicates that the bonding between the CFRP and the tunnel segment at these joint locations steadily deteriorates under the combined effects of normal stress and shear stress and completely fails due to shear stress. From the deformation state depicted in Figure 14, the cohesive elements at the joint originate from stretching between the CFRP composite and the tunnel segments and finally fracture under the thermal effect and the loading. Therefore, in the firing process, the lining-composite cavity interface is
dominated by tension and shear in a small range at the joint and compression and shear in a large range at other locations. The main reason for the final interface failure is the complete failure of interface shear performance. This combination of findings supports the conceptual principle that the significance of the shear properties of the bonding interface of CFRP-reinforced tunnel precedes that of the tensile properties. Returning to the issue of different heating curves, the stress variation of cohesive elements of B Block in the HC curve and the RABT curve is shown in Figure 15. During the first 60 minutes of heating, the stress variation of the cohesive elements under RABT curve is almost the same as that under the HC curve. When the heating time exceeds 60 minutes, the normal stress of cohesive elements on the B1-D joint in the HC curve has a linear reduction, while the normal stress of cohesive elements almost maintains at 0.7 MPa. This is due to the influence of the cooling-down phase of the RABT curve. As regards the temperature of epoxy resin shown in Figure 12, in the RABT scenario, the temperature starts to decline slowly compared with the constant temperature rising in other heating curves.

![Figure 44](image1.png)

**Figure 44**  Failure of cohesive elements of B1-D joints: (a) Failure in process; (b) Complete failure.

![Figure 55](image2.png)

**Figure 55**  Stress variation of cohesive elements of B Block in the HC curve and the RABT curve: (a) Normal stress; (b) Shear stress.

**5 CONCLUSIONS**

In this paper, a series of tensile and shear experiments were conducted on specimens of the epoxy resin and the CFRP composite-concrete, subjected to high temperature. Constitutive relations of the residual bonding behavior of the interfaces between CFRP composite and concrete was established, which was integrated into a numerical model of the reinforced shield tunnel structure, including tunnel lining segments, longitudinal joints, and CFRP composites. The temperature distribution and mechanical behaviors of the strengthened tunnel under four fire scenarios was analyzed. From the experimental results, the following main conclusions can be drawn:

- The tensile strength of the epoxy resin increases first and then decreases with the increase in temperature. The variation of shear strength with temperature shares the same tendency.
Based on fitting and regression on the experimental results of the CFRP composite-concrete interfacial bond performance, the constitutive interfacial relationships for both tensile and shear loadings were established.

- After the different fire exposures, the failure modes of the interface of the CFRP composite-concrete are different. When the temperature exceeded 300°C, the epoxy was utterly carbonized and lost its strength. The failure temperature of the interface was between 300°C and 400°C; the tensile property of the interface decreased with the increase in temperature, while the shear property of the interface first increased and then decreased with the temperature rising.

The finite element simulations provide a preliminary insight into the structural behavior of CFRP strengthened tunnel at high temperatures. From the numerical results, the following main conclusions can be drawn:

(1) For shield tunnel structures strengthened by the CFRP composites in elevated temperatures, the composite can significantly resist fire heating. At the same time, the epoxy bonding interface is vulnerable to the fire effect. At the initial stage of fire, the deterioration of the CFRP composite plays a dominant role in the thermal resistance. During the development of fire, the segment deforms in a stress state with compression on both sides and tension in the middle, and the CFRP composite is generally in a state of compression with the overall convergence of the tunnel ring. The adhesive elements at the joint enter the failure state earlier than these at the mid-span.

(2) As the bonding interface extends with the heating, the cohesive elements start to fail gradually from the joint to the segment span. The final failure of the interface is mainly due to the complete failure of the interface shear resistance. The significance of the shear properties of the CFRP-strengthened tunnel bonding interface precedes that of the tensile properties. Compared with the bonding of CFRP composites in the HC curve, the cooling

Taken together, these results suggest that the CFRP-strengthened shield tunnel may face a challenge when a large fire occurs and sustains for a considerable duration. The most important limitation lies in the fact that the test data of prototypical tunnel segments is lacking due to the difficulty of the large fire experiment. Further work on the full-scale experiment and three-dimensional numerical analysis is needed to fully understand the implications of adequate protection on the CFRP-strengthened shield tunnel against fire exposure.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the sponsorship from Shanghai Sailing Program (20YF1451400), the National Natural Science Foundation of China (52208401), and the Research Fund of State Key Laboratory for Disaster Reduction in Civil Engineering (SLDRCE19-A-14).

REFERENCES


Study on fire behaviors of asymmetric double fires with different separation distances in the tunnel

Kun He¹, Yongzheng Yao², Long Shi¹, Hui Yang¹, Xudong Cheng¹
¹ State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, China
² School of Emergency Management and Safety Engineering, China University of Mining and Technology (Beijing), Beijing, China

ABSTRACT
In this study, a series of reduced-scale tunnel fire tests were carried out to investigate the fire behaviors of asymmetric double fires in a tunnel with natural ventilation, including the flame shape and longitudinal ceiling gas temperature distribution. The comparison between the symmetric double fires and asymmetric double fires was also made. The results showed that the height of the flame on the side with the smaller heat release rate is significantly lower, accompanied by a greater flame tilt angle. The ceiling gas temperature distribution is closely related to the merging state. For the mean flame merging scenario, the ceiling gas temperature distribution on both sides are basically equal to each other. For the plume merging stage and non-merging with two separated plumes, the ceiling gas temperature on the side with the larger heat release rate is higher and decays more slowly in the vicinity of the fire source. Ceiling gas temperature attenuation is relatively more rapid in the radial spread region and shooting flow region, while the ceiling smoke temperature attenuation is relatively slower in the one-dimensional tranquil flow region. Finally, different empirical models are established to predict the excess ceiling gas temperature attenuation, considering different merging states and smoke spread regions. This study is of great significance for the protection of tunnel structures in the case of multiple fire sources.

KEYWORDS: Tunnel fire, double fires, asymmetric heat release rates, flame merging, flame tilt

INTRODUCTION
Due to the special semi-confined geometry, the tunnel fire smoke could result in heavy casualties [1, 2], such as in the fire in the Mount-Blanc tunnel between France and Italy with 39 deaths (1999) [3] and the Yanzhou tunnel fire in China with 40 deaths (2014). Therefore, an increasing number of studies focus on tunnel fire safety, including fire development characteristics [3, 4], flame behaviors [5, 6], the maximum gas temperature beneath the tunnel ceiling [7-9], the smoke spread characteristics [10-12], and smoke control methods [13-15]. Most of the previous studies focus on the single fire source scenario and have ignored scenarios with multiple fire sources. Based on the previous study [2], two or more vehicles may burn simultaneously in a tunnel due to vehicle collisions or fire spread, while each vehicle then evolves into one separated fire source. When the number of Heavy Goods Vehicles (HGVs) involved in a tunnel fire increases from one to two, the fire hazard will increase significantly [2]. The multiple fire sources phenomenon causes more fuel burning in the tunnel and a larger total heat release rate, as a result, the smoke temperature increases, which makes it more difficult for evacuees to reach the safe region and for firefighters to reach the position where they can effectively extinguish a fire.

However, studies on fire scenarios with multiple fire sources in a tunnel are relatively limited. Ji et al. [16, 17] investigated the burning behaviors and ceiling gas smoke driven by the longitudinally arranged symmetric double fire sources by a series of reduced-scale fire tests. The results showed that the flame behaviors of multiple fires were much different from that of a single fire in the tunnel and the flame height increases significantly when flame merging occurs, which may result in more serious damage to
the tunnel structure. Fan and Tang [18] disclosed the effects of interactions between the horizontally arranged double fire sources on burning rates and flame behaviors by a series of reduced-scale tunnel fire tests. Tsai et al. [19], Zhang et al. [20] and Tang et al. [21] studied the influences of fire spacing and heat release rate on the critical velocity in a longitudinally ventilated tunnel with double fire sources, respectively. Jia et al. [22], Zhang et al. [23], Ren et al [24] and Wang et al. [25] studied the maximum gas temperature and longitudinal ceiling gas temperature profile of the smoke flow driven by symmetric double fires in a longitudinally ventilated tunnel.

It can be found that previous studies mainly focused on symmetric double fire sources with equal heat release rates. The fire load of each vehicle is often not completely consistent, and the ignition time of each vehicle is also different, which will lead to multiple fires with asymmetric heat release rates in a tunnel fire. A deep understanding of the physics regarding asymmetric double fires is still lacking. Therefore, this study focuses on the fire behaviors of asymmetric double fires in a naturally ventilated tunnel, including the flame shape and longitudinal ceiling gas temperature attenuation. The comparison between the symmetric double fires and asymmetric double fires was also made. A series of fire experiments with asymmetric two fires have been carried out in a reduced-scale model tunnel, considering different heat release rate rates and fire separation distances. The different empirical models for ceiling smoke temperature attenuation in different smoke spread regions are also established based on the flame merging state.

**EXPERIMENTS**

In this study, the Froude scaling law was adopted to conduct the fire experiments, the related scaling correlations are shown in Table 1, where F and M represent the full and model scales, respectively. A total of 48 experiments were carried out in a 1:10 reduced-scale model tunnel. The ceiling, floor and back walls of the model tunnel were made of 0.02 m fire-proof boards, while the front wall was made of 0.01 m fire-proof glass to observe the experimental phenomenon. Two exists of the model tunnel at both sides were kept open during the tests to simulate the natural ventilation. The reduced-scale model tunnel was placed in an experimental hall. The doors and windows of the experimental hall were closed to ensure a stable and quiescent environment during each fire experiment.

<table>
<thead>
<tr>
<th>Terms</th>
<th>Scaling model</th>
<th>Equation number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat release rate (kW)</td>
<td>( \dot{Q}_F = Q_M \cdot \left( \frac{L_F}{L_M} \right)^{5/2} )</td>
<td>(1)</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>( u_F = u_M \cdot \left( \frac{L_F}{L_M} \right)^{1/2} )</td>
<td>(2)</td>
</tr>
<tr>
<td>Time (s)</td>
<td>( t_F = t_M \cdot \left( \frac{L_F}{L_M} \right)^{1/2} )</td>
<td>(3)</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>( m_F = m_M \cdot \left( \frac{L_F}{L_M} \right)^3 )</td>
<td>(4)</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>( T_F = T_M )</td>
<td>(5)</td>
</tr>
</tbody>
</table>

Two gas burners with the same square cross-section were used to simulate the fire source. The side length of each burner is 0.1 m and the wall thickness of the burner was 3 mm. Propane gas with a purity of 99% was used as fuel. The flow rate of propane gas was controlled by two digital mass flow controllers (Sevenstar CS200, accuracy: ±1.0%, S.P. (≥35% F.S.), ±0.35% F.S. (< 35% F.S.)) to vary the heat release rates. The two burners were placed along the longitudinal center line of the tunnel with the top surface 0.02 m above the tunnel floor. The heat release rate of each fire source is calculated as \( \dot{Q} = \chi \dot{m}_{\text{fuel}} \Delta H_c \). The combustion efficiency \( \chi \) of propane is often assumed to be one, and the heat of combustion is 46.45 MJ/kg [26, 27]. The distance between the sides of two burners is defined as the fire separation distance, as shown in Fig. 1. The fire separation distances vary from 0 m to 0.9 m in this study. The detailed experimental scenarios are shown in Table 2.
To measure the maximum ceiling smoke temperature along the tunnel axis, the K-type thermocouples with a diameter of 1 mm were arranged at 0.02 m below the tunnel ceiling along the longitudinal centerline. The thermocouple interval ranges from 0.05 m to 0.4 m. The flame shapes were recorded by a DV camera (25 frames per second) fixed at the side. The image processing methods were widely used to obtain the flame merging characteristics with probability [16, 28, 29]. In this study, this method was used to proceed with 1500 pictures (60 seconds, 25 frames per second) at the quasi-stable combustion stage for each experiment to obtain flame appearance probability distribution contours. In this study, the two flames can be considered non-merged when the flame possibility is smaller than 0.5 [30]. Its physical meaning is the two mean flames will not touch each other.

### Table 2: Experimental Scenarios

<table>
<thead>
<tr>
<th>Test No.</th>
<th>$Q_A$ (kW)</th>
<th>$Q_B$ (kW)</th>
<th>Separation distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-8</td>
<td>5.4</td>
<td>5.4</td>
<td>0, 0.05, 0.1, 0.15, 0.2, 0.3, 0.5, 0.9</td>
</tr>
<tr>
<td>9-16</td>
<td>5.4</td>
<td>10.8</td>
<td>0, 0.05, 0.1, 0.15, 0.2, 0.3, 0.5, 0.9</td>
</tr>
<tr>
<td>17-24</td>
<td>5.4</td>
<td>16.2</td>
<td>0, 0.05, 0.1, 0.15, 0.2, 0.3, 0.5, 0.9</td>
</tr>
<tr>
<td>25-32</td>
<td>5.4</td>
<td>21.6</td>
<td>0, 0.05, 0.1, 0.15, 0.2, 0.3, 0.5, 0.9</td>
</tr>
<tr>
<td>33-40</td>
<td>10.8</td>
<td>10.8</td>
<td>0, 0.05, 0.1, 0.15, 0.2, 0.3, 0.5, 0.9</td>
</tr>
<tr>
<td>41-48</td>
<td>10.8</td>
<td>21.6</td>
<td>0, 0.05, 0.1, 0.15, 0.2, 0.3, 0.5, 0.9</td>
</tr>
</tbody>
</table>

### RESULTS AND DISCUSSION

#### Flame shape

The interaction between the double fire sources in the naturally ventilated tunnel will lead to different and complicated flame behaviors. The asymmetric heat release rates may further result in different flame behaviors. Fig. 2 shows the typical images of the flame shape at quasi-steady burning stage. The following phenomena can be observed:

1. The merging state of two fires in the naturally ventilated tunnel can be divided into three stages with the increase of the fire separation distance, i.e., mean flame vertical merging, fire plume vertical merging and non-merging with two completely separated fire plumes. When the bottoms of the two fire source contacts, the two flames completely merge into one flame. As the fire separation distance increases, the two flames merge intermittently. The two separated flames become completely separated when the fire separation distance is longer than the longitudinal deviation length of the two flames. For symmetric double fire sources with equal heat release rates, the two flame shapes are basically symmetric. However, for asymmetric double fire sources with unequal heat release rates, the height of the flame on the left side is significantly lower than that on the right side with a greater heat release rate. It can be also found that the flame height becomes higher after the flame merging occurs.
(2) Due to the long-narrow and restricted structure of the tunnel, the longitudinal induced airflow will be formed during a fire in the naturally ventilated tunnel [30]. Therefore, the two flames still tilt inward when the fire separation distance is relatively large (such as \( S \geq 0.5 \text{m} \)) even though flame merging does not occur. However, it can be found that the flame tilt angle is asymmetric for the asymmetric double fire sources with unequal heat release rates. The flame tilt angle of the flame on the left side is significantly larger than that on the right side with a greater heat release rate due to asymmetric flame interactions.

![Fig. 2](image)

(a) Two fires with symmetric heat release rates \( QA-QB: 5.4 \text{ kW}-5.4 \text{ kW} \)

(b) Two fires with symmetric heat release rates \( QA-QB: 5.4 \text{ kW}-16.2 \text{ kW} \)

Longitudinal temperature distribution beneath the tunnel ceiling
The change in the flame shape of the two fires will also lead to different longitudinal temperature distribution profiles. Fig. 3 shows the time-averaged temperature profile below the ceiling along the tunnel axis under different fire separation distances. The following characteristics of ceiling gas temperature distribution could be observed:

1. The merging states of the two fires significantly have an obvious effect on the characteristics of ceiling gas temperature distribution. When the fire separation distance is relatively small, there is only one peak temperature because the two fire plumes merge vertically before impinging on the ceiling. However, when the fire separation distance is relatively large, there are two peak temperatures when the two fire plumes are completely separated and impinge the ceiling separately as shown in Fig. 2.

2. For symmetric double fire sources with equal heat release rates, the ceiling gas temperature distributions on both sides of double fire sources are basically consistent. When there is only one peak temperature for small fire separation distances, the position of the peak temperature appears at the center line of double fire source for symmetric double fire sources. When there are two peak temperatures for large fire separation distances, the two peak temperatures are basically equal to each other.

3. For asymmetric double fire sources with unequal heat release rates, the ceiling smoke temperature distributions on both sides of the fire sources are different, which is also related to the fire merging state. For zero fire separation distance, the ceiling gas temperature on both sides of the maximum temperature and the position of the maximum ceiling gas temperature is symmetric as the two flames are completely merged. As the fire separation distance increases, the position of peak temperature is closer to the fire source with the larger heat release rate due to the smaller flame tilt angle. Also, the ceiling smoke temperature on the side with the larger heat release rate is higher and decays more slowly than that on the side with the smaller heat release rate, even for the plume merging state, such as \( S/D=1.5 \). When there are two peak temperatures for large fire separation distances, the temperature on the side with a larger heat release rate is much higher than that on the side with a smaller heat release rate.
Models for ceiling smoke temperature attenuation in the vicinity of the fire source

Because of the initial limitation of the side walls, the radial ceiling jet flow gradually transforms into one-dimensional spreading flow[31-33]. Based on the previous studies [12, 34], the smoke spreading along the ceiling in a naturally ventilated tunnel can be divided into three regions, namely the radial spread region (Region I: $x_m \leq l_b$), the shooting flow region (Region II: $l_b < x_m \leq x_c$) and the one-dimensional tranquil flow region (Region III: $x_m \geq x_c$). In Regions I and II, the inertial force is greater than the buoyancy of the area close to the fire source [35], which may leading to severe air entrainment. The air entrainment into the ceiling jet flow will result in a reduced inertia force, and the shooting flow changes to tranquil flow when the buoyancy and inertia force approach the equilibrium state [34]. Correspondingly, the air entrainment from the lower air layer in Region III becomes limited.

Fig. 4 shows the non-dimensional longitudinal excess ceiling gas temperature on the right side of the fire source. Significant different temperature attenuation trends in different smoke spread regions can be observed. Ceiling gas temperature attenuation is relatively more rapid in Regions I and II and the ceiling gas temperature attenuation is relatively slower in Region III ($x_m / H \geq 1.5$ in the present study). For Regions I and II, the longitudinal distance from the fire source is generally short, therefore, we attempt to get a unified empirical model to predict the ceiling gas temperature attenuation. It can be also found that the non-dimensional excess gas temperature gradually decays slower with the increase of fire separation distance. This further indicates that the ceiling gas temperature attenuation is affected by the merging stage. In the following part, the three different merging states, namely mean flame vertical
merging, fire plume vertical merging and non-merging with two completely separated fire plumes, were considered.

![Diagram](image.png)

**Fig. 4** Non-dimensional longitudinal excess ceiling gas temperature on the right side of the fire source along the whole tunnel

In this study, the range of heat release rate is wide and the flames almost approach or even directly impinge the tunnel ceiling in most scenarios. This results in a significant ceiling gas temperature range and a relatively large density defect ($\Delta \rho$ compared to the surrounding air), which should not be ignored. Therefore, the plume radius at the ceiling level, defined as $b$, is introduced in the following discussion, which can be expressed as follows [36]:

$$b = 0.42 \left( c_p^{4/5} \rho_\infty^{4/5} T_\infty^{2/5} g^{1/2} \right)^{1/12} \frac{T_{\text{max},c}^{3/5} Q^{2/5}}{\Delta T_{\text{max},c}}$$

where $c_p$ is the specific heat of air at constant pressure (kJ/(kg·K)), $\rho_\infty$ is the density of ambient air (kg/m$^3$), $T_\infty$ is the ambient temperature (K), $g$ is acceleration of gravity (m/s$^2$), $T_{\text{max},c}$ is the maximum gas temperature below tunnel ceiling (K), $\Delta T_{\text{max}}$ is the maximum excess gas temperature below tunnel ceiling (K) and $Q_c$ is the convective heat release rate that is often assumed as $Q_c = 0.8Q$ for propane [36].

Fig. 5 shows the non-dimensional excess gas temperature data in Region I and II ($x_m/H \leq 1.5$) as a function of the non-dimensional distance. For fire scenarios with mean flame vertical merging, the total heat release rate, namely $Q_a + Q_b$, was used to calculate the plume radius at the ceiling level (defined as $b_m$) because the two fire plumes merge vertically and behave as a single fire. For scenarios with plume vertical merging and two completely separated fire plumes, the plume radius at the ceiling level (defined as $b_c$) was estimated by using the single heat release rate due to the different non-dimensional excess ceiling gas temperature decays on both sides of the fire source. That is, the plume radius at the ceiling level on the left side is estimated by using $Q_a$, while the plume radius at the ceiling level on the right side is estimated using $Q_b$. Moreover, when the two fire plumes are completely separated, the ceiling gas temperature outside of the fire sources is studied and the ceiling gas temperature was normalized by the maximum temperature rise induced by the single fire sources. For comparison, the temperature attenuation data of symmetric double fire sources are also shown in Fig. 5.

For mean flame vertical merging scenarios, the non-dimensional excess ceiling gas temperature data cluster together well for both double fires with symmetric and asymmetric heat release rates, as shown in Fig. 5(a). Due to limitation of the side walls, the ceiling smoke temperature are just slightly higher than the predicted value estimated using the previous model for the smoke flow driven by a single fire source underneath an unrestricted ceiling [36]. As shown in Fig. 5(a), the non-dimensional excess ceiling gas temperature in Region I and II can be well matched by the following empirical model:
For fire plume merging scenarios, the non-dimensional excess gas temperature data on both sides cluster together well when the $\mathbf{b}_s$ was used as the characteristic length scale, as shown in Fig.5(b). The data for Region I and II can be matched by the following empirical model:

$$\frac{\Delta T}{\Delta T_{\text{max}}} = \begin{cases} 
1, & \frac{x_m}{\mathbf{b}_m} < 0.8 \\
(0.8+0.25\frac{x_m}{\mathbf{b}_m})^{-1.12}, & 0.8 \leq \frac{x_m}{\mathbf{b}_m} 
\end{cases}$$

(7)

For scenarios with two separated fire plumes, as shown in Fig.5(c), the non-dimensional excess temperature in Region I and II can be estimated by the following empirical model:

$$\frac{\Delta T}{\Delta T_{\text{max}}} = \begin{cases} 
1, & \frac{x_m}{\mathbf{b}_s} < 0.8 \\
(0.8+0.25\frac{x_m}{\mathbf{b}_s})^{-0.68}, & 0.8 \leq \frac{x_m}{\mathbf{b}_s} 
\end{cases}$$

(8)

Fig.6 shows the comparison between the experimental value and predicted value given by Eqs (7)-(9) for Region I and II. It can be found that most experimental data are distributed within the ±20% error lines, which indicates the non-dimensional excess gas temperatures given by Eqs (2)-(4) are reasonably validated.
Fig. 6  Comparison between the experimental value and predicted value given by Eq.s (7)-(9).

Models for ceiling smoke temperature attenuation in the one-dimensional tranquil flow region
For the one-dimensional tranquil flow, the air entrainment coefficient is usually very small [37, 38] and the air entrainment rate into the upper smoke layer is very low, which finally results in a relatively slower temperature decay. The previous study indicates the longitudinal ceiling gas temperature attenuation for the one-dimensional tranquil flow fell into a good exponential decay [2], which could be expressed as:

$$\frac{\Delta T}{\Delta T_{ref}} = \exp\left(-k \frac{x_{ref}}{H}\right)$$  \hspace{1cm} (10)$$

where \(x_{ref}\) is the distance from the reference point (m), \(H\) is the tunnel height (m) and \(\Delta T_{ref}\) is the excess gas temperature at the reference point (K). In this study, the starting point of the one-dimensional tranquil flow region (\(x_{ref}/H = 1.5\)) is selected as the reference point. Also, the three different merging states are considered. Fig. 7 shows the non-dimensional excess gas temperature data (\(\Delta T/\Delta T_{ref}\)) in Region III as a function of the non-dimensional distance (defined as \(x_{ref}/H\)). It can be found that the non-dimensional excess gas temperature data cluster together for both symmetric double fires and asymmetric double fires for a given merging state, which indicates the effect of the asymmetric fire size rate on the non-dimensional excess gas temperature decay in the one-dimensional tranquil flow region is very limited.

For mean flame merging scenarios, the non-dimensional excess gas temperature below the ceiling for Region III could be expressed as:

$$\frac{\Delta T}{\Delta T_{ref}} = \exp\left(-0.096 \frac{x_{ref}}{H}\right)$$  \hspace{1cm} (11)$$

For fire plume merging scenarios, the non-dimensional excess gas temperature for Region III below the ceiling could be expressed as:

$$\frac{\Delta T}{\Delta T_{ref}} = \exp\left(-0.079 \frac{x_{ref}}{H}\right)$$  \hspace{1cm} (12)$$

For scenarios with two separated fire plumes, the non-dimensional excess gas temperature below the ceiling for Region III could be expressed as:

$$\frac{\Delta T}{\Delta T_{ref}} = \exp\left(-0.076 \frac{x_{ref}}{H}\right)$$  \hspace{1cm} (13)$$

Fig. 8 shows the comparison between the experimental value and predicted value given by Eq.s (11)-(13) for Region III. It can be found that the experimental data are distributed within the \(\pm 20\%\) error.
lines, which indicates the non-dimensional excess gas temperatures given by Eq.s (11)-(13) are reasonably validated.

Fig. 7  Non-dimensional excess gas temperature data in Region III as a function of the non-dimensional distance \( x_{ref}/H \).

Fig. 8  Comparison between the experimental value and predicted value given by Eq.s (11)-(13) for Region III.
CONCLUSIONS

In this study, a series of reduced-scale tunnel fire tests were carried out to investigate the characteristics of fire behaviors of asymmetric double fires in a tunnel under natural ventilation, including the flame shape and longitudinal temperature distribution. The difference between the symmetric double fires and asymmetric double fires was also studied. Empirical models for different merging states and smoke spread regions were established. The major conclusions of this study are summarized as follows:

(1) For asymmetric double fire sources, the height of the flame on the side with the smaller heat release rate is significantly lower than that on the right side with the greater heat release rate. Due to longitudinal induced airflow in the naturally ventilated tunnel, the two flames still tilt inward even though the fire separation distance is relatively large and flame merging does not occur. The flame tilt angle of the flame on the side with a smaller heat release rate is significantly larger due to asymmetric flame interactions.

(2) The characteristics of the ceiling gas temperature distribution profile were affected by the merging states of the two fires. When the two fire plumes merge vertically, there is only one peak temperature. When the two fire plumes are separated before impinging on the ceiling, there are two peak temperatures. For symmetric double fire sources, the ceiling smoke temperature distributions on both sides of fire sources are consistent. For asymmetric double fire sources, when mean flame merging occurs, the ceiling smoke temperature on the side is the same. But the ceiling smoke temperature on the side with the larger heat release rate is higher for the scenarios with plume merging and non-merging with two separated plumes.

(3) The temperature attenuation trends of the smoke flow in the naturally ventilated tunnel in different smoke spread regions are significantly different. Ceiling gas temperature attenuation is more rapid for the radial spread region and shooting flow region, while the ceiling smoke temperature attenuation is relatively slower in the one-dimensional tranquil flow region. Based on the flame merging state, the different models are established for both the radial spread region and shooting flow region by using the plume radius at the ceiling level as the characteristic length scale, which is described as Eq.s (7)-(9). For one-dimensional tranquil flow region, the different exponential decay models developed are described as Eq.s (11)-(13).

ACKNOWLEDGEMENT

This work was financially supported by the National Key Research and Development Program of China (No. 2022YFC3005201), Youth Innovation Promotion Association CAS (No. CX2320007001), Fundamental Research Funds for the Central Universities under Grants (No. WK2320000056) and USTC Tang Scholar.

REFERENCES

2. Ingason, H., Y.Z. Li, and A. Lönnmark, Tunnel fire dynamics. 2014: Springer.


Evolving tunnel research and safety in USA

Gary English (Deputy Chief, retired)
Underground Command and Safety, Washington, USA

ABSTRACT

Transportation Tunnels are some of the safest and most critical elements of national, regional, and local transportation infrastructures, however a single “poorly designed and managed” [1] tunnel test, not focusing on important issues left a legacy of tunnels with undersized fire and fire life safety systems, or simply no safety systems. Our modern research continues to evolve our understanding of tunnel fires and improvements to safety, yet many research needs are unmet.

Early assumptions on tunnel safety from fire size, fire growth rate, and dangerous goods fires have been proven incorrect by more recent research and unfortunate incidents where assumptions on maximum fire size have been shown to be incorrect in actual fires. Also, limited dissemination of modern research beyond scientific papers leaves many designers, engineers, and responders to search for research conclusions and real-world examples to provide facts from which to derive user safety and inform practitioners.

Application of research is still a challenge as US federal recommendations fail to understand critical applications rationale of tunnel safety regulations, thus undermining their recommendation application.

As the ISTSS attracts an international tunnel research participation, this paper will provide an overview of US research processes, a practical example of research derived from a fatality incident history challenges and current US research is outlined in this paper. However, no more than a cursory glance is possible given short length. Recognizing the international tunnel community maybe unaware of the US tunnel research, this paper looks at a cross section of tunnel fire research and recommendations in the hopes of greater collaboration.

Paper presumes the reader understands how tunnel geometry both limits heat release rate (limited available oxygen) while simultaneously accelerating the fire growth rate and recognizes user safety difficulties presented by constrained geometry, limited emergency egress, combined with fire-imposed tenability limits of heat, vision obscuration and toxic gases.

Note - although the term ‘fixed fire fighting system’ (FFFS) or ‘water-based fixed fire fighting system’ (WBFFS) are sometimes applied to fire sprinkler systems, this use is very limited and often misleading. In the over 300 National Fire Protection Association (NFPA) codes and standards, these terms are only used in two standards, NFPA 502 Road Tunnels, Bridges, and Other Limited Access Highways’ and NFPA 750 ’Standard on Water Mist Fire Protection Systems. Whereas many other standards use the term fire sprinklers and the dedicated NFPA standard on fire sprinkler installation, NFPA 13 and handbook have over 1300 hundred pages. Therefore, using the acronym FFFS can be problematic and has created unintentional confusion and challenges as some tunnel engineers, designers, operators, believe this FFFS is a ‘new’ form of fire sprinklers exclusive to tunnels, which is incorrect. Typical fire sprinkler systems are installed in tunnels without significant variations unless water additives are used to suppress flammable liquid fires. Also, searching for fixed fire fighting systems, or FFFS will yield a very small portion of the available volumes of research and installation guidance compared to researching ‘fire sprinkler’. Hence the term, fire sprinkler is used throughout this document.
This paper focuses on key US research projects and tunnel incidents with embedded links for ease of access. Bold and underlined text are key statements.

**KEYWORDS:** Tunnel Safety, Fire Research, Regulations, Fire Sprinklers, FFFS, Fire systems, Ventilation

**US TUNNEL FIRE RESEARCH HISTORY**

One of the first US major transportation tunnel research projects was the 1921 Holland Road Tunnel in New York which addressed dangers of vehicle exhaust trapped in the road tunnel and identified a new mechanical ventilation system to remove exhaust gases out of the tunnel to protect motorists. Design pushed clean air from a parallel plenum system below the roadway into the tunnel and pulled contaminated air out via a second, negative pressure parallel plenum above the roadway, in turn this was exhausted to the outside. Research determined the number of air exchanges per hour to ensure motorists would not be exposed to excessive exhaust gases.

Transverse ventilation systems were installed in new tunnels for decades to address vehicle emissions, but these systems was not designed to address fire, i.e., heat, smoke, toxic gases, and loss of visibility (obscuration). Ironically the same Holland tunnel experienced a lethal dangerous goods (carbon disulfide) fire in 1949 resulting in 1 death, 66 injuries, 13 vehicles destroyed and major damage to the tunnel structure and systems. (Figure 1) The relatively new transverse system was incapable of managing fire byproducts.

Many transverse ventilation road tunnels were designed for a 20 MW fire. A research basis for this fire size is unclear. Increasing reports of tunnels where the combination of a 20 MW design fire size and transverse ventilation being insufficient to protect motorists from larger fires resulted in research.

Meanwhile, the new Seattle Battery Street tunnel (1954) (Figure 2) recognized challenges with ‘ventilation only’ as the single method to protect motorists and structure as this approach does not address a growing fire producing more smoke, gases, and heat. Fires simply burn until fuel is consumed, or firefighters intervene. Delaying has resulted in major tunnel damages. This tunnel opted to use proven fire sprinkler technology from buildings since 1806. This became the first road tunnel to install fire sprinklers. If tests to prove effectiveness were conducted, results are not available.

The 1965 Offenegg Tunnel sprinkler research allegedly proved tunnel sprinklers ‘dangerous’ due to production of steam, loss of visibility and explosions. This single research project resulted in European and North American tunnel standards banning tunnel sprinklers for decades and thereby forcing reliance almost solely on mechanical ventilation to protect occupants. Ventilation improved dramatically, but in this interim almost no substantive tunnel sprinkler research was initiated. More

---

2 [https://hoboken_pastperfectonline.com/archive/A0A5A939-E6D7-4196-B9BF-101635106840](https://hoboken_pastperfectonline.com/archive/A0A5A939-E6D7-4196-B9BF-101635106840)
recent research reviewed by Fire Protection Research Foundation (FPRF) stated “The Offeneg tests were poorly designed and managed. The results of excessive steam, loss of visibility, reignitions, and explosions, were not normal outcomes of sprinklers.” [1]

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) recognizing the inadequacy of presuming a 20 MW fire was the maximum fire size. This resulted in a joint effort by the Federal Highway Administration (FHWA) and Massachusetts Highway Department who were designing the Boston Central Artery tunnel Project (CAP). They conducted the Memorial Tunnel Fire Ventilation Test Program (MTFVT) comprehensive fire tests ³.

These tests demonstrated the ability for longitudinal mechanical ventilation (LV), pushing air from entry point(s) and out the exit portal(s) to address fire greater than 20 MW while providing better tenability for motorists (except for those stopped in traffic downstream of the fire incident). CAP then built nearly 6.5 Km (4 miles) of tunnels under downtown Boston using this method. LV became the prominent method of road tunnel ventilation across the country and is still the predominant method.

1995 MTVFT tested ventilation using a 100-Megawatt (MW) fire size (MW is measurement of energy produced from a fire), i.e., using the volume of flammable liquid (FL) in a heavy goods vehicle fuel tank, or 800 L (200 US gal) if released. Based on engineering estimates this would be a 4.5 m² (48 sq ft) exposed surface area which produces a nominal heat release rate of approximately 10 MW. Multiple pans were used simultaneously to reach the 100 MW fire HRR. However, using pans artificially limits the spill area, and therefore the FL vapor production from 800 liters was actually underestimated. In fact, spill of this volume could create a much larger surface area, thereby increasing vapor production and increasing HRR, albeit for a shorter burn time. Some make the incorrect assumption an 800 L (200 US gal) of flammable liquid will ONLY reach 100 MW. (Figure 3) Also, as this study was limited to heat from FL spill, this did not address Boiling Liquid Expanding Vapor Explosion potential of a fuel tank from external flame⁴.

Unfortunately, tunnel fire standards incorrectly identified this 100 MW fire size as the ‘largest design fire size’. But in practice, a much greater volumes of DG routinely enter tunnels as this is allowed if in separate packaging on the same cargo vehicle. Although the tunnel design is based on legal use of a tunnel, the illegal use is not considered in design criteria, but must be addressed in practice for tunnel operators and firefighters. Also, experienced fire officers recognized this 100 MW maximum design fires is not accurate in tunnels as fire size is constrained by the oxygen limits created by combination of tunnel ventilation, geometry, and the fuel type, not the artificial constraints of a pan.

Fire officers were correct as the ‘maximum 100 MW Flammable Liquid’ design fire was surpassed by an ordinary combustible tunnel fire in Mont Blanc Tunnel (1999) which reached a calculated 190 MW. (Figure 4) Although this number exceeded common expectation, this was confirmed when 2003 Runehamar tunnel fire research demonstrated “A typical commodity found in HGVs trailers could produce a rapidly growing fire producing a peak heat release rate of 200 MW.” [2]

⁴ https://trid.trb.org/view/485925
Rather than depending solely on research to frame the maximum potential fire size and make critical predictions on fire size, studying actual fires can provide valuable lessons to designers, engineers, owners, and responders. The 1982 Caldecott tunnel flammable liquid tanker fire was analyzed by NIST and identified this fire created a 400 MW size\(^5\). The 2015 Skatestraum tunnel flammable liquid fire reached 440 MW\(^6\). So the question becomes why tunnel fire standards, such as 502 do not specifically recognize this larger fire size, which could have been greater if the same fire had occurred in a three or four lane tunnel where more oxygen is available.

**Rail tunnels**, also have fires with significant consequences. Earliest rail tunnels built for use with coal fired steam engines sometimes installed mechanical ventilation to provide essential oxygen for coal combustion. Today, many train tunnels used by freight and passenger rail have no life safety systems: lighting, ventilation, exits, etc. and in some cases local fire departments use Mobile Ventilation Units brought to a tunnel portal to induce longitudinal ventilation. Often bulk dangerous goods and passenger rail share the tunnel simultaneously, which could be a catastrophic combination.

![Figure 5 Cascade tunnel vent door](image1)

![Figure 6 The Metro Project](image2)

The 1900 US Washington Cascade tunnel (through a mountain range similar to Alps) was replaced in 1929 with 12.6 km (7.8 miles) tunnel with overhead catenary and electric engines, and later with diesel in the 1950s to minimize the time of coupling and uncoupling the electric engines. Early ventilation system took an hour to clear the diesel fumes before another train could enter. Research analysis resulted in reconfiguring ventilation using separate ventilation portals and adding a ventilation door which reduced time to clear fumes to thirty minutes maximum. (Figure 5)

THE METRO PROJECT (2009-2012) (RISE et.al.) conducted in-depth analysis of full-scale fire tests in passenger type rail cars in a single-track tunnel with actual luggage on board. This simulated the expectation passengers would leave many items behind when fleeing a train accident and/or fire in a tunnel. Luggage et.al. were separately analyzed in fire tests as the ‘carried on’ fire load of luggage, backpacks, purses, baby carriages, and contents and determined this could account for nearly half of the fire size of a train fire. The expected fire size for these full-scale tests in a single-track tunnel was predicted by many to be 15-20 MW, yet carefully measured tests yielded a fire of 77 MW which could have been greater if more oxygen was available as in a two-track tunnel. (Figure 6). This strongly indicates many rail tunnels with ventilation presumed accurate at a design fire of 15 -20 MW fire may be overwhelmed. Oxygen levels downstream of fire were below survivable limits\(^7\).

**TUNNEL FIRE REGULATIONS**

Unlike many countries, the US lacks a nationwide road or rail tunnel government ‘minimum mandatory tunnel fire safety requirements’ to address tunnel fires in design, installation, operations, and emergency response. However, “The Federal Rail Administration [FRA] does require the use of

---

7 [https://www.metroproject.se/publications.html](https://www.metroproject.se/publications.html)
primarily small-scale flammability and smoke emission tests and performance criteria for interior materials, such as seats and all wall and ceiling panels; and fire endurance tests for structural components such as floors... (this) include a requirement for conducting fire safety analysis for new and existing equipment and requirements for the inspection, testing and maintenance of fire safety related equipment.” [3]

Though component testing and analysis may not adequately address the interrelationships of several interior materials combusting simultaneously as would occur for interior train fire. This might explain why the Runehammer tests resulted in higher HRR than anticipated, simply there were more surfaces combusting than a single test could achieve.

There are US federal agencies tasked with oversight, funding, and other key tunnel components. But for fire regulations, either the ‘International Fire Code’ (International Code Council) or National Fire Protection Association (NFPA) ‘Fire Code’ is used. Lacking a national fire code, each state or local jurisdiction adopts a fire code. State Fire Code is administered and enforced by the ‘fire code official’, and/or the ‘Authority Having Jurisdiction’. This individual or group is designated by the fire code adopting authority to interpret and enforce the regulations and may increase (not decrease) these minimum requirements. Very rarely, state Departments of Transportation, Rail Authorities, or similar agencies may also have the authority to adopt, enforce and interpret fire safety regulations for their own projects, and only if they are specifically authorized in their charging statements. Structural Fire Codes are limited to buildings and systems and are not applicable to vehicles (cars, trucks, trains) hence NFPA document fills this gap for rail tunnels to address train vehicles with some limits.

NFPA mission is ‘To help save lives and reduce loss with information, knowledge, and passion.’ NFPA delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach, and advocacy; and by partnering with others who share an interest in furthering our mission. NFPA delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach, and advocacy; and by partnering with others who share an interest in furthering our mission. NFPA membership totals more than 50,000 individuals around the world categorized in 12 groups, engineers, code officials, fire safety systems, etc.

REGULATIONS DRIVING RESEARCH

Two key NFPA tunnel transportation standards provide detailed regulations where requirement from state adopted fire codes are lacking and may be adopted as legal minimum requirements by state or local jurisdictions. NFPA 502, and NFPA 130 ‘Fixed Guideway Transit and Passenger Rail Systems’ (130).

NFPA standards are updated every three years by a technical committee made up of volunteer subject matter experts who review public inputs or bring specific concerns based on practical difficulties or expected problems. Technical committee make recommendations for standard language changes which are reviewed and approved by the NFPA Standards Committee. Standards are available online. As tunnels continue to incorporate fire systems engineered for surface buildings, several other standards, each with their own technical committees, are also applied in tunnels, such as NFPA 13, Installation of Fire Sprinklers, NFPA 72 Fire Signal and Alarm Code, NFPA 14 Standpipes etc. Although both 502 and 130 have tunnel ventilation requirements as well as nonbinding annex language, NFPA has not produced a ‘stand alone’ tunnel ventilation standard. New regulations are added based on proven best information but are done so with caution as imposing a new regulation or a revision without in-depth understanding of impacts can have unintended consequences. Research is used to detail a problem, proposed resolutions, and impacts. NFPA 502 committee recognized fire sprinklers (rarely called FFFS elsewhere in NFPA) were becoming more widely accepted based upon newer research and asked for synthesis and additional research on these systems, and the interrelationship between fire sprinklers, emergency ventilation and, as fire sprinklers can prevent extraordinary fire heat, the ability to reduce passive fire resistance.
RESEARCH DRIVEN BY BETTER UNDERSTANDING OF TUNNEL SYSTEMS AND FIRES

For US Road Tunnels, three organizations share vital roles in promoting tunnel technology and safety to the highway community. The Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and the Transportation Research Board (TRB) collaborate at the national and international levels to serve the broader transportation community.

Federal Highway Administration (FHWA) tunnel mission is to ‘develop, promote, and advance road tunnel and engineering principals, technology, and maintenance practices in the United States’. This agency manages the Tunnel Operations Maintenance Inspection and Evaluation program and US National Tunnel inventory\(^8\). FHWA has no enforcement ability of fire regulations, but provides funding for major road projects and has funded or co-funded several important tunnel fire research projects including: Design Fires in Road Tunnels\(^9\), and Integrated Design of Fixed Firefighting Systems and Emergency Ventilation Systems\(^10\), which is referenced in the Tunnel Fire Sprinkler section.

AASHTO is a nonprofit, nonpartisan association representing highway and transportation departments in the 50 states, the District of Columbia, and Puerto Rico. It represents all transportation modes including air, highways, public transportation, active transportation, rail, and water. Its primary goal is to foster the development, operation, and maintenance of an integrated national transportation system. AASHTO sub committee, T 20, comprised of tunnel owners and operators who, through the full committee make requests for tunnel research deemed essential. (This committee will be renamed shortly)

Among other research requests, T 20 advanced for funding to investigate ‘Legacy Ventilation Systems and Modern Understanding of Tunnel Fires’. Since US tunnels have been constructed for decades (Graph 1) and only recently science and real-world experience determined larger than expected fire size and growth rate, and therefore capacity of the vast majority of older tunnel ventilation systems is inadequate. Thus, if a large fire occurs, ventilation may be insufficient and emergency evacuation compromised. For the legacy problem, research could compare the current knowledge of potential and probable fire sizes against specific tunnels geometry and ventilation systems against the state of the practice when the tunnel was designed. Identifying a tunnels ventilation systems and comparing this against probable fire outcomes could identify risk to occupants, structure, systems and potentially cost to repair if a fire occurs. This requires identifying the scope and scale, of possible fires. Results could inform tunnel owners, operators, and firefighters of challenges with these existing systems, and possibly provide possible remedies or improvements.

One possibility to address undersized ventilation includes retrofitting fire sprinklers to keep the heat release rate and fire growth rate within the bounds of these older ventilation systems capacity. The same research topic is under consideration for funding at TRB, Standing Committee on Underground Structures and Tunnels, AKB60.

“Transportation Research Board (TRB) is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board’s varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest.” [4]

TRB advances policies, specifications, guidance, and technologies through cooperative meetings, workshops, webinars, and publications, as well as through strategic planning and research to foster

\(^8\) [https://www.fhwa.dot.gov/bridge/inspection/tunnel/inventory.cfm](https://www.fhwa.dot.gov/bridge/inspection/tunnel/inventory.cfm)
\(^9\) [https://trid.trb.org/view/1110472](https://trid.trb.org/view/1110472)
\(^10\) [Integrated Design of Fixed Firefighting Systems and Emergency Ventilation Systems](https://trid.trb.org/view/1110472)
innovation, technology transfer, and the accelerated deployment of cost-effective safety technologies.” [5]

Graph 1. US Rail Tunnels constructed by period

TRB data source, TRID, is an integrated database that combines the records from TRB’s Transportation Research Information Service Database and the OECD’s Joint Transport Research Centre’s International Transport Research Documentation (ITRD) Database. TRID contains over 1.3 million records of transportation research worldwide, combined from TRB’s Transportation Research Information Services (TRIS) Database and OECD’s Joint Transport Research Centre’s International Transport Research Documentation (ITRD) Database. Members of TRB have access to over 161 tunnel research project results.

INCIDENT DRIVEN RESEARCH – EXAMPLE

Major incidents uncover and identify tunnel challenges in design, construction, operations, and response and may result in several research efforts. This occurred in the Washington Metropolitan Area Transit Authority (WMATA) January 2015 incident. “Train 302, with approximately 380 passengers on board, stopped in the tunnel after encountering heavy smoke and was unable to return to the station before power to the electrified third rail was lost…The incident resulted in one fatality, 91 injuries, and $120,000 of property damage” [5]. Investigation of this January 2015 fatality fire in L’Enfant Plaza station smoke accident along with multiple previous tunnel fires in the United States and Europe resulted in National Transportation Safety Board Accident Reports/ RAR1601 which was forwarded to the Federal Transit Administration to “Issue regulatory standards for tunnel infrastructure inspection, maintenance, and repair, incorporating applicable industry consensus standards into those standards (R-16-01) and Issue regulatory safety standards for emergency egress in tunnel environments. (R-16-02)” [6]

This also resulted in federal legislation Safety Directive 16-2 ‘Required Actions to Address Open Safety Findings Issued by the Tri-State Oversight Committee to the Washington Metropolitan Area Transit Authority”[11].

To comply with the rule making, a rail research agency, Transportation Technology Center was engaged, “…to research areas of transit safety risk, identify existing specifications and guidelines for rail transit tunnel design, construction, maintenance, and rehabilitation, and perform a gap analysis to establish the need for additional standards, guidance, or recommended practices to support and further the safe operation of the United States’ public transportation industry.” [7]

Their paper “presents industry needs with a focus on security and safety that were identified by reviewing past tunnel incidents and related literature. The compilation of past tunnel incidents includes available reports published by the National Transportation Safety Board and other U.S. and European agencies. These reports generally involve rare but high-risk events such as fires and flooding and emphasize public safety. A summary of needs obtained through a literature review emphasizes the need for continually updating specifications and best practices. The industry needs findings include the need for working fire detection, ventilation, and emergency egress along with coordinated emergency response plans that can be utilized by trained personnel.” [8]

To expand on that study, FTA sponsored a more detailed study into tunnel emergency egress to aid the identification and modification or development of voluntary standards or recommended practices through the American Public Transportation Association (APTA) Standards Program. The necessary research and background studies conducted under this project also inform evidence-based safety policy and decision-making (regulations, directives, advisories, etc.) for FTA’s Office of Transit Safety and Oversight (TSO), as appropriate.

These findings are reported in FTA Research, Research Report and Findings: “Emergency Egress in Rail Transit Tunnels”, OCTOBER 2022, FTA Report No. 0232. After completion of literature review, relevant elements were documented, and gaps identified to be incorporated into a voluntary standard.

Three standards were identified as relevant to tunnel evacuation, NFPA 130, NFPA 502, and Safety Railroad Tunnels Technical Specification for Interoperability (SRT TSI) which is a design standard set by the EU in 2014 to be applied to all transit railways in the EU. The motivation for this standard was to ensure that all EU countries adopted the same minimum standards for passenger rail. SRT TSI includes many important components of tunnel egress but often differs from the U.S.

Emergency ventilation design is covered in NFPA 130 and 502, as well as an APTA white paper which provides information (APTA SS-SEM-WP-013-10), “Operational Strategies for Emergency Smoke Ventilation in Tunnels”[12].

FTA Report No. 0232 Key findings:
Finding 1: A voluntary standard or recommended practice for new tunnel design could consider including the following elements, most of which can be addressed through the incorporation of NFPA 130 by reference. These include Emergency lighting, Emergency signage, Number of egress points, Walkway design, Door design, Traction power design, Safe areas, Communication, Emergency ventilation. (Note this recommendation for a voluntary standard failed to recognize NFPA 130 includes non-binding annex materials (voluntary) embedded within the standard. Suggesting their recommendations be included as annex materials within the NFPA 130 document would have made accessing the recommendations both easier to access and more widely distributed than a stand-alone document in APTA.

Finding 2: Whereas NFPA 130 is comprehensive, there are some potential gaps, as referenced in Table 4-1.

(Author note: Close examination of the 4-1 gaps may be used by the NFPA 130 technical committee to research their validity, modify existing language, and/or develop new 130 language to meet gaps.)

**Finding 3:** APTA may update its white paper on emergency ventilation to reflect progress in ventilation methods and detection methods. (Author note: APTA produced this paper in 2010. Newer understanding of tunnel fire and ventilation may suggest an update is in order)

**Finding 4:** Public transit agencies should consider the use of new voluntary standards or recommended practices for tunnel design improvements of their existing tunnels; however, not all existing tunnels could meet NFPA 130 criteria due to their original design. (Author note: NFPA 130 and other standards cannot be required to be applied to existing tunnels but may be a mandate for new tunnels. Voluntary standards, being voluntary, cannot be required to be met. Combined, a voluntary standard or insertion into NFPA 130 annex, makes Finding 4, non enforceable (See AASHTO T-20 ‘Legacy Tunnel Ventilation and Modern Understanding of Design Fires’ comments.)

This FTA document failed to recognize key criteria for regulatory documents, i.e., NFPA 130 and 502, are included in Fire Code as referenced publications which can (by state or local fire code official) require enforcement of these standards. Also, rather than creating a new voluntary standard, NFPA 130 technical committee could approve recommendations into the 130 ‘non mandatory’ section, i.e., voluntary annex language. This reaches 130’s larger audience and provides cohesive approach within existing recognized NFPA standards. This approach will be reviewed by 130 technical committee for 2026 edition.

**Other Related Research**
In addition to the federal efforts, there were other research projects. Transportation Research Cooperative Program developed, with a select panel of experts ‘Planning and Design for Fire and Smoke Incidents in Underground Passenger Rail Systems, 2017’

**TUNNEL FIRE SPRINKLERS**
Almost no specific US road tunnel sprinkler research occurred in the US since the infamous 1965 Offeneg tunnel tests, other than limited tests in MTFVTP. Leaving tunnel experts at a significant disadvantage when faced with fires well beyond ability to manage with their undersized ventilation. These potentially large fires can be suppressed by fire sprinklers early in the fire growth stage which

can improve survivability and reduce need for passive fire resistance and ventilation. In addition, sprinklers can dramatically reduce tunnel damage and closures for repairs. These advantages has caused the road tunnel industry to rethink sprinkler use. Meanwhile building fire sprinklers had extensive research and testing and several NFPA standards cover their applications and installation (NFPA 13) and testing (NFPA 25). Currently only 16 of the 531 US tunnels have fire sprinklers.

**Sprinkler Density and Emergency Ventilation Systems (EVS)**

Concern regarding the interaction between fire sprinklers and EVS led 502 to request FHWA to sponsor research “FFFS and Emergency Ventilation Systems for Highway Tunnels - Literature Survey and Synthesis”, which produced following key findings:

- “For optimization of the EVS when FFFS is used, the additional airflow resistance introduced by the FFFS spray should be small with respect to other airflow resistance in the tunnel from items such as vehicles, wall friction, buoyancy, fire and external wind.” [9]
- “EVS should not cause excessive water droplet drift as to cause a negative effect on water droplet delivery to the fire zone…. This result shows that droplet drift downstream becomes more significant for smaller water drop sizes. Typical deluge system drop sizes are not affected too much. Operation of multiple FFFS zones might overcome issues with water droplet drift.” [9]
- “FFFS can have an enhancing effect on ventilation performance under longitudinal ventilation. The confinement velocity needed for longitudinal smoke control can be reduced with the use of the FFFS.” [9]

**Sprinkler Design Density** - Critically, 502 allows reduction in HRR for design purposes based on sprinkler engineering analysis, including: activation time (to full discharge), resilience, and reliability. But there is limited US guidance on specific sprinkler density in road tunnels which is a very consequential factor. NFPA 502 Table E.5 provides summary of ‘Major Research Programs with FFFS’ and includes good references. Research is also identified in 502 Annex O.5.

PIARC “FFFS in Road Tunnels”[14] provides density information from five countries with a range of 0.68 L/min (0.18 gpm/ft²) to 1.32 L/min (0.35 gpm/ft²) Australia has several tunnels with the majority featuring 1.47 L/min. (0.39 gpm). All of these countries use higher densities than is common in the US tunnels.

FHWA research synthesis on tunnel fire sprinklers has shown, “various small and full-scale tests indicate that a reduction in peak fire heat release rate (HRR) of 50 to 70% is likely (assuming prompt activation of the system and a water application rate of .57 to .76 L/min (0.15 to 0.20 gpm/ft² )”).[10]

Most importantly, “Comparatively low density .57 to .76 L/min (.15 to .20 gpm/ft² ) in the US likely explains why the FHWA synthesis uncovered such poor fire suppression results of peak HRR reduction of only 50 to 70%, i.e., significantly less suppression than expected of modern fire sprinklers.” [11]

As an alternative to using disparate test results to determine density (some of which did not achieve full suppression), 2019 Seattle SR 99 tunnel used density based on NFPA 13 ‘Installation of Sprinkler Systems’, which provide density for structures with similar fire loads, i.e., automobiles, heavy goods vehicles, etc. in an exhibition hall, for which Extra Ordinary Hazard Group II, with 1.32 L/min (.35 gpm/ft² ) is required. (Graph 1) However, exhibition hall larger and higher interior spaces result in a slower fire growth rate than tunnels as they lack comparable geometries, so even these densities might be inadequate.

---

Seattle 2019 SR 99 stacked tunnel uses 1.14 L/min (.30 gpm/ft²) which is a lower density requirement due to larger sprinkler zone simultaneous flow area. Note selection of this higher density only recognized potential of large, 200 MW ordinary combustible fire, as only illegal use of tunnel by DG would likely result in a fire greater than 200 MW as occurred in two tunnel flammable liquid fires exceeding 400 MW. Although Australia uses a density similar to NFPA 13 and Seattle SR99, more tunnel research is needed on densities to fit the actual fire loads in tunnel geometries including larger cross sections. At least one tunnel is planned without restrictions on DG, and four lanes wide which will provide more oxygen, thus likely producing potentially even greater fire sizes than heretofore measured.

**Graph 2 NFPA 13 Density with US Tunnel Density, SR 99, 13 Required, PIARC, AU**

**Sprinkler Cost** As few US tunnels are being built with fire sprinklers, cost information is either out of date, or not readily available. There are three construction options which affects cost. 1) Including sprinklers in original construction, least expensive, 2) retrofitting into existing structure, which necessitates modifications, adding control systems and water supply, i.e., increased costs, 3) Including water additives to improve firefighting for both Class A (flammable liquid fires) and Class B (ordinary combustibles) which adds costs offset by reductions in passive fire resistance, reduced ventilation needs and lower water sprinkler demand. Adding Class B or universal foam (A/B) to standpipes will improve effectiveness of fire hose lines.

At time of construction, 2.4 Km (1.7-mile) Eisenhower Johnson Colorado twin tunnels cost 24 M € ($25 M) for a retrofit i.e., 290 €/m² ($28 ft²) which included a new 757,000 L (200,000 gallon) reservoir for water supply. Presidio tunnel in San Francisco was 104 €/m² ($10/ft²). Other new tunnel sprinkler systems ranged from 125–166 €/m² ($12-$16 ft²).

**Water Additives to Suppress Flammable Liquid Fires** Since water alone in densities used in fire sprinklers is ineffective on suppressing FL fires, additives are carefully proportioned with water to achieve suppression and extinguishment. Additives use specific chemical formulas added to water to improve suppression and extinguishment of FL and others. These are discussed in NFPA 11 Standard for Low, Medium, and High Expansion Foam, and NFPA 30, Flammable and Combustible Liquids Code. Note the 2021 edition of NFPA 30 introduces and emphasizes the term “ignitible liquid” compared to “flammable and combustible liquid.” The terms “flammable and combustible liquid,” have been changed to “ignitible (flammable and combustible) liquid”. *This revision does not affect existing code requirements, only the nomenclature used to describe the liquids.* New language
emphasizes the use of Liquid Class (Class IA, IB, IC, II, IIIA, and IIIB), which are tied to closed cup flash points, or in the case of Class IA and IB liquids, are tied to both the closed cup flash point and the boiling point. The term “flammable liquid” is now defined as a Class I liquid and a “combustible liquid” is defined as a Class II or III liquid.

Water additives can also be used for Class A ‘ordinary combustibles’, i.e., burning tunnel cargo, and vehicles (not fuel). The most common FL additive, Aqueous Film Forming Foam (AFFF) was specifically formulated for Class B, flammable/combustible liquid fires, by the military and is widely used, but is less effective on Class A, ordinary combustible fires. Water additives must pass UL performance tests to obtain listings. Having a UL listing for an additive is necessary to satisfy fire code officials of their performance. Providing information on independent tests may not provide proof needed.

AFFF “… has been used as a fire-extinguishing medium for flammable and combustible liquids. Unlike other extinguishing agents - water, dry chemical, CO₂, etc., a stable aqueous foam can extinguish a flammable or combustible liquid fire by the mechanisms of either cooling, separating the flame/ignition source from the product surface, suppressing vapors and smothering. It can also secure for extended periods of time against reflash or reignition. Water, if used on a standard hydrocarbon fuel, is heavier than most of those liquids and if applied directly to the fuel surface, will sink to the bottom having little or no effect on extinguishment or vapor suppression. If the liquid fuel tank is heated above 212°F [100°C], the water may boil below the fuel surface throwing the fuel out of the contained area and spreading the fire. For this reason, foam is the primary fire-extinguishing agent for all potential hazards or areas where flammable liquids are transported, processed, stored, or used as an energy source.” [12] (also note, the direct application of firefighting hose streams into a tank whose liquid temperature is above 100°C, may result in a steam explosion which pushes the already heated liquid out of the tank and readily ignites into a fireball.)

Figure 7 Tunnel AFFF concentrate injection pumps, Figure 8 AFFF concentrate storage

Four US tunnels currently allow unrestricted passage of Dangerous Goods (DG) as they have deluge water sprinkler systems with the option to use AFFF. However, the AFFF foam solution cannot be mixed with water at the primary water pump and distributed via the long tunnel fire sprinkler supply pipes as this causes physical breakdown of the foam properties. Instead, costly separate pipes are added parallel to the combined fire sprinkler/standpipe is used along with injection pumps (Figure 7) which inject foam concentrate from storage tanks (Figure 8) to individual foam proportioning valves just in advance of the deluge zone valves. This system produces AFFF solution identical to that with proven fire suppression history used in the hundreds of thousands of non tunnel flammable liquid buildings handling flammable liquids.

Recently, Hughes Engineering and FPRF conducted life fire performance research tests, “Evaluation of Water Additives for Fire Control and Vapor Mitigation - Two and Three Dimensional Class B Fire Tests” with three types of flammable liquid additives with different suppression mechanisms of: disrupting fire tetrahedron, or encapsulating fuel, aqueous film
forming (described above). From these water additive fire test evaluations comes the following key statement: “Fire sprinklers can immediately respond to a fire while it is still small, controlling the spread of deadly heat, flames, and toxic smoke.” [13]

During tests, a newer formula water additive which disrupts the fire tetrahedron appears to outperform other FL suppression methods and uses a lower 0.5% instead of the 3% or 6% for AFFF. This additive achieved UL listing for Class A, B and D fires. This low concentrate requirement will likely allow use in a fire sprinkler supply pipe to deluge valves vs costly parallel foam concentrate pipe. **This relatively inexpensive addition to existing and future tunnel sprinkler system could very significantly change transportation of HM across those countries which consider installing deluge sprinkler systems by dramatically reducing transport times of bulk DG and reduce ‘risk transfer’ of dangerous goods to populated areas and sensitive waterways.** Specific research on this application is recommended. To the authors knowledge use of water additives in mist systems on a scale necessary to suppress bulk FL spill fires has not been undertaken in the US. There is one major US tunnel with mist, however, DG are banned in this tunnel.

AFFF formulas are being changed as they contain ‘per and polyfluoroalkyl’ substances (PFAs) which have proved to be environmentally damaging and harmful to humans. The replacements are receiving ongoing evaluations and UL listing approvals.

“Fire sprinklers are widely recognized as the single most effective method for fighting the spread of fires in their early stages – before the fire can cause severe injury to people and damage to property.” [14]

**US RESEARCH NEEDS – Sprinklers, 2023 US Research, Future Research Opportunities, Tunnel Safety Research**

**Sprinklers**

- **Optimal Sprinkler Water Density** - Tunnel ultra fast fire growth, fire loads producing extreme high heat release rates, tunnel geometry and shielding effects of HGV near sprinkler heads, might require different water density and sprinkler patterns than provided in NFPA 13. Therefore, research is needed to optimize density and sprinkler installations for inclusion in NFPA 13, and NFPA 502. In the interim, future tunnel sprinklers could adopt density from NFPA 13 equivalent fire loads to improve performance.

- **Dangerous Goods** - For Road tunnels which intend to allow HM, they can either follow current successful practice of installing a dedicated fire deluge sprinkler system with parallel water additive supply lines, OR incorporate water additives into sprinkler supply lines. If additives in supply line is considered, testing to ensure configuration and additive efficacy. Additive should be listed for both Class A and Class B fires as water additive sprinkler water will be applied to all combustibles by sprinklers or hose lines.

- **Water Additives Are Not All Equal** - Selection of additives using appropriate listings is important. Additional testing on additive could discern which additives meet tunnel specific requirements, of which low density, without PSAs, and Classes, i.e., A, B.

- **Structural Ceiling/Wall protection** - Fire sprinklers could be installed to both suppress the fire and directly wet and cool interior surfaces as is done in some buildings. Thus, preventing structural damage from large HGV fires with direct flame impingement on interior surfaces. This could reduce need for passive fire resistance. Modeling and/or testing to prove this is needed.

- **Legacy Ventilation System** - For tunnels with legacy ventilation, retroactively installing fire sprinklers could suppress fire size to a level where existing ventilation is adequate. Research is needed to discern specifics of varying legacy ventilation capacities, practicality, effects of sprinklers and costs.
• **Tunnel Operator and Firefighter Training** - Although many tunnels provide vigorous training and written guidelines for systems operations, fire sprinklers require special awareness and training which can enhance fire sprinkler effectiveness. There are no guidance documents on ‘Best Practices for Fire Sprinklers in Road Tunnels’. This could be achieved by a synthesis project garnering international sprinkler information and the effectiveness of sprinklers on various tunnel fire scenarios and interaction with responders.

• **Large Flammable liquid spills** - Although fires within zones should be suppressed by deluge sprinklers with additives, flammable liquids might spread outside the active zone(s). Research is needed to confirm limits of water additive to flow with the FL and suppress a fire beyond the fire deluge zone.

• **Water Mist** - Research is needed on effectiveness of mist systems on large flammable liquid spill fires within fire zones and if flammable liquids spreads beyond the zone.

• **Mobile Ventilation Units** - Are being used to induce longitudinal tunnel air flows; however, methods and effectiveness has not been researched.

• **Initiate Data Collection** - Lacking data on tunnel fires (cause, origin, and impacts) and fire system effectiveness in actual fires leaves designers to estimate effectiveness of sprinklers in actual conditions.

### 2023 US Tunnel Fire Research Projects

- **Final Results Pending** - FHWA ‘Evaluation of Integrated Design of Fixed Fire Fighting Systems and Emergency Ventilation Systems’. Literature syntheses and computer modeling complete, full-scale testing is pending

- **Approved awaiting research award** - Fire Protection Research Foundation (FPRF) initiated synthesis to examine ‘Emergency Egress and Rescue Challenges in Rail Tunnels’ based on varying exit distance in the standard and practical limits of firefighter air supply systems.

- **Pending funding approval** - AASHTO ‘Legacy Ventilation Systems and Modern Understanding of Tunnel Fires’

- **NPFA 130 Technical Committee address relative findings in FTA’s “Emergency Egress in Rail Transit Tunnels”**

- **Research proposal under development** - Tunnel Flammable liquid “Fire Suppression with Additives in Tunnel Sprinkler Supply Pipe”

### US Research Opportunities from Future US Tunnel Safety Challenges

- American Disability Act accommodation for evacuations may be required

- Multi modal rail tunnel use increases (combining dangerous goods and passenger trains)

- Higher density occupant loads (bus trains) in road tunnels will challenge existing tunnel egress capacities

- Alternate fuels for large HGV fires in tunnels create greater challenges than passenger vehicles. Newer water additives may be more effective at suppressing alternate fuel fires

- Wider tunnels (four lanes are planned) will increase volume of people to evacuate (potentially 3,000 in one km) which may necessitate increasing exiting capacities. Also a wider tunnel will provide more oxygen to a fire which could result in higher HRR

### US Research Recommendations Tunnel Safety

- Consolidate research safety recommendations for prioritization and funding

- Identify tunnel fire potentials and include in minimum regulations

- Establish US Tunnel Safety Assessment program

- Compare and adapt effective international best practices

- Develop US Tunnel Center of Excellence similar to several other countries

- Develop a national tunnel incident database to improve design, prevention, and response
• Identify tunnels with inadequate ventilation systems and either install FFFS or upgrade ventilation, potentially both as needed
• Identify reductions in passive fire resistance and systems resilience requirements with use of FFFS

SUMMARY

Early tunnel fire research left the US with many tunnels lacking adequate ventilation and no real means to prevent the larger fires (200 MW) possible with legal ordinary combustibles. Lack of fire sprinkler testing over the last few decades means considerable knowledge must be gathered through research and real-world experience. Soon there will be five US tunnels with foam deluge which works exceedingly well for suppressing flammable liquid fires in surface buildings which manufacture, process, store and handle flammable liquids. Several research needs are listed, and funding is difficult, but if we expect the US tunnel industry to meet the safety expectations of the public, cooperating in nationwide and international research is essential. In the meantime, the US has several research projects coming which should benefit the international community and we look forward to sharing results.

REFERENCES

[3] “Comparison of the U.S. and European Approaches to passenger Train Fire Safety”, Markos, Volpe National Transportation Center, USDOT pg. 1

Graphs
1) ‘Security and Safety of Rail Transit Tunnels’
   https://journals.sagepub.com/doi/full/10.1177/0361198118822819
2) NFPA 13, Standard for the Installation of Sprinkler Systems Density Table 19.3.3.1.1

Tables
1) “Emergency Egress in Rail Transit Tunnels”, FTA Report No. 0232. Table 4-1

Figures
1) https://i.redd.it/qxfsv0vrk551.jpg
5) https://www.youtube.com/watch?v=o0mU-H5vw1k 14:17 min
6) https://www.youtube.com/watch?v=xRlpuSBU_kQ 2:51 min
7) Author, Mt Baker AFFF injection pumps
8) Author, Mt Baker AFFF supply tanks
A known unknown concerning the road-based transport of dangerous goods

Christian Henrik & Alexander Kuran
University of Stavanger, Norway, Stavanger, Norway
E-mail: christian.h.kuran@uis.no

KEYWORDS: Dangerous Goods, Heavy Goods Vehicles, Adaptive Non-conform behaviour, Regulation, Empirical study

INTRODUCTION
The road-based transport of dangerous goods is heavily regulated, in both a Norwegian and international context. In Norway the Norwegian Directorate for Civil Protection is responsible for the quality of education and certification of safety advisers and for certificates which allows the individual drivers to transport dangerous goods. It is often assumed that rules and regulations in the Heavy Goods Transport (HGV) are usually followed (Njå et al., 2012), yet recent studies show that this is not the case (Kuran and Njå 2016, Kuran 2018). The extended abstract is based on longitude observational fieldwork from 2016 to 2020 (Kuran 2021a) in the HGV-sector. The empirical finding is through the lens of systems theory, (Leveson 2011) intended to challenge an assumption made in the risk management of tunnels in Norway. This assumption is that safety that rules and regulations pertaining to dangerous goods are not commonly broken and bent, constituting a known unknown in the risk analysis of tunnels.

METHOD
The data used in the study is based on ethnographic methodology using fieldwork in a sociotechnical system, the HGV-sector (Kuran 2021a). The presence of the researcher in the field as both observer and actor, together with informants over time allows for a gradually expanding informal exchange of knowledge and access to the day-today work of truck drivers, transport managers and forwarders. The time spent in the field gradually makes it possible for the researcher under various conditions to honestly discuss sensitive concepts of the transport of dangerous goods, both when rules and regulations are followed, and when they are not.

EMPIRICS
The results of the fieldwork indicate that in the Norwegian HGV-sector that:
1. That pieces of dangerous goods are often secretly transported with mixed cargo.
2. That drivers sometimes do not know the nature of the cargo they are transporting.
3. That there is speculation on behalf of transport buyers, camouflaging dangerous goods in attempts to reduce the cost of transport.
4. That the Norwegian public roads administration (NPRA) often does not find hidden pieces of dangerous goods in their routine controls.

There are especially three explanatory factors for this presented by informants in the study:
1. That the bending of rules and regulations are necessary to survive in the business.
2. That there is a divide between serious and unserious actors in the sectors.
3. That this divide in informed by the perspectives of the actors themselves.

DISCUSSION AND CONCLUSION
Since the Inspectors of the NPRA often do not find hidden pieces of dangerous goods in their routine controls it is reasonably easy to subvert the regulations pertaining to dangerous goods. A concept of
Adaptive non-conform Behaviour (ANB) can be used to explore why strict regulations might be routinely broken in the HGV-sector:

*The term adaptive non-conform behaviour cuts across all levels in the system and covers the outright violation of safety-related rules and regulations and activities that deviate from established good praxis. Non-conform behaviour can include strategic adaptations to external and internal socioeconomic pressures. Actors in the industry claim non-conform behaviour is a prominent characteristic of the day-to-day activities. (Kuran 2021b)*

The concept of ANB is used to situate the emic concept of rule-bending in an ethical and theoretical context of the sociotechnical systems of the HGV-sector. The systems theory perspective uses an approach to feedback and constraint in formalized hierarchies, (Rasmussen 1997, Leveson 2011), while also exploring that informal feedback loops exist (Kuran 2017).

The relevance of ANB for the risk management of tunnels are apparent. In Norway both the NPRA and Directive 2004/54/EC mandate the utilization of risk assessment to improve tunnel safety. In the national Guideline for the risk analysis of road tunnels (Norwegian Directorate of Public Roads 2007) the types of risk analysis recommended are Standard risk evaluation og detailed risk analysis depending on tunnel type, and that the transport of dangerous goods should be considered if it surpasses the normal or expected. The results of this study suggest that the bending of rules (ANB) in the sector pertaining to the transport of dangerous goods is so comprehensive that the idea of the normal is skewed, and that the presence of ANB in the sector at a systems theoretical problem represents a known unknown in risk analysis of tunnels, especially pertaining to tunnel fires.

This calls for an application of ANB in research in the HGV sector to provide more a more accurate picture of the transport of dangerous goods to inform risk analysis of tunnels.

REFERENCES

Case study on the ventilation design of the Kennedy Rail Link

Melchior Schepers¹, Wout Verborgt¹ & Xavier Deckers¹, Bart De Pauw²
¹Jensen Hughes
²Tuc Rail, Ghent, Belgium
E-mail: melchior.schepers@jensenhughes.com

KEYWORDS: Tunnel Fire, FDS, IDA, CFD, Evacuation, Ventilation

INTRODUCTION
The Kennedy tunnel is a combined road and rail tunnel that runs under the river Scheldt near the city of Antwerp. It is one of the busiest rail links in Belgium and an integral part of the rail network that connects the two major Belgian cities, Antwerp and Ghent. In 2009, a study was commissioned by the Belgian railways to study the preventive measures for the Antwerp Kennedy Connection as part of a broader Business Continuity Strategy. On this basis, a list of investment measures to be taken was proposed in 2009-2010. For the Kennedy rail tunnel several technical measures to be implemented with regards to fire safety were determined and included the installation of a completely new ventilation and evacuation system as well as a complete overhaul of all tunnel technical installations. In 2020 the renovation of the tunnel started and with most of the installations complete final acceptance tests are set to take place in 2023.

TUNNEL VENTILATION DESIGN AND FIRE SAFETY MEASURES

The tunnel ventilation system in the Kennedy Rail Link consists of four batteries of jet fans on each side of the tunnel in combination with a ventilation shaft midway along the tunnel which houses two axial fans capable of extracting 175m³/s each. The pre-design of the system was based on limiting the exposure time of travelers to smoke in the case that a fire would occur. Using IDA and FDS simulations a design for the system was developed.

To further aid evacuation a fully addressable public address system is installed alongside dynamic evacuation LED lighting built into the handrails. To study the interaction of these systems with the proposed ventilation scenarios a QRA analysis was undertaken in which the risk assessment methodology discussed in [1] was followed. The methodology consists of two sequential event trees. The first one leads to a critical event i.e. ‘Train stoppage in the tunnel due to or at the same time as a fire occurs’. This leads to a critical event frequency which serves as input to the second event tree, which then further elaborates the different consequence scenarios. The consequence modelling was performed via a coupling of pathfinder, FDS and IDA simulations which were coupled via an automated scripting procedure. This allowed to run more than 1200 evacuation scenarios in combination with the relevant fire and ventilation scenarios to obtain a detailed overview of potential fatalities. The end result of the analysis was an FN-curve for the overall tunnel. By varying both the ventilation regimes and the safety measures on the rolling stock itself the effect of the different ventilation regimes and measures on the FN-curve could be obtained. Figure 1A shows the outcome of such a sensitivity analysis for a variation in the amount of trains equipped with an automatic brake overrule. Figure 1B shows the relative importance of various events and to which degree they affect the occurrence of the critical event.
Figure 1: A) Sensitivity of the FN-curve to a percentage of the rolling stock being equipped with an automatic brake overrule. B) Relative importance of different events on the occurrence of the critical event.

TESTING AND COMMISSIONING

The testing and commissioning of the installed ventilation system is currently ongoing and is set to be finalised mid 2023. The tunnel has three different cross sections varying from square to round. In all of these sections cold flow tests have been performed with measurement locations being selected according to the modified log-Tchebycheff traverse pattern as described in NBN EN ISO 5802, shown in figure 2B for the round cross section. The anemometry units consisted of telescopic tripods which could be adjusted in height to suit the various tunnel cross sections, cf. figure 2A and C. Measurements were recorded using hot ball probes (thermal anemometers) and logged using dataloggers. The data acquisition was performed in sequence for every vertical chord, with every measurement taking at least three minutes to obtain steady state values. In addition to steady state measurements, transient measurements were also performed by means of start-up and die-down tests of the jet fans. During the die-down tests, all four jet fan batteries on one side were operated in unison. Once steady state conditions were achieved, all the fans were turned off until ambient conditions were reached again. From this data an equivalent wall roughness for the tunnel can be determined.

Figure 2: A) Jet Fans and wind measurement; B) log-Tchebycheff traverse pattern in the round section; C) telescopic anemometry tripod with thermal anemometers.

The measurement data is currently being processed to validate the 1D analyses performed in IDA Tunnel, with the steady state values showing good correspondence between the predicted values and the first measurements. Following the validation of the simulations via the measurement data the ventilation scenarios will be re-evaluated and adapted accordingly. The final commissioning of the TVS will happen via a real fire test.

REFERENCES

Computer aided resilience assessment

Kalliopi Anastassiadou¹, Ulrich Bergerhausen¹, Franziska Linstroem², Christoph Zulauf²
¹Federal Highway Research Institute (BASt), Bergisch Gladbach, Germany
²EBP Schweiz AG, Zürich, Switzerland
E-mail: bergerhausen@bast.de

KEYWORDS: Resilience, infrastructure assessment, cost-effectiveness of measures, resilience management, IT tool

INTRODUCTION

Dealing with disruptive events, such as a cyber-attack at a tunnel control center or a car accident with fire exposure inside a tunnel, is a major challenge for transport infrastructure owners and tunnel operators. To maintain the functionality of the transport infrastructure during disruptive events or to restore it as quickly as possible after such events, applicable concepts and methodologies are required, which enable a systematic assessment of the functionality of the road infrastructure [1]. Based on that, adequate measures can be identified and prioritized e.g. based on their cost-effectiveness. Therefore, a computer-aided resilience assessment tool for a practical implementation was developed to strengthen the resilience of a road system on a long-term basis.

METHODOLOGICAL CONCEPT FOR RESILIENCE ASSESSMENT

The user works out the regular planning of measures in his field of expertise (e.g., construction management, maintenance management or traffic management) for a network element or a road section and/or for specific infrastructure elements of such. Thus, the goal is that no separate investigation is required for the resilience assessment, but that it is embedded in existing management systems and their processes. If a network element or a road section is assessed from the perspective of the department, a supplementary resilience assessment is carried out with the help of the tool. In addition to the road, a road section can also contain structures such as tunnels, for which a resilience assessment is conducted.

1. Vulnerability analysis: The first step is to make a pragmatic assessment of the vulnerability of the road section and/or for specific infrastructure elements. This is based on an assessment of route-specific characteristics (e.g., traffic volume, capacity utilization, alternative access options, etc.) and an assessment of the exposure to hazards with regard to the guarantee of functionality (e.g., natural hazards, technical hazards, etc.).
2. Resilience screening: The aim of the second step is the overall examination of the resilience of a system in its current state, considering any measures already planned, as well as the identification of potential fields of action in which the system performance should be improved with regard to its resilience.
3. Assessment of measures: The identified potential measures are then assessed in terms of their resilience effect. Measures change either the frequency of occurrence of disruptive events or the impact.
4. Resilience optimization: Based on the determined resilience effect and considering a cost-effectiveness analysis of the individual measures [3], an aid to the decision maker a ranking list of prioritized measures or combinations of measures is drawn up that is optimal for the resilience of the system.

As a result, the resilience assessments yield a list of supplemental or adapted departmental measures that could be considered from the perspective of maintaining the function of the roadway segment and/or engineering constructions and an associated pragmatic rating.
IT TOOL AND USER GUIDE

The developed methodology concept was implemented in an IT tool. The tool allows users to pragmatically assess additional measures from a resilience perspective. It also allows for an assessment or ranking of their appropriateness in terms of an initial assessment. In order to show the user, the functionalities and the handling of the tool, a user guide was created. The user guide explains the most important functionalities of the tool by means of a short description and corresponding screenshots and illustrations and shows step by step how to use the IT tool. The following technical requirements for the IT tool were defined during interviews with experts and stakeholders. These are simple and pragmatic use, usability, compatibility and interfaces.

IMPLEMENTATION CONCEPT

With the implementation of the methodology in an application-oriented IT tool, the foundations are laid to be able to consider the issue of resilience of road sections or network elements of the road network in existing management systems and action planning in the future. However, this also requires a concept that supports the implementation of the developed resilience approach and the IT tool in practice. Ultimately, the concept and the tool will only add value and increase the resilience of transport systems if they are accepted and applied in practice. The three pillars include the following activities are communication and information, education and training and exchange of experience.

CONCLUSION

With this research, an important milestone for the integration of resilience assessment as a component of transport infrastructure management has been achieved and the foundation laid for transferring theoretical concepts from research to practice, so that decisions in infrastructure management to maintain the functionality of roads can be better prepared and measures or investments better justified in the future. In addition to the further development of the methodology, a web-based IT tool was developed. The IT tool is intended to help managers and owners of transport infrastructure to assess the resilience of their infrastructure. To facilitate the use of the IT tool, a user guide as well as an implementation concept were developed showing how the methodology and IT tool are to be applied in practice.

REFERENCES

1. Anastassiadou, Kalliopi; Bergerhausen, Ulrich; Roth, Franziska; Deublein, Markus (2020): Identification and prioritization of resilience measures for road infrastructures. In: Toni Lusikka (Hg.): Rethinking transport - towards clean and inclusive mobility. Proceedings of TRA2020, the 8th Transport Research Arena. Finnland: Finnish Transport and Communications Agency Traficom (Traficom research reports, 7 (2020)).
2. Deublein, Markus; Roth, Franziska; Bruns, Frank; Zulauf, Christoph (Hg.) (2021): Reaktions- und Wiederherstellungsprozess für die Straßeninfrastruktur nach disruptiven Ereignissen. = Response and recovery process for the road infrastructure after disruptive events. EBP Schweiz; Bundesanstalt für Straßenwesen; Wirtschaftsverlag N.W. Verlag für Neue Wissenschaft. Bremen: Fachverlag NW in der Carl Ed. Schünemann KG (Berichte der Bundesanstalt für Straßenwesen B, Brücken- und Ingenieurbau, Heft 165)
3. Deublein, Markus; Roth, Franziska; Bruns, Frank; Zulauf, Christoph (Hg.) (2020): Stand der Technik hinsichtlich der Bewertung von Resilienzmaßnahmen = State of the art regarding the evaluation of resilience measures. EBP Schweiz; Bundesanstalt für Straßenwesen (Report in the context of the BASSt road infrastructure research program FE 89.0320/2016).
Using existing Radar infrastructure for tunnel safety management and emergency response

Sebastian Baucutt, Ozair Baig
Navtech Radar, Wantage, UK
E-mail: sebastian.baucutt@navtechradar.com

KEYWORDS: Radar, Stopped Vehicle Detection, Smoke Diving, Situational Awareness, Systems Engineering

INTRODUCTION

Road tunnel fire safety usually involves high uncertainty and high-stakes decisions. Using familiar systems in the event of an emergency is a key part of minimising risk and increasing confidence in decision making. This speed of response is increased further by ensuring that systems are accessible remotely before arriving at an incident. By improving early awareness within in an incident it is possible to reduce the impact and save lives.

Using existing ITS radar technology for stopped vehicle detection in the event of an incident can maximise the information available to emergency services, improving emergency preparedness. This consists of two key benefits, the first being the ability of radar to ‘see’ through fog, smoke, fire and still accurately detect vehicle and pedestrian positions. When compared to traditional CCTV and thermal cameras, six minutes into a controlled fire exercise in a tunnel, the control centre has no visibility of the situation.

The second benefit is to provide operators and emergency services with a remotely accessible visual map of an incident. Each vehicle and pedestrian is detected, tracked, and identified. When an incident occurs, this situational awareness solution transmits the tracked information in real time, directly to the tunnel operators. By reducing the reliance on in-tunnel operatives and emergency telephone users this enables a smoother, faster, and safer response – minimising casualties, risk to emergency services, and response time.

BACKGROUND

Stopped vehicles in live lanes are a recognised problem on road networks worldwide. Anywhere that a vehicle stops amongst moving traffic there is a high risk of a secondary incident. This problem is increased in areas where there is nowhere for a driver with a known problem to move to safety before the vehicle stops. Examples of this can include in roads with no hard shoulder, including tunnels, and in roadworks. In these situations, response time to the initial stop is critical, to either stop traffic approaching the stopped vehicle or to remove the vehicle.
For these reasons, stopped vehicle detection is becoming increasingly commonplace on roads that face this restriction. Examples include on the All Lane Running sections of the UK Strategic Road network[1], in extreme weather in Sweden[2] and in road tunnels worldwide, including Switzerland and Norway[3].

The most common types of stopped vehicle detection are either radar or video based. These solutions provide alarms into the relevant road control centre (RCC), to allow road operators to make the type of rapid response detailed above.

INNOVATION FOR EMERGENCY SERVICES

It is considered that the presence of Navtech Radars Emergency Situation Awareness system in major tunnels will address many of the issues highlighted. Continuous understanding of an incident regardless of conditions gives both emergency services and road operators situational awareness of any incident.

This live time information allows smoke divers to rapidly move forward in tunnels safely, maximising the ability to get people out of harm’s way. In complex situations where there is no clear ventilation strategy that will be key to ensuring the best outcome for people within the tunnel.

Furthermore, by replaying the track information leading up to an incident, the likely cause can be established, ensuring that it is known (for example) how many vehicles are involved in a crash. Again, the benefits for the emergency response teams is to remove uncertainty or ambiguity over who and what were present in the tunnel at the time of an incident.

Whilst this system cannot prevent incidents occurring, it is expected that there will be significant time savings for response seen, and in turn the outcomes for people involved in major tunnel incidents will dramatically increase. The emergency responders are no longer reliant on information being given from the tunnel, through an emergency contact phone to the VTS and then to the respondents – instead there is a direct picture given to the people who are taking action.

Testing has taken place alongside thermal cameras and CCTV cameras to benchmark relative performance in smoke and fire. This has given real time information to emergency services, allowing faster understanding and reaction to evolving situations.

DISCUSSION

With two upcoming major installations, a full discussion of the benefits and limitations of detection methods, alongside evidence from live testing of radar-based systems in Norwegian tunnels shall be presented. These will allow qualitative feedback from both road operators and emergency services, and ensure that this is not a one time project but a key response to the request from the Accident Investigation Board Norway for technology to allow faster response by emergency services in fire.

3 Jensen, ‘WHY RADAR IS THE PREFERRED TUNNEL INCIDENT DETECTION SYSTEM IN THE RENNFAST TUNNELS’.
Computational Assessment of Critical Velocity Criteria in Rail Tunnels

Janaya Walter, Sonia Taylor, Adrian Milford, & Samson Li
Arcadis IBI Group, Vancouver BC, Canada
E-mail: janaya.walter@ibigroup.com

KEYWORD: critical velocity, train fires, tunnel ventilation, smoke control, fire safety

INTRODUCTION
In the event of a rapid transit/passenger train fire within a tunnel, a longitudinal ventilation strategy is commonly adopted to provide a tenable egress route towards the nearest exit, station, or cross-passage that is upwind of the fire location. Insufficient ventilation capacity results in smoke propagation against the intended ventilation direction and into the path of egress, known as backlayering. In the context of NFPA 130 [1] critical velocity is defined as the minimum ventilation velocity necessary to control backlayering and maintain a tenable environment along the path of egress upwind of the fire, and is an important criterion in tunnel ventilation system design. Underestimation of the critical velocity would have implications on the safety of tunnel ventilation in rail systems, while overestimation could result in unnecessary increases in design complexity and cost of construction and long-term operation.

Critical velocity is influenced by a number of parameters, including the geometry of the tunnel, heat release rate, fire intensity/distribution along the length of the tunnel, and interaction with surrounding obstructions. Multiple equations have been developed to estimate critical velocity. The methodology proposed by Kennedy [2] (the “Kennedy equations”) is commonly applied in rail tunnel ventilation design and is included in the Subway Environment Simulation analysis software documentation [3], as well as in the annex material of NFPA 502 prior to the 2017 edition. The 2017 and the 2020 editions of NFPA 502 [4] have revised the critical velocity methodology (however the 2020 changes were recently redacted in a tentative interim amendment [5]). The updated equations correspond with substantial increases in critical velocity for the range of design fires applicable for rapid transit and subway projects. These changes have raised questions about the suitability of previous critical velocity calculations and if there is a need to adopt the more stringent values from the updated 2017/2020 NFPA 502 equations for rail tunnel ventilation analysis [6,7,8,9].

The influence of the blockage ratio/tunnel height inherent to common bored rail tunnel configurations (single bore vs twin bore) on critical velocity for train fires has not been extensively studied. In this study, CFD analysis is used to examine the influence of the tunnel configuration on critical velocity and to compare the predicted behaviour with the critical velocity equations discussed above.

MODEL
Using Fire Dynamics Simulator v6.7.9, CFD simulations were performed to assess the extent of backlayering within two tunnel configurations, shown on the right: a) single bore tunnel with a dividing wall (low blockage ratio) and b) twin bore tunnel (high blockage ratio). A six-car, interconnected gangway train is positioned in the centre of the tunnel and a 10 MW fire (assuming 100% convective heat release) is positioned in the third, upwind car. All train doors along the safety walkway side are open and the window glass in the incident car are assumed to have broken and fallen away.

A velocity inlet boundary condition is positioned ten hydraulic diameters from the front of the train. A distance of fifteen and twenty hydraulic diameters was also assessed to ensure no dependency on the inlet positioning; minimal difference was noted between
the three distances. A mesh sensitivity study was also performed with 0.2 and 0.1 m mesh resolution. The resulting flow behaviour in and around the train were in close agreement between the two meshes, but the 0.1 m mesh yielded $y+$ values less than 30 which falls outside the range applicable for the near wall treatment that is applied in the model [10]. Therefore, a 0.2 m mesh resolution was adopted.

The critical velocity for each tunnel configuration was calculated using Annex D equations from the 2014, 2017, and 2020 editions of NFPA 502. The 2014 and 2017 methods were calculated using the annulus area around the train whereas the 2020 method is dependant on the height and width of the tunnel rather than annular area around the train. The calculated critical velocity values summarized in the table on the right represent the corresponding average upwind velocity (full tunnel area) for the inlet boundary condition.

RESULTS AND DISCUSSION

The graphs presented below plot the steady-state air temperature, averaged over 200 s, at the tunnel ceiling along the length of the tunnel. The furthest upwind point of the fire is positioned at 0 m; elevated temperatures to the left of this point (negative position values) indicates the presence of backlayering.

For the single bore tunnel, the 2014 critical velocity (1.56 m/s) is sufficient to prevent backlayering, and controlled backlayering is observed for the case with 1.20 m/s upstream air velocity. The backlayering in the 1.20 m/s case is concentrated to the crown of the tunnel; the tenability of the egress path upstream of the fire is not impacted as the temperature remains at ambient at a height of 2.0 m above the safety walkway and there is no smoke at occupant height. Compared with the CFD results, the 2017 and 2020 calculations (2.34 m/s and 2.82 m/s respectively) overestimate critical velocity substantially.

The twin bore tunnel, with a higher blockage ratio and lower tunnel height than the single bore tunnel, exhibits greater backlayering sensitivity over the range of air velocities examined. The 2014 critical velocity (1.10 m/s) exhibits controlled backlayering, extending approximately 25 m along the crown of the tunnel from the upwind end of the fire. Temperatures along the egress path at a height of 2.00 m above the safety walkway is maintained at tenable levels beyond approximately 3.5 m from the upwind end of the fire and the egress path is maintained free of smoke beyond approximately 15 m upwind of the fire. In this case, the 2014 critical velocity is sufficient for maintaining the tenability of the egress path. Backlayering is prevented completely with an air velocity of 1.30 m/s, well below the 2017 and 2020 critical velocity values (1.70 m/s and 2.84 m/s respectively).

<table>
<thead>
<tr>
<th>NFPA 502 Revision</th>
<th>Single Bore (m/s)</th>
<th>Twin Bore (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>1.56</td>
<td>1.10</td>
</tr>
<tr>
<td>2017</td>
<td>2.34</td>
<td>1.70</td>
</tr>
<tr>
<td>2020</td>
<td>2.82</td>
<td>2.84</td>
</tr>
</tbody>
</table>
CONCLUSIONS

The configuration of rail tunnels, specifically the tunnel height and blockage ratio, has an impact on critical velocity and on the corresponding level of conservatism of the 2014, 2017, and 2020 critical velocity equations presented in Annex D of NFPA 502, especially when evaluated relative to egress path tenability in accordance with the NFPA 130 definition of critical velocity and not solely on the onset of backlayering at the crown of the tunnel.

For the single bore tunnel with dividing wall investigated in this study, the simulation results indicate that the 2014 NFPA 502 critical velocity calculation (Kennedy equations) provides a conservative estimate of critical velocity, and the egress path (evaluated at a height of 2.0 m above the safety walkway) is maintained free of smoke and at ambient temperature with tunnel airflow that is approximately 25% lower than the 2014 value. The 2017 and 2020 NFPA 502 equations substantially overpredict the airflow needed to prevent backlayering, and more importantly to achieve egress route tenability.

The twin bore tunnel, with a higher blockage ratio and smaller tunnel height above the train, exhibits some backlayering for the 2014 critical velocity value, although the egress path is maintained tenable from a short distance from the upwind end of the fire which satisfies the fundamental objective of facilitating safe occupant egress. The conservatism observed in the 2014 calculation of critical velocity for the single bore tunnel configuration is not observed for the twin bore configuration, where the calculated airflow instead corresponds to maintaining a tenable egress path with controlled backlayering. Airflow approximately 18% higher than the 2014 NFPA 502 equation was needed to prevent backlayering entirely. Similar to the single bore tunnel configuration, the 2017 and 2020 NFPA 502 equations provide a significant overprediction of the airflow needed to maintain egress route tenability.

REFERENCES

Smart dynamic exit sign system for tunnel fire evacuation: A lab-scale demonstration

Ho Yin Wong, Xiaoning Zhang, Meng Wang & Xinyan Huang
The Hong Kong Polytechnic University
11 Yuk Choi Rd., Hung Hom, Kowloon, Hong Kong
E-mail: xiaon.zhang@connect.polyu.hk

KEYWORDS: Tunnel fires, Dynamic exit signs, Internet of things, Smart evacuation

INTRODUCTION

In case of a fire, the exit sign system aims to guide occupants to leave the confined built environment or reach the refuge floor as soon as possible. However, conventional exit signs may not be clear enough to draw occupants’ attention in an emergency [1,2]. Owing to low conspicuousness, occupants normally choose escape routes by mere instinct, which may leads them to dangerous locations with dense smoke and heat. This not only delays the overall evacuation process, but also wastes precious egress time. Many occupants will inhale too much toxic gas while they are walking via undesirable egress routes. Thus, the true effectiveness of using traditional exit signs in fire evacuation is questionable [3]. This study proposes a smart dynamic exit sign system for a 2-D tunnel environment that can facilitate fire evacuation and prevent people from walking into danger in a fire outbreak. We use a laboratory tunnel mock-up of 170 cm long (i.e., 1:50 reduced scale) [4] to demonstrate this new exit sign system.

Figure 6 Overview of the smart dynamic exit sign system

FRAMEWORK OF SYSTEM

The dynamic exit sign system is developed for evacuation in tunnel during fire events. The schematic diagram of the proposed system is shown in Figure 1. In the physical tunnel, temperature sensors are
pre-install on the ceiling of the tunnel to collect the real-time temperature data. During the fire, the collected data are sent to the cloud data centre through the wireless network. The data can be processed to get the fire information (e.g., fire location and fire size), and then the real-time fire information can be rendered and displayed on a user interface. Besides, the dynamic exit signs are pre-installed on the tunnel wall. During a fire, the flashing patterns of each dynamic exit sign will be controlled by the pre-set algorithm according to the fire location.

**REDUCED-SCALE DEMONSTRATION**

In this study, mini dynamic exit signs are manufactured by the 3D printing method with the LEDs displayed inside each sign. The sensors adopted are thermocouples which are installed inside the tunnel to record the temperature profile. A propanol pool fire is set to simulate a vehicle fire, and it can be moved along the tunnel during the demonstration. When the fire changes its location, the sensors receive instant temperature data that are then sent to the cloud data centre. After the cloud data centre receives the temperature data, the mini dynamic exit signs show a dissuasive pattern (the red cross) towards the fire source and show a persuasive pattern (the green arrow) away from the fire source. A demonstration of the small-scale tunnel dynamic exit sign system is shown in Figure 2.

![Figure 2](image)

*Figure 2  Demonstration of dynamic exit sign system in a small-scale tunnel*

With the real-time data collected from the small-scale tunnel, the cloud data centre computes and identifies the fire location [4]. Hence, the digital tunnel model with fire information can be rendered and displayed on the user interface and responds to the changes instantly. Besides the fire location, the real-time display of each dynamic exit sign can also be visualized on the user interface.

**FUTURE WORK**

Currently, the system is under further development. The goals of this smart tunnel exit sign system are to (1) define principles for the accurate control of each exit sign and provide reliable evacuation guidance for various tunnel fire scenarios, (2) display useful data of the hardware on the user interface, including the temperature of sensors, battery condition of dynamic exit signs and some generated graphs; and (3) improve the system resilience, e.g. manually control the signage status on the user interface in case of partial system failure. Eventually, this smart dynamic exit sign system will be demonstrated for fires in real-scale tunnels and other built environments, where the system will be controlled by real-time sensor data and the artificial intelligence algorithm.

**REFERENCES**

Initial airflow conditions for fire scenarios based on traffic parameters

Jakub Bielawski¹, Wojciech Węgrzyński¹, Aleksander Król² & Małgorzata Król²
¹Building Research Institute, Warsaw, Poland
²Silesian University of Technology, Gliwice, Poland
E-mail: j.bielawski@itb.pl

KEYWORDS: airflow, piston effect, vehicle movement, wind effect

INTRODUCTION

This study focuses on the piston effect of vehicle traffic on tunnel airflow and how traffic management can affect the optimization of the longitudinal ventilation system performance. The observations and conclusions are based on measurements from a tunnel under one of the limbs of the Martwa Wisła river in Gdańsk, Poland.

THEORETICAL APPROACH

The velocity and direction of airflow in the longitudinally-ventilated tunnel in case of fire could be determined using a theoretical pressure model derived from the Bernoulli equation. This model is based on the general flow theory for steady-state one-dimensional turbulent duct flow [1]. However, prior to the fire, airflow mainly depends on the wind conditions, air resistance at portals, friction along the tunnel, and traffic conditions, according to equation 1.

\[ \Delta p_{\text{wind}} + \Delta p_{\text{veh}} = \Delta p_{\text{in}} + \Delta p_{\text{out}} + \Delta p_{D-W} \]  

The movement of vehicles transfers momentum to the air and can alter the longitudinal airflow velocity induced by wind. This phenomenon of momentum transfer from a moving object is called the piston effect. Comprehensive modeling of the piston effect requires accounting for many factors, but even a simplified approach can lead to meaningful and practical results. A method to determine the pressure jump that appears at the front of a moving vehicle based on vehicle velocity, relative to air velocity was proposed [2]. The pressure equilibrium from the previous study [3] can be written with the equation with additional terms, according to equation 2.

\[ \frac{1}{2} \rho C_d u_{wind}^2 + \frac{1}{2} n A_p c_x \rho (u_{veh} - u_{air})^2 = \xi_{in} \frac{1}{2} \rho u_{air}^2 + \xi_{out} \frac{1}{2} \rho u_{air}^2 + \lambda \frac{\rho L u_{air}^2 A_t}{2D_h} \]  

WIND EFFECT

In previous work [3], wind-induced pressure was determined as a function of the angle of attack (AOA) and velocity refers to the portals using CFD simulations. The obtained values are shown in Figure 1. A wind flows with an angle of attack in the range of 0° to ± 60° has the greatest values of pressure induction to the tunnel tubes, while an angle of attack in the range of 90° to 270°, has no significant effect. It should be emphasized that the discharge coefficient \( C_d \) of portals depends on the wind AOA.

![Figure 1. Pressure induced by the wind at tunnel portals [3]](image-url)
TRAFFIC PARAMETERS
Traffic conditions in the tunnel were described as quantitative parameters. The number of vehicles causing the pressure jump in the tunnel was estimated from the traffic intensity (vehicles entering the tunnel per hour) and average vehicles velocity. Traffic conditions depend on many factors such as lane distribution, vehicle distance, blockage ratio, vehicle speed and share of large-scale vehicles. Liang et al. presented the influence of individual factors based on CFD analyses [2].

DISCUSSION
A series of calculations were carried out for wind scenarios with constant an angle of attack equals 0° and a reference velocity ranging from 3 m/s to 15 m/s in comparison to traffic conditions with the velocity of passenger vehicles ranging from 60 km/h to 100 km/h and traffic intensity ranging from 0 to 1600 vehicles entering the portal per hour. The results obtained for the leeward and windward tubes are shown in Figure 2.

It was concluded that the wind has no significant effect on the airflow in the tunnel under the conditions considered with the traffic present. The effect of external atmospheric conditions on backflow force can only be observed at low traffic intensity. However, just 38 passenger vehicles entering the portal per hour moving at 60 km/h could offset the pressure caused by a worst-case wind scenario. The airflow in the normal operating mode (pre-fire) depends mainly on the traffic conditions, which can be regulated by e.g. changing the speed limit, blocking lanes, or banning HGVs. Based on this study, it is recommended to initialize the CFD simulations with the flow due to traffic conditions. Considering initial tunnel airflow caused by the movement of vehicles can improve the performance of the longitudinal ventilation system and prevent backlayering in the first minutes of a tunnel fire. The influence of wind in the later stages of fire development will be considered in future work.

REFERENCES
A study on the smoke proof test of a positive pressure deployable evacuation passage for subway stairs

Duckhee Lee, Won-Hee Park, Joo-Young Jung, Tae-sun Kwon
Korea Railroad Research Institute
176, Railroad Museum St., Uiwang-si, Gyeonggi-do 16105, Korea
E-mail: dhllee27@krri.re.kr

KEYWORDS: Deployable escape passage, smoke proof, positive air pressure

INTRODUCTION
Inhalation of toxic fumes is the direct cause of casualties, accounting for most of the casualties from fires. In particular, in the case of the stairway that serves as a passage between floors, it is a section where many casualties occur because it is often a passage through which smoke moves and also an evacuation route through which evacuees move. This study is to introduce the deployable evacuation passage installed in the stairway and introduce the performance evaluation performed in the pilot installation section.

SMOKE PROOF PERFORMANCE TEST SETTINGS
A pilot deployable evacuation passages were installed in the connecting stairs from the waiting room at the subway station to the ground level. Smoke proof performance test was conducted and the smoke was generated with a smoke generator (ViCount 5000, 2kW made in UK) on the waiting room floor at the lower end of the stairs, and approximately 300kW heat buoyancy was added using a hot air blower(TK-30K, made in S.Korea). The generated smoke naturally flow out through the stairs due to heat buoyancy. The evacuation passage was operated and the smoke density was measured based on the light transmittance of the outside and inside at the same time. The smoke concentration detector at the measuring point was set at the height of 1.5m from the floor.

![Figure 1 Pilot Installation of deployable evacuation passage at subway stairs](image)

TEST RESULTS
The evacuation passage installed in this study was 17.6 m long, 1 m wide and 1.7m high, and a ring blower of thrust 360 mm Aq. 10 m³/min volumetric flow at operating pressure 352 mm Aq. was also installed at the ground level 20m away from the stair entrance to supply relatively positive pressure in the passage. The lower part of the passage had an automatic end door, but the upper part was just fully opened, and the test was conducted in a state of insufficient sealing due to the gap between the screens.
of the four different units constituting the passage structure and the step at the bottom of the stairs. The pressure difference was not measurable because many part of the passage was opened to outside. The optical transmission intensity was measured at inside and outside passage simultaneously for smoke density (smoke concentration) calculation at three different positions with optical sensors and He-Ne laser light sources. The optical light extinction method based on Bouguer’s law was applied to estimate smoke density. And the smoke proof ratio was calculated by deviding the difference of smoke density inside and outside of the passage by the outside value. As a result of the test, the averaged smoke proof ratio of three points was evaluated as 90.7%. The optical smoke density of the most upper part of three positions is shown in figure 3. The smoke proof ratio is, of course, a variable of the pressure difference between the inside and outside of the passage. The next study is plan to be conducted with more developed deployable passage structures in complete sealing.

![Figure 2 Smoke density measurements at the Upper part of stairs and in the passage](image)

**Figure 2 Smoke density measurements at the Upper part of stairs and in the passage**

![Figure 3 Smoke density measurements through the stairs and evacuation passage](image)

**Figure 3 Smoke density measurements through the stairs and evacuation passage**

**REFERENCES**


Smoke ventilation tests for multipath subway lines using reduced scale tunnel and station model

Won-Hee Park, Yoiung-min Cho, Su-whan Youn, Tae-sun Kwon, Duckhee Lee
Korea Railroad Research Institute
176, Railroad Museum St., Uiwang-si, Gyeonggi-do 16105, Korea
E-mail: whpark@krri.re.kr

KEYWORDS: Fire spalling, polypropylene fibres, thermal properties, mechanical properties, pressure measurements

INTRODUCTION

In Korea, in the case of a tunnel with an extension of 10 km or longer, a model test on the operation mode of the smoke control and ventilation facilities in emergency is performed through a scale model test before construction, and the result is reflected in the design result to be supplemented and then constructed [1]. In this study, we tried to verify the performance of the installed smoke control system by conducting a scale model experiment on the Sinansan Line, which requires a smoke control system with an extension of more than 40 km in the tunnel section.

Figure 1 Experimental set-up.Diagram of ventilation facilities for studied tunnels and stations

REDUCED-SCALE MODEL TUNNELS

The Shinansan Line, a double-track tunnel, has a unique structure that connects the Wolgot-Pangyo Line, a double-track tunnel, with a direct connection, a single-track tunnel. In this study, as shown in
Figure 1, the area where the two routes meet was selected as the area of interest. The Shinansan Line, the Wolgyo-Pangyopan Line, the direct tunnel and the section including the Gwangmyeong Station (Shinansan Line platform, Wolpan Line platform), around 8 km of the Shinansan Line main line, and around 8km of the main Wolpan Line were made into miniature models. A model of 1 formation of 3 cars (total length 60m) and 1 formation of 6 cars (total length of 120m) were produced based on froude scale law[2].

FIRE TESTS

For eight scenarios assuming that a 20 MW fire occurred, which is a condition in which one train in the tunnel was burned down, it was confirmed whether smoke removal and exhaustion could be properly performed during operation of the smoke control system. As a result of measuring the critical velocity, it was 2.2 m/s for the double-track tunnel (height of 7.1 m) and 2.0 m/s for the single-track tunnel (height of 6.9 m). In order to simulate the fire buoyancy of the scale model, it was reduced to 1/50 used a methanol fire source, and measured the critical speed in a miniature railway tunnel using a smoke cartridge for smoke visualization and details such as the location of the fire source have been described in the paper[3]. It was lower than 2.5 m/s, which is the standard critical velocity for smoke control performance used as a standard in Korea. In addition, as a result of operating the smoke control and exhaust facilities in the ventilation operation mode in the tunnel model for each scenario, the ventilation air velocity was measured at 2.5 m/s or higher in all scenarios. In addition, it was confirmed that backflow did not occur in the results of the visualization experiment to confirm the smoke movement direction, and through this, it was judged that the capacity and operation mode of the smoke control and exhaust system of this tunnel were appropriate. Figure 2 shows the behavior of smoke in two cases where the smoke control direction is different when the fire train is stopped in the tunnel of the Wolpan Line.

![Figure 2 Control of smoke emitted the fire at railcar located on Wolpan Line](image)

REFERENCES

Generation of carbon monoxide in fires partially suppressed by water sprays

Haydn Lewis\(^1\) & Nils Johansson\(^2\)

\(^1\) Jensen Hughes Pty Limited, Sydney, Australia
\(^2\) Division of Fire Safety Engineering, Lund University, Lund, Sweden

Email: Haydn.Lewis@jensenhughes.com

KEYWORDS: Carbon monoxide, fire suppression, combustion, toxicity, shielded fire

INTRODUCTION

Fires occurring within the built environment constitute diffusion flames. The diffused region of combustion results in inefficient mixing of fuel and oxygen, resulting in a proportion of by-products being produced. Within the built environment approximately two-thirds of fire related fatalities are a result of carbon monoxide (CO) inhalation [1]. The current available data and performance-based design approaches utilise ventilation conditions as the driving factor responsible for the species yields to be applied within an analysis. The influence that suppression systems have on combustion chemistry are not currently considered and therefore the potential fraction of toxic species within combustion gases may be underestimated. Deluge and mist suppression systems are increasingly prevalent within new tunnel infrastructure works or as an upgrade to existing assets. The suppression of fire by water sprays is a complex physio-chemical process, involving a number of competing mechanisms, all of which have not yet been fully understood. Water droplets interrupt combustion through six physical and chemical mechanisms; cooling, inerting, thermal radiation attenuation, inhibiting, blanketing and flame blow-off [2]. Existing literature has primarily focused on the mechanisms associated with the effects of water sprays on extinction and reduction of HRR of fires with limited investigation of the effects on species production. Some high-level results showed a short duration peak in CO upon suppression followed by a reduction with decreasing HRR [3]. The aim of this study was to assess the factors that influence CO production when water sprays partially suppress fires to allow fire safety engineers to conduct their assessments within tunnel projects with a greater level of understanding of the environmental conditions which may be produced. It is not the intention of this study to oppose the use of fire suppression systems.

EXPERIMENTAL METHOD

An experimental setup was configured to enable the analysis of droplets interacting within the flame whilst minimising the impacts of suppression on HRR. Tests were performed with various water droplet sizes (\(D_{50}: 103-287 \, \mu m\)), water flow rates (0.37-1.01 L/min), fuel types (heptane and propane), HRRs (40-80 kW), and both full cone and hollow cone sprays. The set of experiments undertaken are detailed within Figure 1. Tests were undertaken beneath an oxygen consumption calorimetry hood and the quantity of water not interacting with the flame measured.

RESULTS AND DISCUSSION

This study has shown that the levels of CO present within a fire environment can increase significantly upon water suppression where the suppression does not act to significantly reduce HRR, as may be the case within a shielded fire scenario. Figure 1 shows the CO concentrations recorded during a period of free-burning, baseline readings and how these readings change upon activation of water suppression. It’s noted that the increased variability in CO values when water sprays are applied is a result of the complex interaction of momentum flows of both the water spray and flame. In an attempt to consider how these interaction volumes vary between each test, the quantity of water vaporised within each test was recorded.

A variable analysis was performed illustrating that the key factor in CO generation within suppression is the rate of droplets which interact with the flame. All the individual variables of this study
influenced the size and shape of the interaction volume. Smaller droplets featuring more efficient heat and mass transfer, as well as being more chemically inerting, were shown to result in significantly greater levels of CO being recorded.

It was observed that when the other variables were kept stable, tests undertaken with heptane produced much greater concentrations of CO when water suppression was applied when compared to the propane tests. This suggests that fuels with a natural tendency to generate CO as a combustion by-product are more likely to be more influenced by the combustion inhibiting mechanisms of suppression. Upon activation of suppression, the volume fraction of CO recorded increases significantly. It is acknowledged that properly designed suppression systems are likely to significantly reduce the HRR of a fire and in turn, reduce the amount of fuel molecules undergoing combustion. However, in the event of ineffective suppression scenarios such as shielded vehicle fires, the toxicity levels within the tunnel environment could be significantly underestimated.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Fuel</th>
<th>HRR</th>
<th>Nozzle</th>
<th>Pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>C₇H₁₆</td>
<td>High</td>
<td>Full</td>
<td>1.5</td>
</tr>
<tr>
<td>T2</td>
<td>C₇H₁₆</td>
<td>High</td>
<td>Full</td>
<td>2</td>
</tr>
<tr>
<td>T3</td>
<td>C₇H₁₆</td>
<td>High</td>
<td>Full</td>
<td>3</td>
</tr>
<tr>
<td>T4</td>
<td>C₇H₁₆</td>
<td>High</td>
<td>Hollow</td>
<td>1.5</td>
</tr>
<tr>
<td>T5</td>
<td>C₇H₁₆</td>
<td>High</td>
<td>Hollow</td>
<td>2</td>
</tr>
<tr>
<td>T6</td>
<td>C₇H₁₆</td>
<td>High</td>
<td>Hollow</td>
<td>3</td>
</tr>
<tr>
<td>T7</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Full</td>
<td>1.5</td>
</tr>
<tr>
<td>T8</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Full</td>
<td>2</td>
</tr>
<tr>
<td>T9</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Full</td>
<td>3</td>
</tr>
<tr>
<td>T10</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Hollow</td>
<td>1.5</td>
</tr>
<tr>
<td>T11</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Hollow</td>
<td>2</td>
</tr>
<tr>
<td>T12</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Hollow</td>
<td>3</td>
</tr>
<tr>
<td>T13</td>
<td>C₇H₁₆</td>
<td>High</td>
<td>Full</td>
<td>1.5</td>
</tr>
<tr>
<td>T14</td>
<td>C₇H₁₆</td>
<td>High</td>
<td>Full</td>
<td>2</td>
</tr>
<tr>
<td>T15</td>
<td>C₇H₁₆</td>
<td>High</td>
<td>Full</td>
<td>3</td>
</tr>
<tr>
<td>T16</td>
<td>C₇H₁₆</td>
<td>High</td>
<td>Hollow</td>
<td>1.5</td>
</tr>
<tr>
<td>T17</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Full</td>
<td>2</td>
</tr>
<tr>
<td>T18</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Hollow</td>
<td>3</td>
</tr>
<tr>
<td>T19</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Full</td>
<td>1.5</td>
</tr>
<tr>
<td>T20</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Full</td>
<td>3</td>
</tr>
<tr>
<td>T21</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Hollow</td>
<td>1.5</td>
</tr>
<tr>
<td>T22</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Hollow</td>
<td>2</td>
</tr>
<tr>
<td>T23</td>
<td>C₇H₁₆</td>
<td>Low</td>
<td>Hollow</td>
<td>3</td>
</tr>
</tbody>
</table>

**CONCLUSION**

This study represents a proof of concept to a combustion and suppression phenomenon that is largely under researched and not typically considered within the fire engineering industry. Laboratory-scale experiments have shown that suppression can interrupt the combustion process and pathway to oxidation and produce up to 250% more CO than the corresponding free-burning fires. The key factors influencing the production of CO as a result of water suppression were found to be:

- The size and shape of droplet-flame interaction volume,
- The characteristic diameter of droplets within the suppression spray, and
- The rate of water flux applied.

The adoption of typically applied species yields within tunnel environments featuring extended travel distances may be significantly underestimating the potential toxicity which occupants may be exposed to. The results obtained suggest that species yields should be modified where it could be anticipated that suppression systems may not result in extinguishment of a fire scenario.

**REFERENCES**

A numerical investigation on suppressing shielded fires with water mist systems

Azad Hamzehpour Vittorio Verda & Romano Borchiellini
Department of Energy (DENERG), Politecnico di Torino
C.so Duca degli Abruzzi 24, 10129, Torino, Italy
E-mail: azad.hamzehpour@polito.it

KEYWORDS: Water mist system, CFD, shielded fire, tunnel fire, FDS, fire suppression system

INTRODUCTION
In more realistic fire scenarios, the fire is shielded by an obstacle preventing water droplets from reaching directly to the flame and this can happen in a car or train fire in a tunnel. The aim of this research work is to investigate the effect of obstacles with different characteristics on the performance of water mist systems in suppressing shielded fires. Different shielded fire scenarios are defined and developed in Fire Dynamics Simulator (FDS). Three water mist systems including a high-pressure nozzle (working pressure of 100 bar) and two low-pressure nozzles (working pressure of 10 bar) are employed separately to compare their performances. Different obstacles in terms of size and distance from the nozzle are used to analyze the effect of these parameters on the extinguishing process. The results of this research work can be useful for 1- deepening our current knowledge about the interaction between the droplets and flames when the fire is covered by an obstacle, and 2- evaluating the capability of water mist systems with different characteristics on suppressing more realistic fire scenarios in tunnels.

NUMERICAL PROCEDURE
In the literature, only a few experimental studies have focused on shielded fires in tunnels [1,2]. The main idea of this research is to study the shielded tunnel fire and the real physics happening in the mist-plume area and to analyze the impact of the obstacle (representing car or train ceilings) above the fire on the performance of fire suppression systems. In this regard, FDS models have been developed to test different fire scenarios. Multiple meshes are used in each model to decrease the computational cost. A grid independency study is performed to evaluate the proper grid size. The model is first validated against available experimental data. After validation, there is a possibility to further analyze the shielded fire scenarios and proper design of water mist systems. Thermocouple trees are used to measure the near-flame temperatures (below and above the obstacle). In this research work, different cases including 25 cm × 25 cm, 50 cm × 50 cm, and 1 m × 1 m obstacle sizes at two heights, 80 cm and 150 cm above the floor are defined. The general procedure to simulate the shielded fire and the water mist system in FDS is shown in Fig. 1. The fire source is the diesel pool fire (30 cm × 30 cm pan size) with a peak HRR value of 75 kW. The combustion reaction of this work is based on the implemented simple chemistry in FDS. The boundary conditions and inputs are given to the FDS model with respect to the experimental data [3]. Moreover, the pressure zone is considered in models to resolve pressure-related issues. The extinction and evaporation models in FDS are employed to predict the suppression phenomenon by mist droplets. Additionally, the burning rate reduction is estimated through the ‘E_COEFFICIENT’ sensitivity analysis and using experimental measurements. The application time of the spray systems is also considered as a variable in this work.

RESULTS AND DISCUSSION
The validation results show a good agreement between experimental and numerical predictions. The validation procedure has been carried out for two cases including a dry test with no water mist system and a wet test with the water mist system. The simulation output of the dry test perfectly matched the measured quantities (O₂ concentration and temperature). However, the simulation results show an
over/underprediction of the quantities for the wet test after nozzle activation. The validation for both cases is considered satisfactory.

The HRR measurement, the temperature evolution at different locations, the extinguishing performance of nozzles, and the effect of the obstacle size and its distance from the nozzle on the performance of the water mist system were analyzed and will be presented in more detail in the poster. The comparison between the performance of nozzles with different characteristics in suppressing shielded fires shows that the high-pressure nozzle performed better in some cases in terms of extinguishing time. As an instance, the HRR comparison between 4 cases using a low-pressure nozzle is displayed in Fig. 1. This nozzle failed to suppress the shielded fire with the obstacle size of 1 m × 1 m. The results show that a high-pressure nozzle and a low-pressure nozzle performed almost the same in terms of extinguishing time in some cases due to the higher flow rate and cone angle of the low-pressure mist system. The second low-pressure nozzle has a longer extinguishing time compared to the other nozzle due to the lower flow rate although the pressure is the same. In extinguished cases, some droplets have a chance to bypass the obstacle to reaching the flame. It was proved that the characteristics of nozzles and shielding conditions affect the extinguishing performance of water mist systems.

Figure 1. The general procedure of the FDS simulation

ADDITIONAL TESTING AND FUTURE WORKS
An experimental campaign is designed to perform shielded fire tests using different water-based fire suppression systems. As a future work, the suppression study of LIB fires will be conducted. The use of additives for improving the performance of fire extinguishing systems will also be investigated experimentally. The combination of the shielded fire with different shielding conditions and the ventilation condition in tunnels is of importance, and the performance of water-based suppression systems should be investigated in such a situation.

REFERENCES
The development of an e-learning course designed to strengthen Swedish ambulance commanders decision-making in road tunnel incidents

Johan Hylander¹, Satish Strömberg², Anton Westman¹,³
¹Department of Surgical and Perioperative Sciences, Surgery, Umeå University
SE-901 87 Umeå, Sweden
²Faculty of Arts, Humlab, Umeå University,
SE-901 87, Umeå, Sweden.
³Department of Anaesthesia and Intensive Care Medicine, Karolinska University Hospital
SE-141 86, Huddinge, Sweden.
E-mail: johan.hylander@umu.se

KEYWORDS: education, e-learning, decision-making, road tunnels, emergency medical services, road tunnel safety

INTRODUCTION

Increasingly complex road tunnels are currently under construction. For example, the Stockholm bypass will upon its completion in 2030 consist of 18 km road tunnels. Its twin tube structure will include multiple subsea passages and on/off ramps [1]. The rescue effort into the confined environment of a road tunnel remains a collaborative challenge for emergency services (police, fire and rescue services and emergency medical services). A heavy responsibility is shared by the tunnel owner and emergency services’ commanders to collaborate proficiently, to minimize fatalities and to reduce long-term sequelae for people injured in the aftermath of a road tunnel incident. That said, Swedish ambulance commanders have been described as infrequent participants in road tunnel exercises and they have limited experience of managing road tunnel incidents [2]. This may hamper the efficiency of the rescue effort. Ambulance commanders have requested specialized training in road tunnel management with emphasis on the tunnel structure including specific risks and safety systems as well as a deeper knowledge of the tasks of the collaborative organisations at the incident site to be better prepared for future tunnel incidents [3-4]. A specialized e-learning course could provide the ambulance commanders with a solid base of knowledge on which informed decisions can be based.

Aim: The aim of this study is to create an e-learning course to facilitate the ambulance commanders decision-making in incident management concerning road tunnel incidents.

METHOD

We created an e-learning course based on requirements of emergency services personnel and collaborative personnel (including road traffic control centre, roadside assistance and emergency dispatch centre) [3-5]. The e-learning course was further developed in collaboration with stakeholders within the Swedish Transport Administration (including roadside assistance and road traffic control centres), emergency services and emergency dispatch centres. The specialized e-learning course consists of five modules:
• Background and aim. Learning objectives in accordance to Bloom’s taxonomy [6].
• The tunnel structure. Focus on the tunnel structure, safety systems and specific risks.
• From dispatch to arrival. Covering each organisations tasks from dispatch to arrival.
• The focal point of the rescue effort. Focuses on the needs of the injured persons. Covering methods of sorting injured (triage), typical injuries (e.g. traumatic injuries and poisonings due to smoke inhalation) and principles of treatment. Further, emphasis is placed on how each organisation can aid the emergency medical services. Shifting from “silo” mentality to a more holistic approach.
• After action discussion. Presenting a mental model for reflection and “lessons learnt”. Emphasis on successes and areas of improvements.

RESULTS

The e-learning course is currently being evaluated through an intervention study involving two gamified web-based simulations. Data collection is ongoing.

DISCUSSION

Full-scale exercises are expensive and require considerable time for planning and execution. As a result of the COVID-19 pandemic, the use of online educational platforms has increased [7]. The quality of the provided education, however, remains unclear. As the command roles for an organisation in a full-scale exercise is limited to relatively few individuals, there may be limited benefit for the whole organisation. When comparing table-top exercises to full-scale exercises, findings indicate that collaboration, trust and usefulness are reinforced in different ways depending on method [8]. Future exercises may be divided into sequential steps with e-learning being the foundation with table-top and full-scale added on so more personnel (over a larger geographical area) may benefit from an educational point of view.

REFERENCES

The performance of water mist systems on extinguishing shielded fires: An experimental study

Azad Hamzehpour, Vittorio Verda & Romano Borchiellini
Department of Energy (DENERG), Politecnico di Torino
C.so Duca degli Abruzzi 24, 10129, Torino, Italy
E-mail: azad.hamzehpour@polito.it

KEYWORDS: Water mist system, shielded fire, tunnel fire, fire suppression system

INTRODUCTION
Water mist systems are effective tools to suppress and control fires in tunnels. However, in real scenarios, the fire can be blocked due to the existence of obstacles that can represent the ceiling of a train or a car. In shielded fires, there is a small chance for water mist droplets to reach flames or the fuel surface, therefore, the performance study of water mist systems on suppressing shielded fires is of importance, especially in tunnels. In this study, the performance of two water mist systems including one low-pressure nozzle and one high-pressure nozzle on suppressing shielded fires is assessed experimentally. A structure is designed to provide different shielding conditions above a diesel pool fire. Three thermocouple trees are used to measure the temperature at different locations. The blocking effect of an obstacle can be represented by a block ratio [1] and also a plume-spray thrust ratio can be defined to study the interaction between droplets and the fire plume [2]. The nozzle characteristics and the shielding conditions are effective parameters for the suppression process of shielded fires by water mist systems. The results of this work are advantageous for designing fire suppression systems in tunnels by demonstrating the real physics in the area of shielded fire suppression.

FIRE TESTS, WATER MIST SYSTEMS, AND INSTRUMENTATION
Although a few research studies have focused on extinguishing shielded fires in tunnels [3,4], little is known about the effect of the obstacles on the performance of water mist systems in tunnels. This work is aimed at deepening our understanding of the complex interaction between the water mist droplets and the shielded fire in real fire scenarios. The current test is carried out in a 2.4 m×2.4m×3.2 m enclosure and the diesel pool fire with different HRR values varying from about 20 kW to 60 kW is provided using pans with different sizes (20cm×20cm, 25 cm×25cm, and 30cm×30cm). Three thermocouple trees (32 K-type thermocouples) at different locations are used to measure the temperature at different heights. A structure is specifically designed to make shielded fires by providing obstacles of different sizes at various heights. A vent is designed at the lower part of the compartment to provide fresh air, and a fan is installed at the ceiling to exhaust gases. The schematic view of the experimental campaign is illustrated in Fig. 1(a). Two nozzles with different characteristics (a multi-orifice low-pressure nozzle (LPN) with a pressure of 10 bar, and a multi-orifice high-pressure nozzle (HPN) with a maximum pressure of 100 bar) are used separately to assess and compare their capabilities of suppressing shielded fires. The gas concentrations are measured using a gas analyzer. Different fire tests including a dry test (without water mist) and a test with water mist systems and without obstacles, and several shielded fire tests using different obstacles and positioning with water mist systems are performed. A photograph of the shielded fire test with an obstacle size of 25cm×25cm located at 1 m above the floor is shown in Fig. 1(b).
RESULTS AND DISCUSSION
The temperature evolution at different locations and O₂ and CO concentrations for a case without obstacle and mist spray and two cases with an obstacle using LPN and HPN are illustrated in Fig. 2. The outputs revealed that in the case of shielded fire with the obstacle size of 25cm×25cm located at the height of 1m from the floor, both LP and HP nozzles were able to suppress the fire in a long time compared to the uncovered fire. Although the pan size and the obstacle size are the same, some droplets are able to penetrate the fire plume by bypassing the obstacle to decrease the flame temperature. The gradual increase of O₂ and gradual decrease in CO were seen in both cases after activation. The obstacle size and its vertical distance from the nozzle are important parameters affecting the suppression performance of water mist systems. It was seen that temperatures close to the fire and far-field temperatures for successfully suppressed cases first increased for a few seconds and then decreased to the ambient temperature.

![Figure 1. (a) The schematic view of the test bench and (b) a photograph of the shielded fire test.](image)

![Figure 2. The temperature evolution of (a) a fire test with no obstacle, (b) a shielded fire test with LPN, (c) a shielded fire test with HPN, O₂ and CO concentrations and smoke temperature in the exhaust for (d) dry test, (e) shielded fire test with LPN, (f) shielded fire test with HPN](images)

ADDITIONAL TESTING AND FUTURE WORKS
The report of the tests and obtained results will be displayed on the poster. Other shielding conditions will be tested to further develop the correlation between shielding conditions, nozzle characteristics, and the suppression performance of water mist systems. The possibility of using foam agents for shielded fire applications will be tested as well. In addition, an FDS model is developed to predict the performance of water mist systems in suppressing different shielded fire scenarios.
REFERENCES


Monitoring of airflow and airborne particles, to provide early warning in underground mines

Madeleine Martinsen & Erik Dahlquist
Mälardalens University
Universitetsplan 1, 722 20 Västerås, Sweden
E-mail: madeleine.martinsen@mdu.se

KEYWORDS: Sensors, Smart sensing, Mining, Safety, Digitalization, Artificial intelligence (AI), Bayesian networks (BN).

INTRODUCTION
Future mining is predicted transitioning to completely autonomous operation. This means that few or no personnel are on site and can act if any risk situation arises. This, in turn, calls for faster diagnostics so that the right measures are taken at the right time and before a dangerous situation becomes a fact.

BACKGROUND
From the ENSAF project a series of tests [1-2] was conducted and an understanding of gas dynamics and sensor technology was obtained. The outcome from that project suggested placing different kinds of sensors (gas, temperature, FLIR camera etc.) in the facilities and on the mining vehicles which continuously send data from these to a central diagnostic system in order to detect risks in an early phase. A mockup test, with gas sensor mounted on a mining machine, was conducted together with Boliden and Epiroc with satisfying results. Epiroc have now installed sensors on vehicles and on rock walls in their test mine Kvarntorp where we are currently testing autonomous routes and collecting data from these sensors to be further analyzed in this project (MORMOR). In this project we aim at creating holistic approach forwards a data-driven technology for mining safety, for monitoring of ventilation in tunnels has shown in many cases to aggravate the fires and for that reason airflow will be monitored.

CENTRAL DIAGNOSTIC SYSTEM
Smart solutions with machine learning and artificial intelligence will be evaluated to identify problems early, partly to locate the problems as close to the source as possible. The information is then used as input to a decision tree model, figure 1, to assess the risks but also to determine the content of toxic gases that can be dangerous to people and machines, through corrosion. The decision model aims at suggesting actions. For example, what should the mining machine do if the hydraulic cable begins to leak, continue to run or stop immediately?

\[ \sigma(t + 1) = f \left( \sum_{i=1}^{n} w_i x_i(t) \right) \]

Figure 1  Holistic approach to a sensor framework
BAYESIAN NETWORK
The idea is to improve complex and time-consuming inspection processes with the goal to prevent dangerous situations, such as fires, from occurring. In order to achieve accurate and earlier detection of equipment defects, Bayesian Networks, BN, [3], decision trees will be introduced for analysis of the trend development [4] of features and as decision support. Neural networks [5-6] represent a brain metaphor that process information. The biological neuron imagines the elementary unit of all biological nervous systems [3,5, 7-8]. They appear to be organized in structures where, after sufficient learning period, collaborate to solve a high number of complex tasks. Further neural computing refers to a pattern recognition [9] methodology for machine learning (ML) where an artificial neural network (ANN) is the resulting model from neural computing [5]. Neural networks are programmed to:

- Recognize
- Associatively retrieve patterns or database entries
- Store
- To solve combinatorial optimizations problem
- To filter noise from measurement data
- To control ill-defined problems

DISCUSSION
In the poster a compilation of the holistic approach for monitoring of airflow and airborne particles in order to provide early warning of irrespirable atmospherics conditions in underground mines will be presented. In a future paper results from the AI/BN model and a discussion of the potential with such a solution will be presented.

REFERENCES
Extending Cross-Passage Distances

Basar Bulut & Mathias Y.B.Lysholt Hansen
COWI A/S
Parallelvej 2, 2800 Kongens Lyngby, Denmark
E-mail: brbt@cowi.com

KEYWORDS: Evacuation, Machine Learning, Metro Tunnel, Performance-Based Design.

INTRODUCTION

NFPA 130 states the maximum distance between exits not to exceed 762m, and between cross-passageways not to exceed 244m, both of which can be increased where supported by an engineering analysis. The clear width of walkways along the tunnel shall be not less than 61 cm.
BS 9992 states the distance between cross-passages not to exceed 500m, and also requires that the passengers shall reach a place of ultimate safety within 2 hours. The clear width of walkways should be not less than 85cm.

To better understand and evaluate the total evacuation time along metro tunnels, more than 1500 different evacuation simulations are performed with varying number of passengers, distance between cross-passages and exits, walkway widths, and number of doors per rolling stock. The results obtained are then trained and tested with a developed machine learning algorithm to evaluate the variables' effects on the total evacuation time.

MOTIVATION

Initial models are performed to evaluate evacuation time with varying walkway widths, assuming the cross-passages are provided at every 240m along the tunnel. Four different walkway widths are proposed between 62cm and 80cm and total evacuation time is decreased with the increase in walkway widths, as expected. Assuming 1600 passengers in 8 rolling stocks, the change in evacuation time with respect to walkway widths is presented in Figure 1.

![Evacuation Time wrt Walkway Width (cp = 240m)](image)

Figure 1: Evacuation time with varying walkway widths (cross-passage spacing is 240m).

Walkway width of 62cm can be considered as acceptable, as per NFPA 130 requirements. Therefore, we considered the evacuation time of 46:33 to be the acceptance criteria for this initial analysis. We performed a second analysis, this time keeping the walkway width of 80cm as constant, while
changing the distance between cross-passages varying from 240m to 640m. Total evacuation time with varying cross-passage spacing is presented in Figure 2.

![Evacuation Time wrt Cross-Passage Spacing (ww = 80cm)](image)

**Figure 2: Evacuation time with varying cross-passage spacing (walkway width is 80m).**

We obtained total evacuation time for cross-passages spacing of 480m as 46:06, which is lower than 46:33. Comparing the results with the prescriptive requirements of BS 9992 is a good match and this formed the basis motivation of the study.

**EVACUATION MODELS**

Further evacuation models are simulated using MassMotion. Different number of rolling stocks with different number of passengers are modeled and the simulations are carried out with varying exit distances and walkway widths. Simulations are performed to obtain as many data as possible which are later implemented in machine learning algorithm to analyze the effect of each variable on total evacuation time.

**MACHINE LEARNING ALGORITHM**

The data obtained is first analyzed to understand the importance of variables on total evacuation time. The cross-passage distance affects total evacuation time 16%, approximately while the number of passengers affects 73%. Effects of walkway width and doors of rolling stock are 9% and 2%, respectively. Finally, the data obtained is split into two sets to build the train and test data to build the machine learning model. Using the model we propose an equation to predict the total evacuation time along metro tunnels.

**DISCUSSION**

In the final poster, the proposed equation will be shared and we will appreciate any feedback. Further evacuation models and machine learning algorithms are being developed and will be shared in the poster presentation.

**REFERENCES**

2. BS 9992, Fire safety in the design, management and use of rail infrastructure – code of practice.
Fire emissions from new and existing materials, an occupational issue now and in the future

Evalyne Arinaitwe, Margaret McNamee and Patrick van Hees
Lund University, Division of Fire Safety Engineering
Box 118, SE-210 00 Lund, Sweden
E-mail: margaret.mcnamee@brand.lth.se

KEYWORDS: Fire emissions, toxicity testing, full scale testing, cone calorimeter, 1/3 ISO room test

INTRODUCTION

The Fire and Rescue Service has a very dangerous work situation, often with high physical and thermal stress and potential exposure to a large number of toxic substances. Several studies have shown that in connection with fires, the risk of exposure to toxic substances is high despite effective technical protective equipment [1]. The American occupational health and safety agency, NIOSH, has classified the profession as high risk, due, among other things, to exposure to carcinogenic pollutants such as polycyclic aromatic hydrocarbons (so-called PAHs). Occupational exposure as a firefighter is classified as carcinogenic, group 1 by IARC 2021 [2, 3]. Several studies, including from the Nordic countries, show increased cancer risk for certain forms of cancer among firefighters [4-6].

Although the risks are known, there is a lack of knowledge about which work steps and situations pose the greatest risk of exposure and health effects within the personnel of the emergency services. The occupational exposure strongly depends on the type of work [7, 8]. Exposure both via the respiratory tract and on the skin is relevant. The exposure via these two routes strongly depends on the degree of protective equipment [9]. It is therefore also very important that protective clothing and other protective equipment are cleaned and handled in a controlled manner after exposure. The exposure also depends heavily on the type of material, the design of the structures and ventilation conditions. The planned project will consider a variety of exposure scenarios, material and experimental scales, including exposure in a tunnel facility at Revinge, Sweden. Emission factors will be calculated, and toxicity will be evaluated with relevance for underground and above ground exposure scenarios (see e.g. [10, 11]).

METHOD

The project is being run as a collaboration between Lund University, Karolinska Institute and the Skåne Region, under project leadership from Lund University. The project is divided into four research work packages and one administrative work package, see figure 1. Experimental and toxicological work shall provide input to risk evaluations of firefighter safety.
EXPERIMENTS

Experiments are planned in a variety of scales. The small scale experiments will start 2023, beginning with the Cone Calorimeter (ISO 5660) and the Controlled Atmosphere Cone Calorimeter (ISO 5660-1), progress to the 1/3 ISO Room test before moving to large scale tests. Exactly which large scale tests will be conducted is yet to be determined but relevant scenarios which will be considered include enclosure fires (essentially the size of a furnished carpentry container) and tunnel fires. Facilities for both types of testing are available at Revinge in Skåne. The large scale tests are planned to start 2024.

EXPECTED RESULTS

The overall aim and goal of the project is to significantly improve the working situation of the emergency services personnel by building a knowledge base to prevent exposure to hazardous substances. The project has the following specific aims:

1) To compile needs, knowledge gaps, risk scenarios and design experiments
2) Quantify emissions and their toxicity from fires in new materials at different levels of ventilation and extinguishing tactics through: a) Controlled experiments on a laboratory scale, b) Scaled-up experiments in the field and c) Toxicity studies of the long-term effects of the emissions
3) Develop tools for improved exposure and risk assessment in the form of proxy molecules for toxic substances that can be easily measured with simplified validated measurement tools. Develop recommendations for selection of protective equipment and protective strategies
4) Communicate and utilize the new knowledge and these tools to create strategies that minimize exposure risk during all phases of a response, from arrival and extinguishment to post-work and residual value investigation.

Figure 1: Overview of project plan and risk evaluation strategy.
REFERENCES


