Proceedings from the Third International Symposium on Tunnel Safety and Security

Edited by Anders Lönnermark and Haukur Ingason
ABSTRACT

The report includes the proceedings of the 3rd International Symposium on Tunnel Safety and Security (ISTSS) held in Stockholm 12-14th of March 2008. It includes papers given by 33 speakers. These papers were presented in seven different sessions; design, case studies, research, active and passive fire protection, fire fighting and security in tunnels. The proceedings consist of 5 specially invited key speakers, 28 accepted papers and 4 poster papers collected from a Call for Paper procedure.

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PREFACE

Safety and Security have been high on the scientific agenda for decades, no more so than after the tragic attacks of 911. The success of the International Symposium on Tunnel Safety and Security is a tribute to the pressing need for continued international research and dialogue on these issues, perhaps in particular connected to complex infrastructure such as tunnels and tunnel networks.

These proceeding include papers presented at the 3rd International Symposium on Tunnel Safety and Security (ISTSS) held in Stockholm 12-14th of March 2008. We are very proud to have been able to establish a symposium that regularly attracts over 200 delegates from all parts of the world and Stockholm is definitely a perfect place for organising such a symposium. Not only is Stockholm one of most beautiful cities in the world, there are also many large tunnel projects ongoing and planned in the region.

For us at SP this journey started when we decided to present the test results from the Runehamar tunnel on a symposium in Borås in November 2003. The name of that symposium was the International Symposium on Catastrophic Tunnel Fires. The international interest for this event forced us to change venues to accommodate the unexpected number of delegates and the symposium itself was very successful with well over 200 delegates. The results presented at this symposium were so interesting and the need for continued dialogue so pressing that we were urged to arrange a new symposium, at a new location a where we knew that there would be a great interest in the results.

Due to SP’s longstanding collaboration with the National Infrastructure Institute’s Centre for Infrastructure Expertise, NI²-CIE, in USA, the venue for the new symposium was chosen in the US in November 2004 in close collaboration with NI². This became the 1st International Symposium on Safety and Security (ISTSS), thereby broadening the scope from fire issues to safety and security. After this event it was agreed to organise the conference every 2nd year with SP as the Conference Organiser and NII-CIE as our main Event Partners. The 2nd ISTSS was organised in Madrid 2006 with Intevia (Spain) and NII-CIE as Event Partners. Now we are in Stockholm with the 3rd ISTSS.

The focus of these symposia has mainly been on fires in tunnels, but it is shifting more and more towards security. The new terrorist threats and focus on how to solve these problems is increasing. The need for expertise in this area for underground infrastructure in general is continuously increasing. Any type of risk analysis and consequence analysis is becoming a major issue. There are many well know and established researchers and practicing engineers that have contributed to this symposium. This is the first time we have had a Call for Papers with submissions from all over the world. We are pleased that so many authors have shown an interest in contributing and believe that the quality of the papers is a testament to the calibre of research that is on-going around the world. All the key speakers are well established and known in their field, and the contents of their papers will definitely interest many readers. It is our hope that these proceedings will provide you with all the latest knowledge found in the field of fire safety and security in undergrounds structures.

Haukur Ingason
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ABSTRACT

The dramatic fires which occurred in European road tunnels in 1999 and 2001 have led to the development of new regulations and recommendations which recognize that tunnel safety is not only determined by the infrastructure. It is indispensable to consider the whole tunnel system, which also includes the operation and the emergency intervention, the users and their vehicles. Beyond that, it has appeared necessary to truly manage safety through an appropriate organisation and procedures. To implement these new concepts, the European Directive 2004/54/EC defines (i) the responsibilities of the major players, (ii) safety references, including minimum technical requirements and provisions for risk analysis, (iii) procedures to ensure safety at the design, commissioning and operational stages, and preserve it throughout the years. The pre-existing French regulations, which inspired the Directive, have been applied for 7 years and the experience gained is described. Finally new research and recommendations are referred to. The conclusions advocate a cultural change to implement new ways of thinking and behaving regarding safety.

KEYWORDS: road tunnel, operation, holistic approach, risk analysis, safety management

INTRODUCTION

Catastrophic fires occurred in the European road tunnels of Mont Blanc (France-Italy; 39 fatalities) and Tauern (Austria; 12 fatalities) in 1999, and St Gotthard (Switzerland; 11 fatalities) in 2001. These dramas brought the issue of tunnel safety to the fore and were the origin of a number of regulatory and research activities. Even more importantly, they are progressively leading to new ways of thinking and ensuring safety in road tunnels and a new behaviour of all those involved.

A first, very important step has been to realize that safety is not only a matter of infrastructure. While previous regulations and recommendations mostly dealt with infrastructure measures, the tunnel community have become aware that a whole system is involved, including also the operation and maintenance, emergency preparedness and intervention teams, as well as the users and their vehicles. Safety can only be obtained from a system, or “holistic” approach, which is necessary to ensure the efficiency and consistency of the measures.

The following, just as important step has been to understand that safety could only be obtained and maintained through an appropriate organisation and the suitable behaviour of all players. This should lead to the implementation of some kind of tunnel safety management system, which aims at ensuring that the design and operation are safe, but also that safety is preserved throughout the years.

This paper first shows how these concepts have emerged and are now supported, if not imposed, by European and national legislations. It highlights the related provisions of the European Directive 2004/54/EC on minimum safety requirements for tunnels in the trans-European road network [1], and presents the experience gained from the implementation of a similar pre-existing system in France. The input of international research in this field is introduced. The conclusion highlights the major elements of a tunnel safety management system and the conditions for its successful implementation.
RECENT REGULATORY DEVELOPMENTS

National approaches

Although it was hardly the subject of public attention, safety in road tunnels had been extensively taken into account in many countries before 1999. In addition to the accumulated experience of designers, contractors and operators, various theoretical and technical research had been conducted, often in great depth, in particular regarding fires. However only a few countries had adopted regulations in this field. The 1999 fires caused a shock in a number of European countries and led to new measures.

Immediately after the fire in the Mont Blanc tunnel and independently of the judicial inquiry, an administrative and technical enquiry was commissioned by the French and Italian governments. In addition to two national reports, a joint report [2] was published which included 41 recommendations intended to improve safety in this and other similar tunnels. These recommendations included better information and training for users as well as stricter regulations on the size and flammability of heavy goods vehicles.

A further section of this paper gives details of other actions taken in France, and in particular the new regulations implemented in 2000. In Switzerland a federal commission examined all aspects of road tunnel safety, and issued recommendations relating to users, operation, the tunnels themselves and vehicles. Other work was undertaken in various countries including Austria and Norway.

European harmonization and legislation

In order to harmonize the various national initiatives, the Western European Road Directors (now the Conference of European Directors of Roads – CEDR: www.cedr.fr) set up a working group comprising representatives from all Alpine countries. Recommendations were prepared, based on the Swiss work as well as experience in other countries, and approved by the Road Directors in September 2000.

This work was further revised and extended by the United Nations Economic Commission for Europe (UN ECE: www.unece.org). This organization, based in Geneva, covers 56 countries and manages various European agreements, in particular regarding road signing and road traffic (Vienna conventions), transport of dangerous goods (ADR), main international traffic arteries (AGR), vehicle characteristics, etc. In early 2000, UN ECE set up a multidisciplinary group of experts on safety in road tunnels. Their final report [3], completed in December 2001, included recommendations on all aspects of safety in tunnels: road users, operation, infrastructure and vehicles (Figure 1). It was subsequently used to improve the European agreements managed by UN ECE.

![Figure 1 Factors influencing safety in road tunnels according to UN ECE.](image)

Road users

Operation

Vehicles

Infrastructure

Safety in road tunnels
The European Union was not initially concerned with tunnel safety, which fell to the Member States under the principle of subsidiarity. However, after the Mont Blanc and Tauern tunnel fires, the heads of State asked the European Commission to address the matter. The Commission’s first step was to include safety in tunnels as a subject in their calls for research tenders. We will later mention several projects and networks financed in this framework. The European Commission subsequently decided to prepare a legislative instrument in the form of a directive. The Commission’s draft was presented at the start of 2003, then discussed by the European Parliament and the Council throughout that year before finally being approved on 29 April 2004. This directive has relied on previous work from the UN ECE and the World Road Association (PIARC) as well as new national regulations, especially the French one, and introduces the main components of a tunnel management system.

EUROPEAN DIRECTIVE 2004/54/EC

Directive 2004/54/EC of 29 April 2004 [1] must be transposed into national legislation by each of the 27 member States of the European Union, which is currently done for most of them. It is also applied in Norway and Switzerland further to bilateral agreements with the Union. This directive applies to tunnels over 500 m and located on the Trans-European Road Network (TERN). At the time of its publication, it covered about:

- 400 tunnels in operation, which have to comply with the Directive within 10 years (15 years for those countries where tunnels represent a large percentage of the TERN),
- 100 new tunnels to be built by 2010, which must comply from preliminary design.

When they transposed the directive, most countries also made all or part of its provisions applicable to other road tunnels, e.g. tunnels over 500 m outside the TERN and/or shorter tunnels.

In the following paragraphs, we will insist on three main aspects of the directive, which are significant elements of a safety management system: definition of responsibilities, procedures and safety measures.

Definition of responsibilities

One of the main benefits of the directive is that it defines, as clearly as is possible at European level, the responsibilities of the most important parties in tunnel safety (Figure 2).

Although few details are given in the directive, the first party is of course the “Tunnel Manager”, who is responsible for the day-to-day operation and safety. At each stage in the life of a tunnel (design, construction, operation), there must be a single manager, even if the tunnel is shared between two different countries.

An “Administrative Authority” identifies the tunnel manager and is responsible for ensuring that all aspects of the safety of a tunnel are assured and all necessary tasks are performed (inspections, safety schemes and plans, risk-reduction measures, etc.). It gives the authorization to operate the tunnel and has the power to suspend or restrict operation if required. The administrative authority may be set up at national, regional or local level and must be single for each tunnel (except bi-national tunnels, for which two different authorities can be accepted).

Although they are imposed few requirements, the “Emergency Services” are mentioned 29 times in the directive! This shows the importance of their role, so that numerous provisions relate to their information, training, possibilities of action, and especially coordination with the tunnel manager.

The “Safety Officer” is appointed by the tunnel manager and approved by the administrative authority. His role is to coordinate all safety measures and bring an independent point of view. This is a new function, which did not previously exist in European tunnels. Its implementation must be carefully planned both to ensure his independency and to avoid that he encroaches upon the
responsibilities of the tunnel manager (who is the only one in charge of the daily operation and safety).

![Diagram of tunnel safety management]

Figure 2  Main responsibilities in tunnel safety management.

The directive also provides for technical expertise:
- Independent “Inspection Entities”, with a high level of competence and quality procedure, must be in charge of inspections, evaluations and tests.
- An “Expert” or an “Organization specializing in this field” has to give an opinion on safety, which is included in the safety documentation. It can be the inspection entity or another body.

**Procedures**

The directive sets up a number of procedures to check safety at design, commissioning and operational stage. They are based on a very important tool, the “Safety Documentation”, which gathers all relevant information and is used for communication between all parties. This documentation is compiled by the tunnel manager and describes the preventive and safeguard measures. Its contents are adapted to each stage (Figure 3) and cover the following topics:
- Description of the tunnel,
- Demonstration of safety (traffic forecast, specific hazard investigation, risk analysis for dangerous goods, possibly other risk analyses),
- Operation and feedback from experience (description of the operational means and measures, emergency response plan, description of the system of permanent feedback from incidents, report and analysis on significant incidents and accidents, list and analysis of exercises),
- Opinion on safety from an expert or a specialized organisation.

The main procedures applicable for new construction are as follows:
- Before construction starts, the safety documentation must be submitted to the administrative authority, then the design is approved by the relevant authority.
- Before the tunnel is opened to traffic, the administrative authority must give its authorisation on the basis of the safety documentation and the opinion of the safety officer.
Figure 3 Contents of the safety documentation at the different stages.

In the case of modifications to an existing tunnel or its operation, the procedures are the following:
- If the modifications are substantial, the same procedure as for the opening of a new tunnel applies before re-opening.
- Any other modification requires an opinion of the safety officer.

A number of procedures apply once a tunnel is in operation:
- The safety documentation must be kept permanently up to date by the tunnel manager.
- Significant incidents and accidents must be reported within one month.
- Exercises must be jointly organised by the tunnel manager and the emergency services, in cooperation with the safety officer.
- Periodic inspections must be carried out at least every 6 years, and measures taken if the tunnel or operation is not considered satisfactory.

Safety measures

The definition of the safety measures to be implemented in a tunnel is based on the combination of three concepts: a holistic approach, minimum requirements and risk analysis.

The holistic approach proposed by UN ECE (Figure 1) has been taken integrated in the directive, which requires a systematic consideration of all aspects of the system composed of the infrastructure, operation, users and vehicles.

The directive includes a series of minimum requirements, with some possibilities of derogation. Most of these minimum requirements are less stringent than the pre-existing French, Swiss, Austrian or German regulations. They deal with:
- infrastructure, with less severe requirements for existing tunnels than for new tunnels,
- operation, with the same requirements for existing and new tunnels,
- information campaigns.
An important role is given to risk analysis, which is requested in several circumstances:
- to justify alternative measures, where derogations are allowed,
- when a tunnel has “special” characteristics, i.e. justifies specific safety measures,
- before regulations on dangerous goods through the tunnel are defined or modified.
Additionally, the safety documentation must include a “Specific Hazard Investigation”, which describes possible accidents and their consequences and substantiates risk-reducing measures: it is a particular type of risk analysis to be performed for each tunnel.

EXPERIENCE GAINED IN FRANCE

New regulations since 2000

When the Mont Blanc tunnel fire occurred in March 1999, France was already in the process of revising its regulations, which dated back to 1981 and applied only to new tunnels. The Mont Blanc catastrophe showed that it was essential to cover existing tunnels too. In the three months following the fire, a safety assessment committee comprising experts from the public authorities and private consultants made a first review of the 40 French road tunnels over 1000 m already in operation or under construction, on the basis of files prepared by the owners, and issued recommendations to improve their safety.

The next task was to look at shorter tunnels and also go deeper. An interministerial Circular dated 25 August 2000 [4] organised the assessment of tunnels over 300 m long, in service on national roads and motorways. It included a Technical Instruction setting out design and operation rules, directly applicable to new tunnels and forming a reference for existing tunnels. These rules were derived from the work performed before the Mont Blanc tunnel fire to revise the regulations and also included lessons learnt from it. A law of 2002 and a decree extended most provisions to all tunnels longer than 300 m, including those owned by local authorities.

The responsibilities and procedures defined by the French regulations were very similar to Directive 2004/54/EC. As a matter of fact, the directive is heavily based on the French system, as France was the only country to have implemented this kind of road tunnel safety regulations, if not safety management system, at the time the directive was drawn up. Consequently, the transposition of the Directive in France did not require major changes to the pre-existing practice and was mostly done in 2006 [5].

The directive only applies to tunnels over 500 m long and located on the trans-European network. Three tunnels concerned by the directive are shared by France with a neighbouring country (Mont Blanc and Fréjus tunnels with Italy, Somport tunnel with Spain), and the transposition took place in the framework of existing international agreements. Apart from these international tunnels, France has 30 tunnels in operation concerned by the directive, but the national regulations apply similar provisions (except for a few exceptions) to about 200 tunnels over 300 m long.

Definition of responsibilities, procedures and safety measures

For all the tunnels entirely in France, the administrative authority is the prefect, who is the local representative of the State in each of France’s 100 “départements”. In addition to the provisions of the directive, a national and a local commission assist the prefect by giving their opinions on applications made. The role of the inspection entities is played by qualified experts and organisations, who are approved at the national level; they also give the expert opinion needed in the safety documentation. Safety officers are only required for the 30 tunnels over 500 m on the TERN concerned by the directive, because it was not felt this additional function would be useful in other tunnels.

The construction of new tunnels as well as substantial modifications of existing tunnels must be
submitted to the prefect at design and commissioning stage. Even without any works planned, a safety
documentation must be compiled and a first authorisation obtained from the prefect for all tunnels in
operation. This authorisation must be renewed every 6 years, after an inspection.

The safety measures to be implemented for new tunnels are defined by the Technical Instruction
mentioned above [4]. This instruction sets out a compensation principle which allows some flexibility
in applying the requirements, provided it can be shown that compensatory measures taken ensure an
equivalent or better overall safety level. Tunnels already in operation may be upgraded either by
applying the requirements of the Technical Instruction or by implementing other preventive or
operational measures. In all cases the owner is required to demonstrate that the proposed measures
will achieve a safety level comparable to the level which implicitly results from the instruction. For
both new tunnels and tunnels in operation, the role of the national and local safety commissions
includes determining whether the compensatory measures proposed are acceptable.

Lessons from seven years’ application of procedures

Since the procedures were established in 2000, the national assessment commission have examined
the safety documentation of 140 tunnels (Figure 4). A very important programme of works to improve
the safety of the existing French road tunnels started in 2001 and should be completed by 2014. Its
total cost exceeds 2 000 million euros, half of which have already been financed. As importantly,
serious improvements are being made in the operation, including better organisation, training and
exercising, and a number of actions are aimed at an improved behaviour of tunnel users.

![Figure 4](image_url)

**Figure 4** Number of tunnels examined by the French national assessment commission at design
and commissioning stage (either new construction or substantial modifications), and in
operation.

Drawing on the experience gained in reviewing applications for a large number of tunnels,
recommendations for compiling safety documentation have been issued. A working party, comprising
experts from the national safety assessment committee, specialised consultants and operators, has
drawn up a “Guide to Road Tunnel Safety Documentation” [6]:

- Booklet 0: Safety documentation objectives (March 2003)
- Booklet 1: Practical method of compiling safety documentation (to be published)
- Booklet 2: Tunnels in operation - From the existing to the reference condition (June 2003)
- Booklet 3: Risk analyses related to transport of dangerous goods (December 2005)
- Booklet 4: Specific hazard investigations (September 2003)
- Booklet 5: Emergency response plans (October 2006)
This guide gives instructions on the two kinds of risk analysis which are compulsory in France:
- Before decision is made on the regulation regarding dangerous goods in a tunnel, a risk analysis must be performed using the quantitative risk assessment model jointly developed by OECD and PIARC [9], as described in booklet 3.
- At all stages, a specific hazard investigation must be performed as described in booklet 4.

As a result of the national safety assessment commission’s deliberations, numerous aspects affecting tunnel design and operation have also been clarified. Details are given in the commission’s annual reports [7] and in documents issued by CETU (Tunnel Study Centre: www.cetu.equipement.gouv.fr). These documents, together with the guide to safety documentation and the committee’s annual reports, may be downloaded free of charge from CETU’s web site in French, and English for most of them.

Feedback from accidents and incidents

For all tunnels over 300 m long on national roads and motorways, significant incidents and accidents must be reported within one month by the owner to the local prefect and to CETU. Reports are submitted over the Internet, using an on-line form to enter the required information. Significant incidents and accidents are understood to include:
- all accidents in which at least one person is injured, even slightly,
- all fires which occur in the tunnel,
- all other events resulting in unscheduled closure of the tunnel, except if they are related to traffic management outside the tunnel.

The reporting system has been in place since 1 January 2001 and applied to 95 tunnels (part of these tunnels have not been on national roads any longer since 2006). The quality of the information received varies from one tunnel to another. Actions are planned to improve matters, in particular by providing incentives to tunnel operators. A total of 150 to 300 events are reported annually, including:
- 20 to 70 accidents with injuries, resulting in 0 to 5 fatalities and 20 to 80 people injured,
- 10 to 25 fires, nearly all of them fortunately minor (Figure 5).

Annual reports are drawn up by CETU and summaries are published [8].

CONTRIBUTION FROM INTERNATIONAL RESEARCH AND NETWORKING

The aforementioned regulatory developments and the current implementation of safety management in European road tunnels have been favoured by research and methodological activities. In the future, new results obtained should be taken onboard to continuously maintain and possibly improve the safety of existing and future tunnels. Current research addresses the technical systems to improve
safety, but also all the aspects of safety management, including methods for analysing and evaluating risks, organisation and communication, especially during operation, human behaviour of all those involved, from the owner and consultants to the operators, emergency teams and, last but not least, the users. We will not try to describe all the research and development activities, but will only mention a few significant European and international efforts in this field.

**European research projects / thematic networks**

In the aftermath of the Mont Blanc and Tauern tunnel fires, the European Union funded a number of research projects related to tunnel safety under its fifth framework programme for research and technological development. All are now completed and their results available:

- **DARTS (Durable And Reliable Tunnel Structures; [www.dartsproject.net](http://www.dartsproject.net))** primarily aimed to minimise cost increases during tunnel construction. Its recommendations take account of risks and requirements throughout a tunnel’s service life.

- **SafeTunnel (Innovative Systems and Frameworks for Enhancing of Traffic Safety in Road Tunnels; [www.crfproject-eu.org](http://www.crfproject-eu.org))** looked at the benefits of communications between vehicles and the infrastructure.

- **Sirtaki (Safety Improvement in Road & Rail Tunnels using Advanced Information Technologies and Knowledge Intensive Decision Support Models; [www.sirtakiproject.com](http://www.sirtakiproject.com))** aimed to enhance operational management of emergencies.

- **VirtualFires (Virtual Real Time Emergency Simulator; [www.virtualfires.org](http://www.virtualfires.org))** developed a prototype simulator for training emergency teams.

- **The largest project, UPTUN (Cost-effective, sustainable and innovative Upgrading Methods for Fire Safety in existing Tunnels; [www.uptun.net](http://www.uptun.net))**, had a budget of 12 million euros and gathered 41 partners from 16 countries. From 2002 to 2006, it developed technologies and an assessment method for improving fire safety in existing tunnels.

Two European thematic networks were also set up under the same framework programme to enable experience to be shared and joint recommendations to be prepared:

- **FIT (Fires In Tunnels; [www.etnfit.net](http://www.etnfit.net))** ran from 2001 to 2005 and produced shared databases on various aspects of fire safety in tunnels and a report relating to design fires, fire-safe design and emergency response.

- **SafeT (Safety in Tunnels; [www.safetunnel.net](http://www.safetunnel.net))** started in 2003 and finished in 2006. It has proposed recommendations covering all aspects of tunnel safety.

The only project funded under the 6th framework programme, L-surf (Large Scale Underground Research Facility: [www.l-surf.org](http://www.l-surf.org)) is a feasibility study on safety and security of enclosed underground spaces, which aims at full scale testing as well as training and education.

**International syntheses**

Before the 1999 catastrophic tunnel fires, most of the work to produce international syntheses and recommendations was conducted by the World Road Association (PIARC: [www.piarc.org](http://www.piarc.org)). This non-political and non-profit making association has 111 member countries and over 2000 members in 130 countries. PIARC’s technical committee on road tunnel operation was set up in 1957 and now has around 60 members and corresponding members from more than 30 countries. Its scope covers road tunnel geometry, equipment, safety, operation and environmental impacts.

**Tunnel construction and civil engineering aspects, on the other hand, are the domain of the International Tunnelling and Underground Space Association (ITA: [www.ita-aites.org](http://www.ita-aites.org)) with which PIARC cooperates continuously. As a number of partners in the aforementioned European projects and networks wished to continue their action to improve underground safety after the end of their contracts with the European Union, they have launched a new Committee on Operational Safety of Underground Facilities (COSUF), under the auspices of ITA. This committee, which is also supported**
by PIARC, aims to develop a world-wide network to exchange knowledge and experience, facilitate cooperation, foster research and promote underground safety.

PIARC also cooperated with the Organisation for Economic Co-operation and Development (OECD: www.oecd.org), culminating in 2001 with the publication of a joint report and a quantitative risk assessment model on transport of dangerous goods through road tunnels [9], available from PIARC.

After 1999, the PIARC technical committee on road tunnel operation decided to give safety matters even greater importance. The majority of the reports it has published from 1999 to 2007 deal with safety-related measures, including recommendations on cross-section geometry [10.1 and 10.2], fire and smoke control [10.3 and 10.4], traffic incident management systems [10.5], good practice for operation and maintenance [10.6]. New reports will be published in 2008 on fixed fire fighting systems [10.7] and operational strategies for ventilation [10.8].

Another set of products deal with human and organisational factors. In addition to brochures about safe driving in road tunnels, prepared by PIARC and published by the European Commission in 2002-2003, reports published in 2007-2008 address the organisation, recruitment and training of operators [10.9], human factors and safety regarding users [10.10] as well as management of the operator-emergency teams interface [10.11]. Finally, several new reports specifically deal with aspects of safety management: integrated approach to safety [10.12], risk analysis [10.13], tools for tunnel safety management [10.14]. All the mentioned reports provide syntheses and give useful recommendations. They can be freely downloaded from the PIARC website.

CONCLUSION: IMPLEMENTING TUNNEL SAFETY MANAGEMENT

The dramatic European tunnel fires of 1999 and 2001, as well as all the work performed since that in numerous national, European and international organisations, have demonstrated the need for managing safety in road tunnels. Safety cannot be obtained and maintained only by hiring competent designers who will plan state-of-the-art provisions, and by operating and maintaining the tunnel according to the best recommendations. It requires an adequate organisation to be put in place to clarify the responsibilities, ensure communication between all parties, have safety checked with an outside view, integrate the feedback from operation, real incidents and exercises into the operation and possibly the infrastructure, etc. Directive 2004/54/EC provides bases. It should be the opportunity to go farther and implement a true safety management system in each significant road tunnel:

- **All parties should be involved and their responsibilities clearly defined.**
  
  Beyond the directive, the role and responsibilities of all major players should be clarified, as well as their interfaces: tunnel manager (including operations personnel in the field), all emergency services, administrative authority (including possible commissions which advise it), safety officer, inspection entity, etc. The users of the tunnel must not be overlooked; their behaviour plays a decisive role in safety and they must be informed and even trained.

- **The safety documentation should encompass all useful information and be a basis for dialogue.**
  
  Dialogue between all participants is essential, and the safety documentation forms a common foundation for this. Drawing up this documentation provides an opportunity to jointly analyse all factors affecting the safety of users and implement the most suitable measures in a coordinated way. Provided it is kept up to date, it also forms a useful repository of all documents needed for subsequent daily operation and exchange of information between parties.
• A technical reference and risk analysis methods should be adopted. Tunnel design and operation, as well as the official procedures, require a common reference. The stipulations of the directive form a basic reference, though in a number of countries a stricter and/or more extensive reference is used (e.g. in France, the Technical Instruction issued in 2000 together with a few additional measures set out in the directive). Risk analysis is essential to choose between alternatives, justify derogations and check general consistency. An appropriate and accepted risk analysis methodology is necessary as well as criteria to evaluate the results.

• Procedures are necessary to ensure safety at design and commissioning stage. Safety in design should be ensured by procedures which involve all parties, including the future operator and emergency services. Long enough before commissioning, the operational and emergency procedures should be jointly established by all those involved; the staff should then be trained and exercises performed. As specified in the directive, procedures should require opinions to be given before work starts and authorisations issued before opening the tunnel; these procedures should based on the safety documentation backed up by an outside point of view from an independent expert.

• Additional procedures are needed to ensure that safety is maintained during operation. Continuous training and exercises are necessary to maintain the efficiency of operational and emergency staff and their coordination. A permanent watchfulness is necessary on the part of the tunnel manager, with the help of the safety officer who gives an outside point of view. The accidents and fires occurring in the tunnel should be collected and analysed. The operational and emergency procedures should be revised as often as needed to take into account the lessons from normal operation and exercises, as well as the feedback from real accidents and fires.

• These regular procedures should be completed by inspections held at least every six years. They should be complemented by a thorough re-assessment of the safety, taking into account changes in the traffic and environment of the tunnel as well as in the technical and risk references.

All these aspects are the component parts of complementary virtuous circles (Figure 6) which ensure that safety is upheld on a day-to-day basis and improved continuously. Beyond the regulatory definitions and procedures, the smooth and efficient management of safety requires that all parties are fully aware of the safety stakes, their own responsibilities and the necessary cooperation with the other parties, who should be considered as partners. This may require information and training of all parties, if not some cultural change. Guidelines, such as those of PIARC [10] or France [6], can help in implementing a true tunnel safety management system.
Figure 6 The foundations of a road tunnel safety management system.

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Remark: References 4-8 can be freely downloaded from www.cetu.equipement.gouv.fr, in French and also English for most of them


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   10.14 Tools for road tunnel safety management, mid-2008
Magic Numbers in Tunnel Fire Safety

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ABSTRACT

In this paper we discuss the phrase “magic numbers” in tunnel fire safety. There is nothing magical about the numbers, but it is magical how they are derived. Sometimes it is even a mystery. A magic number is defined here as a technical design value obtained from a round table discussion of experts without any direct physical validation or traceable origin. They may be based on long experience and some limited experimental data but these numbers are usually a consensus in a group of experts sitting in technical meetings. They also tend to be interpreted as “true values” in the design process and they tend to live their own lives after assignment. Numerous design values that can be regarded as a magic number according to the above definition are analysed and discussed in this paper. Examples of such design values are the choice of heat release rates in MW, the distance in metres between escape routes and the choice of time-temperature curves. Today’s guidelines include various magic numbers and in order to avoid too many prescriptive solutions we need to deal with the problem based on rational engineering solutions, i.e. go from a prescriptive designing towards a performance based designing using results from risk analysis and new research. A way to do this is discussed in the paper.

KEY WORDS Tunnel fire safety, design value, magic numbers, guidelines

INTRODUCTION

Safety of people transported through tunnels is a high priority issue for tunnel owners, safety authorities and fire services. They all want to have tunnels that are comfortable, functional and safe for those who use them. The users should experience a positive and safe environment when travelling through them and they should be able to evacuate safely in case of an emergency. This is the common understanding of how we want the fire safety in tunnels to work. In order to fulfil this, the safety authorities create regulations, standards or guidelines describing in detail how to build the tunnels safe. These documents usually describe the technical solutions in a detailed way. They say that there must be a certain distance between escape routes so people can escape in case of fire. They say that there must be a ventilation system so we can control the smoke spread. They say that there must be portable extinguishers in the tunnel so people can stop early fire development. But they also say that it is the “self rescue” principal that is the base for the rescue and evacuation procedure. This means that it is up to you as a tunnel user to evacuate and respond to a threatening situation. The role of the fire services is in many minds to assist in the self-rescue process. The tunnel owner, safety authorities (regulators) and the engineers that design the tunnel safety provide you with an infrastructure and technical equipment to use in an emergency situation.

As a user, on the other hand, you have a certain responsibility and must understand that in case of fire you should use the escape routes, if available, and not the portals of the tunnel. You should listen to the information given to you in the loudspeakers and act accordingly. You should not wait for any fire services to rescue you; otherwise you may risk your life. At the same time no one will expect you to understand how the ventilation system works in a case of emergency. No one will expect you to be able to extinguish all types of car fires with a hand held extinguisher. But they do expect that you will leave the tunnel as soon as possible. The fire services do not always comply with this description, especially when discussing how much the fire services can assist in the self-rescue process or when fighting the fire. They are usually the ones who have to deal with the practical side of the incident when it occurs.
The large tunnel fires that have occurred in tunnels indicate that the common understanding of how it should work does not always comply with the real situation. Sometimes users do not behave as the designers expect them to. Users stay in the tunnel far too long before they begin to evacuate. Users tend to ignore any signs of danger and they rarely use the escape routes. The fires tend to be larger than designed, the exposure of the construction to the fire is far beyond all expected thermal impacts and durations, and the fire services become viewers of the catastrophe. These types of large incidents are fortunately infrequent. In the majority of tunnel fires, the fire is only a minor incident that complies well with the presumptions given in the guidelines. In most cases they are smaller fires, usually a single vehicle fire where no fire spread occurs between vehicles. The technical systems usually work satisfactorily and the situation can be easily handled by the tunnel operators together with the local fire services. The actual need of the safety systems in these situations varies.

NEED FOR A NEW TYPE OF GUIDELINES

Even if we have good experience of incidents that are not directly threatening to the users, we need to discuss how to improve present guidelines. The enormous research effort that has been conducted in Europe and other parts of the world the past few years requires it. In order to obtain more flexible and cost effective regulations, standards or guidelines, more rational design approaches correlating to risks, the traffic situation, fire load, tunnel geometries and boundaries are needed. Entirely performance-based approaches to all aspects of the tunnel fire safety are probably not possible. We know that prescriptive design, i.e. a design that regulates in a detailed manner the technical solutions, gives the tunnel users a basic safety level; but it is unclear what this basic level corresponds to in real terms. There should, of course, be simple rules for straightforward design, but we should not expect that straightforward design always gives the most cost effective and optimal safety solution. The basic design parameters are, in most road tunnel guidelines, the tunnel length and the traffic volume. These two parameters determine the safety classification of the tunnel. The philosophy behind it is simple. The tunnel length and traffic volume is related to the probability of accidents and fires. How the classification boarders between these two parameters are drawn is a very subjective process based on consensus among experts. Based on these parameters we are able to classify the tunnel and equip it with necessary safety measures.

These types of guidelines work relatively well for conventional tunnels, with simple tunnel geometry and layouts. This approach may not be cost effective for all types of tunnels. For example new type of tunnel structures or solutions which are complex in its layout, relatively long or with intricate and risky traffic situations, may need new solutions. Such examples include the new A86 tunnel in Paris with double-deck tunnels and low ceiling heights. If the regulators determine to solve the problem using prescriptive methods, the design of the technical safety systems will be based on ideas and traditions that were developed for much simpler applications. For example a tunnel system today may look like a ‘Swiss cheese’ and the air flow patterns may be very complicated. Many twin-tube road tunnels with longitudinal ventilation systems have numerous exits and entrance tunnels coupled to the main tube. Guidance standards on how to solve the ventilation in this type of tunnel systems are overdue. The concept of “critical velocity” is very well explored and studied in a scientific way, but there is a need for further developments concerning practical applications and how to introduce new innovative methods into the guidelines.

All the new research knowledge and technical development that is created cannot be fully applied in prescriptive guidelines. Therefore, it is my belief that we need to improve the existing guidelines. We need alternatives based on engineering solutions, i.e. performance based design, rather than guidelines using magic numbers. Law and Beever [1] say that when there are simple and arbitrary rules given there are always more argument and disputes than when an engineering approach is adopted, because the underlying technical assumptions are forgotten or not understood. This is certainly the case in tunnel fire safety. The majority of the experts dealing with fire safety regulatory work in tunnels have backgrounds as engineers, but not necessarily in the field of fire safety science and engineering.
Before we continue the discussion about performance based guidelines, we need to discuss the term magic numbers. Magic number is defined here as a technical design value obtained from a round table discussion by a group of experts without any direct physical validation or traceable origin. It is usually based on historical experience and traditions, different attitudes and perspectives, and reasoning in combination with limited experimental data. The phrase “Magic Number” was used for the first time by Margaret Law and Paula Beever in their paper on Magic Numbers and Golden Rules [1], where they related the subject to fire safety engineering design of buildings.

EXAMPLES OF MAGIC NUMBERS

Design fires

A classical example of a magic number that is often discussed and debated on is the choice of a design fire. The available data found behind the decisions is usually limited and which design fire is used in any given application is at least partly arbitrary. In Table 1, examples of design fires given in MW for road tunnels taken from the PIARC report [2], the French guidelines [3] and the NFPA 502 standard [4].

Table 1 Examples of design fires taken from different guidelines. The design values are given in MW.

<table>
<thead>
<tr>
<th>Vehicle type / Guideline</th>
<th>PIARC</th>
<th>French</th>
<th>NFPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 small passenger car</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 large passenger car</td>
<td>5</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>2-3 passenger cars</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Van</td>
<td>15</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>20</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>HGV (Heavy Goods Vehicle)</td>
<td>20-30</td>
<td>30</td>
<td>20-30</td>
</tr>
<tr>
<td>Tanker</td>
<td>100</td>
<td>200</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 1 shows a variety of numbers that are used for a design of the ventilation systems in road tunnels. Between 25 – 30 fire tests with passenger cars have been performed where the maximum HRR (Heat Release Rate) was measured. Tests both with a single car or multiple cars have been conducted. For other types of vehicles the data is much sparser. Only one documented test with a van has been performed, two tests with a buss, one with a fully equipped HGV and eight tests with a mock up of a HGV fire load. There is no available test data for a petrol tanker, although numerous tests with pool fires have been conducted. This indicates that design values found in the guidelines for road tunnels are based on a rather limited data and there is insufficient data for any type of statistical treatment. The situation is even worse for rolling stocks. The only tunnel tests available on rolling stocks are the few coaches tested in the EUREKA 499 project 1991 – 1992 [5]. This is a fact that regulators are fully aware of and which makes it is easy for them to take decisions on the acceptable levels for the design, unconstrained by scientific evidence.

When the levels have been established there is a reluctance to change them, even when new knowledge is presented. A good example is the HGV test carried out in the EUREKA 499 in 1992. The HGV consisted of a truck and trailer carrying mixed furniture. The maximum HRR was measured to be 120 MW [6]. Despite this test, experts at that time regarded this as an exceptional result as the test conditions with small cross-section and high ventilation rate were not comparable to a normal tunnel. After this test it was pointed out, that HGVs may create higher HRR than 30 MW, but only in special test conditions and/or for short period of time [2, 7]. The reason for choosing 30 MW for HGV, may be found in the argumentation given by Lacroix [3]: In HGV’s, “rather heavy fires are possible but their probability is very low. Some of them can produce very high HRR but during very
short times only. For example the Centre National de Protection et de Prévention has calculated from calorimeter tests performed on much smaller quantities that a full loading of wooden pallets (simultaneously lit at several places!) can produce 100 – 150 MW during 8-10 minutes, afterwards 30 – 50 MW, or polyurethane foam around 150 MW during 5 minutes then nearly nothing. Finally it was decided to choose 30 MW design fire which cover the great majority of the most serious HGV fires.” This is a very vague argumentation and it is not clear how the choice of 30 MW as a design value is related to the time history of the fire or the information given in the text. This level of HRR is, however, reflected in the values found in Table 1, i.e. 20 – 30 MW for HGVs.

The estimations carried out by the Centre National de Protection et de Prévention fit the HRR results of the Runehamar large scale tests [8] actually very well, which showed that the HRR value measured in the EUREKA 499 test was not an exception. A maximum HRR of between 67 – 202 MW was obtained in the Runehamar tests conducted using ordinary commodities including wood and plastic pallets, polyurethane mattresses, furniture and plastic cups in cartoons. The results are shown in Figure 1, together with other available HRR data for HGV fire loads, among them the EUREKA 499 HGV test. The maximum fire duration is definitely short, but that is the case with all burning solid material, even cars and coaches. As can be seen in Figure 1, the time period with HRR higher that 100 MW, is actually quite long in some of these tests. Despite all this new information, there is still reluctance by authorities and regulators to accept this new knowledge and act accordingly. This may be changing as the latest version of the NFPA 502, 2008 edition contains modification of the suitable size of design fire size for HGVs in tunnels, i.e. from 20 -30 MW to 70 – 200 MW.

**Escape routes**

Another magic number that can be discussed is the distances between escape routes. In the majority of regulations today, there are distances given in a fully prescriptive manner. In the new EU directive for road tunnels the distance is set to 500 m, whereas in the Swedish guidelines it is 150 m. The distance can vary significantly between the guidelines, everything from 150 - 750 m in road tunnels and up to 1000 m in railway tunnels. These design values are in most cases based on a consensus of expert groups in each country. There are no extensive scientific studies found behind these values. Today, it is possible with engineering methods (e.g. using FED model by Pursher [9] in combination with CFD calculations) to calculate the time of evacuation and to optimize the distances between the escape routes. This requires a certain design fire given as a function of time. The main problem for designers...
and authorities is the choice of design fire based on the expected traffic situation. This can be done using risk analysis and good engineering discipline but as long as we have prescriptive guidelines and regulations this will not be possible. They do not encourage this type of engineering (analytical) design. In fire safety engineering design of buildings in Sweden and many other countries analytical design methods are common. In Australia (AFAC- Australasian Fire Authorities), however, a performance based design for tunnels has been developed [10].

Temperature

Road tunnel linings are usually designed for standard time-temperature curves according to e.g. ISO 834, EN 1363-1 or ASTM E119, or much more severe curves such as the Hydro-Carbon (HC) curve, see e.g. EN 1363-2, the German ZTV curve or the Dutch RWS curve. It is the decision of the road authorities to choose a curve and a fire duration that is deemed suitable for a particular project. All these curves have been developed for a certain purpose, and not necessarily for tunnels. It is only the ZTV and the RWS curves that have some relationship to tunnel activities. The RWS curve is based on small scale tests using petrol pool fires. The test results from the Runhamar tests [11] confirmed the temperature levels of the RWS curve.

It is only in some design standards that the tunnel height and type of traffic (e.g. dangerous goods) may be considered. However, there is no generally accepted engineering approach available that provides clear guidance on which of the design curves to choose for a given application. Consequently, there is no correlation between the time-temperature curves for the design of linings and the fire heat release rates for designing ventilation systems. These systems are therefore chosen independent of the size and shape of the cross-section or of the thermal properties of lining materials. All these parameters together with the type and amount of fuel (petrol, plastics, woods etc.) together with the ventilation rate will in reality govern the gas temperature in the case of a tunnel fire. It is my opinion that it is possible to develop a rational engineering methodology that can be used for correlating the ceiling gas temperature to the design fire, the ventilation conditions and the cross-section. This type of work and results will definitely be a major contribution and milestone in the engineering fire safety design for tunnels.

Other

There are many examples of magic numbers that should continue to be used in the guidelines, e.g. the distances between hand held extinguishers, emergency telephones (despite the proliferance of mobile phones today), loudspeakers, signals, water supply to fire brigade etc. This is simply because these issues are not easily dealt with using engineering solutions. In a recently published report by Hak Kuen Kim et al.[12] a summary of the main tunnel guidelines including all the detailed requirements for road tunnels is presented.

DISCUSSION

Even though the prescriptive guidelines work reasonably well in the majority of tunnel fires it is a time for reflection over the status and usefulness of existing guidelines. We should try to reduce the amount of magic numbers and give more space for performance based requirements. The performance based requirements should focus on the costly parts of the tunnel structure e.g. smoke management, egress, fire resistance, fire suppression, emergency planning etc. They should be designed in relation to given design fires which are derived from scenario and risk analysis. Also the human behavior should be considered to be integrated in the design and emergency planning. This should include the expected behavior both from the tunnel operator and user in case of an incident, allowing proper training of operating personnel and public education. This part of the design may be equally important as the technical features of the fire safety systems. To give the reader an example on how a performance based requirement may look like we can present an example from the Australian guidelines [10] for design fire: “Different design fire and fire scenarios will need to be considered
and could include one or more of the following:

- Incidents with one vehicle
- Collision incidents (two or three private vehicles, private car and Dangerous Goods Vehicle (DGV), private car and passenger coach, DGV and passenger coach)
- Pool Fires. These generally will cater for incidents involving DGV and flowing liquid spill fires.

The proposed fire scenarios should be documented concerning selection process, aim, fuel characteristic, traffic situation etc. It is also mentioned that it is beneficial to conduct real fire tests prior to tunnel design if such information is lacking.

There are methodologies available on how to work with performance based type of design in buildings. Within NFPA 5000 Chapter 5 and ISO TC92 SC4 “Fire Safety Engineering” there are performance based design related options given which could be modified/adjusted for a fire safety design in tunnels.

New innovative solutions will find their ways into tunnel safety systems if performance based guidelines are practiced. One such innovative solution is the water spray technology. There has traditionally been strong resistance to the use of sprinklers or water mist systems or any other type of suppression system in road tunnels, particularly in Europe. However, the HGV tests in the Runehamar tunnel show that there are good reasons to review many commonly accepted views and attitudes. The surprising test results found in Runehamar have helped to renew interest in water spray or foam systems in road tunnels.

Performance based guidelines should be defined in such a way that they open up for “technical trade-offs” if, for example, a water spray systems is installed. The difficulty in defining trade-offs is that in the extreme, the water spray system would be the only fire safety system installed. Critics of trade-offs are quick to lift such examples to illustrate the pitfalls in a trade-off procedure. However, it is clear that this type of drastic approach will take some time to gain acceptance if ever and is probably not a good idea considering what could happen if the system were to malfunction. Experience must be gained with different trade-off alternatives to ensure that decisions made do not lower safety or endanger the safety system solution in general. The acceptance will entirely depend on the safety level and performance of the system as a whole and the individual components of the system and their interplay. Ultimately, trade-offs are preceded by an understanding of the reliability of individual components during their expected lifetime.

A very good description of the role of the fire safety engineer, if performance based codes are applied, is given by Law and Beever [1]. They say that a common misconception is that the role of fire safety engineer is to predict in detail what will happen in the event of a fire. According to them this is not the case. The fire safety engineer must produce a design which achieves adequate safety levels. In demonstrating this, the engineer may make use of some predictive techniques. However, these do not need to be precise or comprehensive in every instance. A small departure from a coded requirement does not place the task of carrying out a full fire safety analysis on the engineer. If this were true, fire safety engineering would be prohibitive both in terms of cost and from a liability point of view.

Finally I want to emphasize that we need to change our view of the basic boundary conditions defining the tunnel problem, i.e., *tunnels do not burn, vehicles do.* At present, we concentrate solely on the various supplementary systems in tunnels, such as the number of evacuation routes, the type of fire and smoke detection, monitoring systems or ventilation. Tunnels can never be totally fireproof as long as vehicles carrying large quantities of flammable goods use them. Certainly, tunnel operators can install various systems for fire-fighting and smoke evacuation, and can improve escape facilities, nevertheless, such measures are very expensive, and their efficacy can often be questioned. Greater responsibility should be placed on the potential source of catastrophic fires, the heavy goods vehicles that traffic these tunnels with substantial quantities of flammable cargoes, representing a high
CONCLUSION

In this paper the phrase “magic numbers” in tunnel fire safety has been discussed. They maybe based on long experience and some limited experimental data but these numbers are usually a consensus in a group of experts sitting in technical meetings. They also tend to be interpreted as “true values” in the design process and they tend to live their own live. Even if we have good experience with incidents that are not directly threatening to the users, we need to discuss and debate on how to improve tunnel fire safety guidelines. The enormous research effort that has been conducted in Europe and other parts of the world the past few years requires it. In order to obtain better regulations, standards or guidelines, more rational design approaches correlating to risks, traffic situation, fire load, tunnel geometries and boundaries are needed. Entirely performance-based approaches to all aspects of the tunnel fire safety are probably not possible. Past research has proven this to be true, it will be the role of future research to provide solutions to this problem.

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The Use of CFD-FDS Modeling for Establishing Performance Criteria for Water Mist Systems in Very Large Fires in Tunnels

Jack R. Mawhinney and Javier Trelles

ABSTRACT

In this study a computational fluid dynamic (CFD) model was applied to a series of full-scale fire tests of water mist systems conducted in 2006 in the San Pedro de Anes test facility in Spain. Data were collected on the heat release rates (HRR) of very large test fires involving wood pallets and plastic pallets under controlled conditions. Thermocouples placed on the tunnel ceiling and at different distances from the fire recorded temperatures throughout the fire tests. The tests provided valuable insight into the dynamics of water mist interacting with very large fires in a tunnel. The fires were more dynamically complex than assumed in selecting indicators of performance. To assist in understanding the dynamics of such fires and to aid in identifying reproducible “global” performance criteria as an alternative to single-point measurements, the Marioff San Pedro tunnel fires were modeled using a CFD model. The purpose was to evaluate the performance of water mist systems over a broader range of performance indicators than could be measured during full-scale tests. The NIST Fire Dynamics Simulator version 4 (FDS4), a CFD model with a water mist spray nozzle algorithm, widely used in fire science and engineering, was used to simulate the Marioff San Pedro tunnel fires. There is presently extensive international activity by many agencies in applying CFD to tunnel safety problems. However, there are numerous challenges involved in applying a CFD model, with discipline and intent for accuracy, to very large fires interacting with water mist. This paper discusses how specific modeling challenges were approached for this study. The paper illustrates that CFD modeling is a powerful tool for understanding the global benefits of water mist systems.

KEYWORDS: computational fluid dynamics, fire control, fire testing, FDS, heavy goods vehicle, performance criteria, tunnels, water mist.

1 INTRODUCTION

Before a manufacturer’s water mist system design will be accepted by transportation authorities, highway safety officials within each country require fire testing to evaluate the performance and establish design criteria. Since 2000, various full-scale fire test programs involving water mist fire protection systems have been carried out by different groups in numerous countries in Europe. Ideas about how to design fire tests to evaluate system performance and about what constitutes acceptable performance of a water mist system vary between countries and agencies. A common feature of all of the fire test programs undertaken in recent years, however, has been that the test fires are much larger in scale than has been the norm for performance testing of fire protection systems in traditional industrial applications. This is largely the result of tests conducted in 2003 in the Runehamar tunnel in Norway [1], which revealed that the heat release rates from uncontrolled fires in common heavy goods vehicle (HGV) fuel loads could range from 75 to 200 MW.

Very large test fires introduce a number of difficulties for approval-test programs. The large fire sources used, consisting of large numbers of stacked wood or plastic pallets, are not well understood or characterized, particularly in the special conditions created by confinement in a tunnel. Furthermore, in establishing criteria for the minimum level of performance of a fire-control system,
often the choice of a particular condition as a pass or fail criterion is based on a theoretical construct that does not take into account the chaotic environment of a very large fire. Most fire test protocols for water mist systems establish pass/fail criteria based on single-point measurements, such as a thermocouple temperature reading or a heat flux value at a certain height and distance from the fire. It is difficult to compare single-point measurements between tests because of the highly variable local conditions generated by large fires. Assuming that the test materials have consistent burning properties, local ventilation conditions may be modified by obstructions, with a disproportionate effect on heat release rate and fire growth rate. Transient flame extensions create erratic readings such that it is not possible to ensure a specific condition such as temperature or heat flux, to within one or two meters. Fuel packages change shape and height over the course of a fire, causing apparently illogical spatial and temporal variations in readings.

In the fire test scenarios developed by the International Maritime Organization for evaluating water mist systems for marine machinery spaces on ships, a 10 MW fire was considered to be a “large” fire [2]. The IMO water mist test protocol for machinery spaces intended that the fires be extinguished within 15 minutes. In contrast, a water mist fire protection system for tunnels is not expected to extinguish HGV fires. The objective of the water mist system is to control the fire, prevent temperatures in the tunnel from exceeding extremes, and to prevent fire propagation to other vehicles in the tunnel. A controlled fire in a tunnel may have peak heat release rates of 20 to 50 MW while being prevented from growing to its full potential, which may be as high as 100 to 150 MW. Although the HRR during the control period may be only a fraction of what the fuel package would achieve without the water mist system, a sustained 20 MW fire is nonetheless a large fire, and it generates a large volume of flame. The controlled fires are highly sensitive to apparently small changes in ventilation or spray penetration; therefore the HRR itself will not be a steady-state value. It is important to recognize the dynamic nature of these fires in selecting appropriate criteria for measuring performance of the fire protection systems. The progression of events associated with controlled, but still large, test fires in tunnels does not follow a linear path that can be consistently confirmed by a few single point measurements.

Marioff Corporation Oy of Finland conducted a program of full-scale fire test involving HGV fires in the San Pedro de Arnes Tunnel Safety Test (TST) facility (San Pedro tunnel) in Asturias, Spain in 2006. Hughes Associates, Inc. (HAI) acted as a third party witness and reporting agent for the tests. The tests evaluated the performance of a high pressure water mist system against fires in stacks of standardized wood pallets and of wood pallets interspersed with polyethylene (HDPE) plastic pallets. The tunnel was equipped with instrumentation to allow calculation of the heat release rate (HRR) of the fires by oxygen calorimetry, and thermocouples were mounted on the ceiling and at various locations in the tunnel. Details of 11 tests conducted in the San Pedro tunnel, including heat release rate data and temperature plots are provided in the test report [3].

Examination of the HRR data and the time-temperature plots in the San Pedro tunnel tests supported the following observations:

- The water mist prevented fires from reaching the full potential peak HRR for the fuel array; fuel arrays of potentially 75 MW were sustained between 20 and 40 MW; fuel arrays of potentially 100 MW were limited to approximately 60 MW.
- Continued burning of fuel packages at 20 to 25 MW generated significant volumes of flame
- Because of shadowing by unburned pallet stacks temperatures closer to the fire could be cooler than temperatures farther from the fire, confounding simplistic performance criteria.
- Temperatures directly over the fuel package where flames impinged on the ceiling were 800°C or higher over short sections of ceiling.
- Expectations that the water mist system should limit temperatures above the fire to 500°C, or that temperatures farther from the fire “ought to be” lower than closer to the fire, could not be met.

At the same time, it was evident that dramatic reductions in the severity of the impact of the fires on the overall tunnel environment were realized in all tests. Whether the temperature measured at a point...
was 450°C instead of 350°C, at 8-m instead of 5-m from the fire, or at 15-min instead of 10-minutes after activation, imposed a demand for precise control that was inconsistent with the chaotic variability of the large fires. A few single point readings of temperature at pre-selected points were not adequate to reflect the broader thermal management benefits of the water mist system. The quest was initiated for "global performance criteria" that would allow one to evaluate the benefits of a fire control system, in spite of the large variability and uncertain reproducibility of single point measurements. Global performance criteria, for example, should be based on measures that are not subject to the large variability associated with single-point measurements.

A review of tunnel safety literature from recent conferences and symposia reveals that CFD modeling is being widely used as an investigative tool for tunnel safety issues [4, 5]. Computational fluid dynamics (CFD) modeling provides a means to visualize and analyze the phenomena involved in the tunnel fires beyond what can be observed or measured directly. To this end, HAI simulated the Marioff San Pedro tunnel fire tests using the NIST Fire Dynamics Simulator (FDS4), which is a CFD model with water mist spray nozzle algorithms. If the model can be shown to predict conditions similar to those measured during the full scale tests, within the uncertainties inherent in the test data, it will be confirmed to be a useful tool for evaluating the performance of water mist systems over a broader range of conditions than could affordably be tested.

2 DESCRIPTION OF THE FDS4 MODEL

The San Pedro de Anes Tunnel Safety Testing Centre (San Pedro test tunnel) is 600-m long, with an S-bend curvature and a -1% gradient. The tunnel is built at grade in concrete, with dimensions equivalent to a two-lane road tunnel. A false concrete ceiling was installed to create a rectangular cross-section with dimensions 9.50 wide by 5.17-m high. The dimensions of the test tunnel are as shown in Table 1 and Figure 1.

<table>
<thead>
<tr>
<th>Table 1. Dimensions and features of the San Pedro test tunnel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length: 600 m</td>
</tr>
<tr>
<td>Width: 9.50 m</td>
</tr>
<tr>
<td>Height: 5.17 m with false ceiling</td>
</tr>
<tr>
<td>Cross section (with false ceiling): 49.4 m²</td>
</tr>
<tr>
<td>Minimum radius (S-bend): 400 m</td>
</tr>
</tbody>
</table>

Figure 1. Cross-sectional view of the San Pedro test tunnel.
Computational Domain

Fire Dynamics Simulator, version 4.0.7 (FDS4), was used. FDS4 is a three-dimensional large eddy simulation (LES3D) CFD program developed at the National Institute of Standards and Technology (NIST) Building and Fire Research Laboratory (BFRL) [6, 7]. FDS is developed specifically for studies related to fire science and engineering. At the time this work began Version 5 was at an early release state. Version 4.0.7 was employed for the current study.

To achieve an adequately small cell size, only a 140-m long section of tunnel between Station 0+320-m and 0+460-m was modeled. This section incorporated the second half of the S-bend, the water mist system piping and the instrumented portion of the tunnel. Figure 2 illustrates the domain and Table 2 summarizes the characteristics of the computational domain. Although the tunnel was 9.5-m wide, the FDS domain had to be 23-m wide to accommodate the curvature. The FDS4 domain was divided into cells of dimension \( 0.250\text{-}m \times 0.230\text{-}m \times 0.215\text{-}m \). This was adequate for tunnel flows, but not sufficient to resolve flow in the pallets. The domain included a centerline, stations marked at 10 m intervals, ceiling thermocouples, four thermocouple tree stations, and a fuel load. The left end of the tunnel contains the forced-flow boundary condition governing the inlet air velocity. The right end is open. Unused space is blocked out. The line down the middle of the tunnel represents the tunnel centerline. Vertical bars demarcate the projections of the 10 m stations along the tunnel centerline and are numbered accordingly. This domain contains three parallel lines of water mist nozzles, 3.3-m on either side of a center line, with nozzles 0.1 m below the ceiling at 4-m spacing between stations 356 m and 424 m. Thermocouples and water mist nozzles are placed to within plus or minus half the resolution given in Table 2.

Thermocouples were spaced at 5-m intervals along the centerline 0.1-m below the ceiling surface. There were four vertical thermocouple tree stations placed along the tunnel, two upstream (T1 and F1) and two downstream (F2 and T2) of the fire location. Plots of the temperatures recorded at these locations throughout each test were presented in the test report [3]. These data could be used to compare with the results of the FDS4 simulation, as a means of validation.

![Figure 2. The computational domain for the San Pedro test tunnel fire simulations.](image)
Table 2: Summary of FDS4 input parameters used in the simulation series.

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD Domain</td>
<td>Facility</td>
<td>San Pedro de Anes Research Tunnel</td>
</tr>
<tr>
<td></td>
<td>Simulation dimensions</td>
<td>140 m×23 m×5.17 m</td>
</tr>
<tr>
<td>Numerical</td>
<td>Grid dimensions</td>
<td>560×100×24 cells</td>
</tr>
<tr>
<td></td>
<td>Cell size</td>
<td>25.0 cm×23.0 cm×21.5 cm</td>
</tr>
<tr>
<td></td>
<td>Total # of cells</td>
<td>1,344,000</td>
</tr>
<tr>
<td></td>
<td>Wall boundary conditions</td>
<td>Concrete</td>
</tr>
<tr>
<td></td>
<td>Floor boundary conditions</td>
<td>Concrete</td>
</tr>
<tr>
<td></td>
<td>Ceiling boundary conditions</td>
<td>Concrete/Promat Promatect-H</td>
</tr>
<tr>
<td></td>
<td>Gravity vector (-1%)</td>
<td>(0.0981, 0.0, -9.8095) m/s²</td>
</tr>
<tr>
<td>Spray Nozzle</td>
<td>Type</td>
<td>Marioff 4S1MD6MD(1000,10RE) water mist</td>
</tr>
<tr>
<td></td>
<td>Configuration</td>
<td>4 m×3.3 m grid</td>
</tr>
<tr>
<td></td>
<td>Activation criteria</td>
<td>Times as determined from test data</td>
</tr>
</tbody>
</table>

Water Mist Drop-Size Characterization

The original spray model in FDS4 was based on the spray distribution characteristic of standard sprinklers. High pressure water mist nozzles have a very different drop size distribution and range of velocities and spray angles. The standard spray model in FDS4 uses a composite Rosin-Rammler log-normal distribution, as shown in Eq. (1).

\[
F(d) = \left\{ \begin{array}{ll}
\frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\ln[d / d_m]}{\sqrt{2} \sigma} \right) \right] & \text{if } d \leq d_m \quad \text{(Log - Normal)} \\
1 - e^{-\frac{d}{d_m}} & \text{if } d > d_m \quad \text{(Rosin - Rammler)}
\end{array} \right.
\]  

(1)

The parameters of interest are the log-normal standard deviation \( \sigma \), and the Rosin-Rammler exponent, \( \gamma \). In a study performed by HAI in 2004 [8], the FDS spray model was found to provide a poor fit to the fine fraction leg of the distribution because FDS4 calculates \( \sigma \) from \( \gamma \) and imposes a slope continuity requirement at the intersection between the two branches of the composite distribution curve. Hence FDS4 was modified so that both \( \gamma \) and \( \sigma \) could be input and then processed as input in all the pertinent calculations within FDS4. The drop size distribution for the 4S 1MD 6MD 1000 open spray nozzle was determined experimentally by Marioff. The second nozzle used in the tests (thermally activated 2N 1MD 6MD 10RE) had the same orifice sizes, therefore the same drop size distribution was used for both types of nozzles. The three measured values for Dv10, Dv50 and Dv90 were used. These represent the drop diameters for the 10, 50 and 90 percent cumulative volume fractions of the spray, where Dv50 is the median diameter \( d_m \). The values from the measured cumulative volume fraction distribution curve are the best choice since it is the unadulterated distribution. The measured drop size distribution gave Dv[50] = \( d_m = 89 \) micron, Dv[10] = 35 micron, and Dv[90] = 171 micron. From these data it was determined that the \( \gamma = 1.84 \) and \( \sigma = 0.728 \). Figure 3 shows the resulting Rosin-Rammler/log-normal distribution for the water mist spray characterization.
Spray Nozzle Characterization

The spherical model within FDS4 was used for characterizing the spray distribution pattern of a multi-port nozzle. Figure 4 shows the sphere with radius of 0.2 m divided into 1056 solid angles. Droplets can be introduced through any of the user-defined solid angles that make up the sphere. The nozzle had one port on the center axis and 6 circumferential ports, which were evenly spaced around the circumference 45° from the south pole. The single center jet was modeled using the 48 solid angles around the south pole of the sphere. Thus, 54 of the solid angles were assigned a non-zero flow value. Required inputs are the initial droplet velocity $u$, and the mass flux, $\dot{m}''$, through the face of each solid angle. The total mass discharge rate from all orifices, as a function of pressure, was provided by the “K-factor” for the nozzle. FDS4 would introduce droplets from each face in Figure 4 according to the relative value of $\dot{m}''$ for that solid angle.

Each batch of drops reflected the drop size distribution determined for the overall spray defined earlier. The initial velocity at each face was determined from orifice flow calculations. It was noted that the temperature of the water in the piping system varied in different tests, depending on the allowed pre-burn time and the number of nozzles opened. An estimate of different initial water temperature was made. Table 3 presents the nozzle characterization parameters used for the tests simulated in this study. It should be noted that in the previously referenced HAI spray characterization study [8], it was found that the quality of the tracking of the particle distribution from the nozzle (under non-fire conditions) improved significantly with decreased grid size, and was optimal at a grid size approximately $1/10^6$ the size used in this simulation. Due to computational
limitations such a fine resolution grid was impossible to apply to the 140-m tunnel length.

Table 3. Nozzle characterization parameters used in the simulations.

<table>
<thead>
<tr>
<th>Test Identifier</th>
<th>Run Pressure (bar)</th>
<th>$T_{H_2O}$ ($^\circ$C)</th>
<th>4S 1MD 6MD 1000</th>
<th>2N 1MD 6MD 10RE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$u$ (m/s)</td>
<td>$m_c^*(a)$ ($kg/s/m^2$)</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>50</td>
<td>123.5</td>
<td>51.2</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>50</td>
<td>110.5</td>
<td>45.8</td>
</tr>
<tr>
<td>3</td>
<td>78</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>90</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>80</td>
<td>50</td>
<td>110.5</td>
<td>45.8</td>
</tr>
</tbody>
</table>

a.) The subscript “c” stands for center orifice; subscript “r” for ring orifices.

Activation times for the water mist spray nozzles and the operating pressure in each test were obtained from the test data. The pressure in the nozzle characterization files was modified to match the nominal zone pressures for each test.

Modeling the Fuel Package and Heat Release Rate

The HGV fire fuel packages consisted of large stacks of wood “euro-pallets”, with dimensions 7.7 m x 2.4 m x 2.1 m (L x W x H), placed on a 1-m high platform in the center of the tunnel. From oxygen calorimetry a HRR curve for each fire under controlled conditions was obtained. Inputting an actual HRR versus time plot for a crib-like fuel array was challenging. The heat release rate from any given section of a pallet stack can rise or fall according to the wind blowing through the array, contributions from other members as the combustion reaction spreads, and radiative feedback from walls and ceilings. The method employed for this study attempted to capture important phenomena such as the gross heat release rate, flame spread across the fuel load, air flow though the pallet arrays, and the progressive collapse of consumed sections.

Figure 5. Left: photograph of the end-view of pallet stacks showing 5 “columns”. Right: the support structure used in the model for the top-cell method, to allow air to flow through the fuel array.

Because the 0.25-m resolution in the cell height was greater than the vertical dimensions of the
individual pallets, the full detail of the stacked pallets could not be represented. Instead, methods were explored by which some of the flow-through-porous-media effects could be obtained given the limitations of FDS and the resolution used for the simulations. The stacks of pallets were modeled as 5 vertical “columns” representing the stacked wood blocks in the pallets, with air space between and a solid plane for the upper surface of the array. The combustion phenomenon was assigned to strips of cells on the upper plane of the array, as is described below. The structural representation of the fuel load was solely to support the top cells and to model the obstruction-effect of the stacks without creating a solid block obstruction.

Figure 6 is a photograph of a pallet fire at approximately 3 minutes after ignition, with no wind-breaks or tarpaulins and 2 m/s ventilation velocity and prior to activation of water mist. Several approaches were investigated to recreate the flame volume observed around the burning pallets. The approaches included a “block method”, a “full-height top-cell method”, and a “half-height top-cell method”. The “half-height top-cell method” provided the best representation of flame volume above and around the fuel array.

The “Half-Height Top Cell Method” of Modeling Stacked Pallet Fire Growth

For the top cell method, flames were only allowed to come from the top of the support structure representing the pallet load. This was chosen because FDS’s flame height algorithm was calibrated using flat fire bed examples. After trials with a full-height support structure, instead of placing the plane of cells at the elevation of the top of the pallets in the tunnel, the surface of cells was placed at approximately half the height of the pallet stacks. The result was a collection of upward facing “fire bed” cells at approximately 2.9-m below the ceiling. This allowed for a greater volume to be filled with flame than would be the case if the flames originated from the true top surface of the pallets, only 1.9-m below the ceiling. The goal was to get the majority of the flames occurring outside the pallet load as the test photographs indicated.

Figure 6. Photograph from upwind of -pallet fire showing flame volume, with corresponding HRR plot for Test 1. Fire is approx. 12 MW.

The flame spread methodology was as follows. The top surface of the support structure was divided into cells as shown in Figure 7. All cells were assigned a heat release rate per unit area $q''$. 

\[ q'' \]
In the top cell method, cells burn from front to back along the top of the commodity only. The combustion progresses as a traveling band of open cells. Uninvolved cells are denoted with an ±. Cells that burn-out are also shown with an X. For these cells, the supporting structures are removed in order to simulate the collapse of the commodity.

Figure 7. Illustration of the burning sequence of top-cells on the half-height support structure.

This quantity, $q^*$, varied from simulation to simulation, and was determined by taking the maximum HRR achieved in a test and multiplying it by a scaling factor proportional to the cell-life-to-run-time ratio, dividing it by the number of available cells, and dividing it by the area of one top cell. Starting from the middle of the width at the upwind end, and working laterally in both directions, individual cells would start to burn according to the input HRR curve. In the absence of longitudinal flame spread data, each cell was given a finite life of about a quarter of the total simulation time. This created a de facto spreading front across the surface of the fuel load. The number of available top cells varied from simulation to simulation as well, being determined by the fuel array dimensions and by the percentage of the pallets not consumed. Once a strip of top cells ceased to burn, the supporting obstacles were removed as well, simulating the collapse of consumed pallet stacks.

FDS’s oxygen depletion algorithm was turned off. This function would have reduced the HRR if there was insufficient oxygen in a cell. Since the goal of the simulations was to match a confirmed input heat release rate, further automatic reduction by FDS4 was unwanted.

Although it was not possible to conduct a free burn (uncontrolled) fire test in the San Pedro test tunnel, a simulation of a fire without water mist was performed using the FDS4 model. The uncontrolled fire utilized a HRR curve for Test 10, which was a severe fire that reached a peak of 57.5 MW with a minimal application of water mist. The Test 10 HRR curve was used as input for a fire in the location and with the ventilation conditions of Test 1, but without applying any water mist. The curve was a conservative (under) estimate of the severity of an uncontrolled fire in the wood pallets. The results of the simulation revealed the extent of extremely high temperatures and heat flux in both the upwind and downwind directions. The results provided an unambiguous benchmark to which the global performance benefits of a water mist system could be compared.

3 RESULTS

Several plots from Test 1 will be compared to simulation results for Test 1 to demonstrate that the level of agreement was sufficient to justify use of the model for a scenario not tested, namely the uncontrolled fire case. Two field plots are presented to show the contrast between the thermal conditions for a controlled fire case (Test 1) and a simulated uncontrolled fire.

As each simulation run proceeded, a check was performed to determine how closely the top cell algorithm value for HRR at time $t$ was to the smoothed HRR test data. Figure 8 shows the comparison for Test 1.
Figure 8. Comparison of HRR from test data, with the FDS4 simulated HRR curve for Test 1.

In the simulation, the HRR averaged around the smoothed test curve, and the magnitude of the “noise” either above or below the average value was contained within the estimated uncertainty bars. The agreement shown between the simulated and the measured HRR input is excellent.

Figures 9 and 10 show the ceiling thermocouple temperatures for Test 1, for the test and the simulation, respectively. The figures show that the simulation reproduced the major cooling effects associated with the water mist acting on the fire. Just prior to activation of the water mist system at 7:30-mins, the temperature at TC C07, 26 m from the fire area, was measured at 350 °C; the simulation indicated a temperature of 300 °C. At the same time, TC C11 indicated temperatures just over 500 °C; the simulation showed approximately 550 °C.

The differences between test and simulation temperature before activation of the mist system were within 50 °C. The thermocouples above the fuel package recorded temperatures from 800 °C to 1000 °C indicating contact with flame. The simulation predicted temperatures in the same range. Following activation of the water mist, the simulation captured the large reduction in temperatures downwind of the fire. For TCs C10 to C07 the simulation temperatures were generally between 150 °C and 200 °C, whereas the measured temperatures were between 50 °C and 100 °C. Thus, the simulation temperatures were approximately 100 °C higher than measured. While thermocouples in wet conditions may be cooled by the presence of water condensate, it is also the case that the model results were sensitive to the properties of walls and ceiling. The floor pooling function in FDS was turned off to minimize computational demand. It is possible that downwind temperatures would have been lower (in the simulation) if the effect of water accumulated on the floor had been included.
Figure 9. Ceiling temperatures at 5-m spacing, measured in Test 1. TC C13 (highest temperatures) is exposed to flames directly above the fuel array.

Figure 10. Ceiling temperatures at 5-m spacing, from simulation of Test 1. TC C12 (highest temperatures) is 1-m downwind from the end of the fuel array.

Figures 11 and 12 compare selected longitudinal temperature profiles in the tunnel for Test 1, from the test data and the simulation, respectively. The tunnel ventilation air moves from left to right. These plots show the center-line temperature at 5-m intervals between station 345 m and 450 m at the indicated times. In Figure 11, the highest temperatures measured in the test occurred just prior to activation of the water mist system at 450-seconds after start of the simulation. The temperature at station 360 m, 25-m upwind was measured at 200°C – indicating back layering. The simulated temperature at Station 360 m in Figure 12 shows 240°C, within the error bar of 200°C. Following activation of the water mist, the back layering disappears to approximately station 380 m in both figures. Thus, the line of ceiling thermocouples extending over 135-m of tunnel, revealed several “global” benefits of the water mist system – elimination of the back-layering in the upwind direction, and a reduction in down wind temperatures measured in 100’s of degrees. To reveal these global effects of the water mist system required a line of over 20 thermocouples. The effect on the back-layering would not have been so clearly evident from a single-point reading in an area of erratic, variable readings.
Prior to activation of the water mist at 450-s, the downwind simulation results in Figure 12 agree very well with the test temperatures shown in Figure 11. After activation of water mist, the agreement is not quite as close, as simulation temperatures were roughly 100°C higher than measured. Nevertheless, the simulation conservatively predicted the *global* performance, i.e., the scale of the thermal management provided by the water mist system.

Figure 11. Ceiling temperature profile along the length of the tunnel, at instant just prior to water mist activation, and at 5 minute intervals thereafter, measured in Test 1.

The FDS model can be used to evaluate global benefits of a fire protection system beyond what can be measured. In this study, contrasting conditions with and without water mist provided a striking example of how the model assists understanding of the scale of the benefits. Figures 13 and 14 show the results of a simulated heat flux calculation for an uncontrolled and a controlled fire, respectively, at 16 minutes after ignition. The darkened zone (red in color) in the uncontrolled fire (Fig. 13) represents the zone wherein the heat flux to the floor exceeds 5 kW/m², high enough to be untenable for unprotected humans, and to present a serious challenge even for fire fighters in protective clothing. Heat fluxes at elevations above the floor would be higher still. Without a water mist system, the dark area extends from station 390 m to Station 435 m. With the water mist system (Fig. 14) it is confined to a small region at the end of the burning vehicle. The point is made that, when contrasted against conditions resulting from a fire in a tunnel with no fire protection system, the global performance benefit of the water mist system is unquestionable. It is advisable to provide sufficient
instrumentation for performance tests to identify global performance benefits of this scale, without undue reliance on single-point measurements which could be in a zone of high variability.

4 CONCLUSION

This paper has described how full-scale fire tests involving very large HGV fires interacting with water mist in a tunnel are much larger, more chaotic hence less predictable than smaller fires commonly used in fire testing. Criteria used to evaluate performance of water mist systems should not be based on single-point measurements that are highly variable, not reproducible with any degree of consistency and fail to reveal the actual scale of the benefit provided by the water mist system. By combining CFD analysis with full-scale fire test results to validate the general accuracy of the model, it is possible to illustrate the benefits of the fire protection system beyond what can be measured or even practically tested. CFD modelling is a powerful tool for understanding the global performance of water mist systems in tunnel fires. Use of the model makes it easier to develop instrumentation strategies that are consistent with the scale of the uncertainties inherent in large, chaotic test fires.

Figure 13. Heat flux to the floor at 16 min 5 s, for an uncontrolled fire at 16 min 5 s. The elongated dark area between station 390 m and 435 m indicates heat flux at the floor > 5 kW/m².

Figure 14. Heat flux to the floor, Test 1 with the water mist system, at 16 min 5 s. The small dark “island” between stations 394 m to 400 m indicates heat flux at the floor > 5 kW/m².
REFERENCES


Active and Passive Fire Protection –
which Way should we go?

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ABSTRACT

The severe fire accidents in various traffic tunnels during the last couple of years led to an intensive national and international discussion on the best solution of a sufficient fire protection. By this the basic question was risen if an active or a passive fire protection is preferable. The paper investigates this question and comes to the conclusion that starting from the experience in the field of commercial plants and public assembly facilities it is recommended in case of newly built constructions to apply a combination of both. Only if an already existing facility is to upgrade the combined use of active and passive protection measures can be unfeasible or too expensive.

KEYWORDS: tunnels, active and passive fire protection, fixed fire suppression system, fire safety, fire proof cladding

INTRODUCTION

Fires in traffic tunnels can result in real catastrophes as we had to learn at least by the recent incidents in road tunnels as in the Mt. Blanc Tunnel (France/Italy, 24.3.1999), the Tauern Tunnel (Austria, 29.5.1999), the Gotthard Tunnel (Switzerland, 24.10.2001; Figure 1), the Baregg Tunnel (Austria, 14.4.2004), the Fréjus-Tunnel (France, 4.6.2005; Figure 2) and most recently in the Viamala Tunnel (Switzerland, 17.9.2006) or in the funicular tunnel of the Kitzsteinhorn (Austria, 11.11.2000), and in the Metro of Daegu (South Korea, 18.2.2003). All these incidents cost too many lifes and they taught us some new aspects which were neither known nor expected before, if we do not consider the fire in the Nihonzaka road tunnel in Japan 1979, where about 189 vehicles were involved. One of the new lessons has been the extremely fast development of the fire combined with a tremendously fast increase of temperature up to about 1000 °C and even more as well as the enormous emission of masses of smoke from the very beginning of the fire. The second was the fire jump from one car to another even over sections of more than 200 m as in the Mont Blanc Tunnel where no vehicle was stopped. The third and most shocking aspect was the wrong behaviour of many road tunnel users. Too many of them did not realise the danger to which they were exposed. They felt safer in their cars which might be right for the very first minutes and they did not want to leave back their property unobserved. If ever and finally they realised that they are extremely endangered it was too late for a successful escape. They did not save their cars, but lost their not regainable lifes. This is by far the most tragic experience.

Against this background every proposal for any improvement in the direction of avoiding a vehicle fire especially in a tunnel, easing the escape conditions, rescuing tunnel users, and automatic fixed fire suppression is welcome. There never is any stupid idea in this field. But immediately after a new or modified idea is born we have to evaluate systematically and seriously, if it is feasible, effective and reliable. In case the first theoretical judgement is positive we have to investigate carefully the details...
for realisation and finally we should do tests under conditions as realistic as possible. Those tests are a key issue to avoid investments in systems which at the end do not keep what they according to the theoretical thoughts promised. In this connection it is highly recommended – not to say essential – to come to an international agreement and co-operation for planning and conducting the various steps of those practical tests. The increasing shortage of public money asks for a concentration of financial sources. National going it alone must be avoided last but not least against the necessity of harmonised safety concepts in multinational units such like the European Union (EU) or the North America Free Trade Agreement (NAFTA). Purely national efforts will lead to a situation where the first and simplest specific technical aspects are investigated several times again and again instead of combining various important questions in one multinational project supplemented by collecting the different national experience.

Figure 1 Burning lorry in the Gotthard Tunnel (Switzerland) on 24.10.2001.

Figure 2 Fire accident in the Fréjus -Tunnel (France) on 4.6.2005.

BASIC REFLECTION ON FIRE PROTECTIVE MEASURES

In connection with fires the basic idea of using effective countermeasures installed from the very beginning in a facility possibly endangered by fire is not at all a new one. Since many decades it is systematically followed and successfully implemented in the field of industrial plants, storage facilities, warehouse departments, public assembly places etc. In all these types of facilities the combustible masses are more or less steadily lying at the same place. On the contrary, in a traffic tunnel the combustible masses are moving. This results in a completely different situation which makes it much more difficult to handle a starting fire.
Considering any industrial or commercial facility mentioned above one of the first and most important questions in the design stage regarding the fire safety concept is if the main focus should be given to active or passive fire protection means or to a combination of both. An active fire protection measure is normally given with any type of a mainly water based fire suppression system such like a sprinkler or a deluge system. They are to combine with an efficient fire detection and localisation system. In addition smoke extraction and a controlled ventilation system has to be used in those industrial and commercial as well as public assembly facilities. All these technical measures are normally complemented by organisational regulations concerning the use of the facilities. There are specific rules and restrictions for the users how to behave generally. These are prophylactic regimentations to avoid fire accidents.

In the field of industrial and commercial buildings it is usual to supplement the active fire protective means by passive ones. The passive fire protection consists of structural components starting with the application of fire proof construction materials. This can be complemented taking a concrete structure as an example by using additional reinforcement or affixing on the fire side a special fire proof cladding of mineral boards (Figure 3) or layers of specific plaster (Figure 4). Those passive fire protection devices offer some advantages: there is no operational maintenance needed and in general they do not fail in their principle function. But, depending on the type of passive fire protection chosen there are also to consider some disadvantages. In general, those measures generate additional construction costs. Taking mineral boards or plasters the clearance of the available space gets reduced and the construction time extended because of an additional construction step. Aging and corrosion effects could by the time deteriorate the fixing elements of the boards or the adhesion effects of the plaster layer against the original substructure. This can result in a local falling down of the fire proof cladding material. Another disadvantage is given with the fact that there is no visual access to the substructure itself for the purpose of inspection except after removing parts of the cladding. In case of a tunnel there could also be a risk of partial falling down due to alternating suction and pressure loads generated by fast trucks. Additional problems can be caused in tunnels by moisture and seapage water effecting the thermal insulation capacity of the cladding in a negative way. Finally, in general a renewal of the cladding after 25 to 30 years has to be encountered. This means that the cladding has to be installed 3 to 4 times during the life-cycle of a tunnel.

Figure 3 Fire proof cladding of mineral boards in a road tunnel.
Choosing the solution of an enlarged concrete cover for the reinforcement up to 6 or 7 cm requires an additional layer of reinforcement. This has to be set-up towards the fire affected side of the lining with a concrete cover of about 2 cm. Usually a light wire mesh with a grid of 5 by 5 or 10 by 10 cm is applied and fixed to the main reinforcement in a distance of about 4 to 5 cm using binding wire. The additional reinforcing mat shall keep the very first concrete layer and thus avoid an ongoing spalling effect. The disadvantages linked with this solution are given by again an increase of costs due to the consumption of additional construction material, by an additional working step needed, and by a reduction of clear space available because of the enlarged thickness of the lining.

In all cases where not an existing structure has to be upgraded to improve the structural fire resistance but a new structure is to built the preferable use of special fire proof concrete material is strongly recommended. This necessitates a specific mix for a concrete quality of class C25/30 or higher, the application of quarzite instead of chalky aggregates, the addition of about 3 kg/m³ polypropylene fibres, and in special cases additionally the replacement of the maximum core group of aggregates by basaltic gravel. Such a special lining does not require any type of the previously mentioned fire proof claddings, does not ask for additional cubature because of a larger wall thickness and does also not need an additional construction step. This solution offers from the very beginning a sufficient fire protection already during the construction phase. It allows a simple assembling technique for all final installations such as blind ceilings, lamps for lighting or fans in traffic tunnels, traffic signs etc. The structure offers free access for inspection at any time without removing parts of any cladding and in case of tunnels the same life-cycle of about 100 years as the tunnel itself. There are no problems at all caused by alternating loads by sucking and pressure generated by fast running trucks and no problems with regard to cleaning the ceiling or walls for example of a road tunnel. In case of a fire there is nearly no spalling effect (Figure 5) and there is only low damage given in case of a vehicle collision. The additional costs due to the special mix of the concrete are reasonable and generally low.
PREVIOUS WORK ON ACTIVE FIRE PROTECTION

First discussions on active fire protection in form of fixed fire suppression systems in road tunnels started for example within PIARC (World Road Association) at the World Road Congress 1983 in Sydney. Later for the World Road Congress 1999 in Kuala Lumpur, Malaysia PIARC expressed some concerns regarding the installation of fixed fire suppression systems because fires often start in the motor room or in the loading compartment of a heavy goods vehicle (HGV). In its publication PIARC also mentioned that under specific conditions extinguishing water could cause an explosion, flammable gases could be produced and may cause explosion and vaporised steam could hurt people. Furthermore, it was stressed that an early activation of the fixed fire suppression system could lead to an immediate destratification of the smoke and thus effect the escape procedure in a negative way. The released water masses as well as the vaporised steam and fog like conditions could significantly reduce the visibility and again effect the escape procedure in a negative way. Finally, PIARC saw the problem of high maintenance costs.

On the other hand PIARC stated 1999 that sprinklers could be used to cool down vehicles to stop any fire spreading from the burning vehicle to others in its vicinity. With regard to the escape process PIARC expressed then that sprinklers or deluge systems – if they are installed – must not be activated until all occupants have evacuated.

In the past this view about the use of fixed fire suppression systems tended to be negative. This created an extended discussion world-wide. During the last years a lot of research work on fixed fire suppression systems has been conducted. The aspects previously mentioned by PIARC have been studied to more details. In the result the findings gained by these intensive investigations provide a better insight in the pros and cons of fixed fire suppression systems. This forms a better basis for a more up-to-date judgement.

PRESENT STATUS

Taking into consideration the latest research activities and their results one has clearly to be aware that fixed fire suppression systems in most cases are not able to extinguish major and severe vehicle fires as often still assumed. Neither are they technically able to create such a far reaching effect nor are they layed out for it especially considering financial aspects. In this direction quite often an overestimation not to say a misunderstanding can be met among clients. The aim of using fire
suppression systems is instead to slow down the fire development, to reduce or completely avoid a fire spread from one vehicle to another and so to improve the conditions for escape and rescue.

Tunnel fixed fire suppression systems (Figure 6) did not find a far ranging application so far. Their effectivity and general benefit is worldwide under an intense discussion [1, 2, 3]. For example one important question is related to the optimum timing of activating the system not to harm the escape and rescue process by destroying the smoke stratification. Another open question deals with the general cost-benefit evaluation of those systems in comparison with the safety measures commonly taken nowadays.

Figure 6  Test of a water mist system (Fogtec), conducted within the UPTUN Research Project.

To gain better knowledge in this direction it is necessary to conduct an internationally agreed test program with large scale tests. First steps in this direction have been the tests in the Runehamar Tunnel in Norway (Oct. 2004) and in the Virgolo Tunnel in Italy (Febr. 2005). Both large scale tests were conducted in the frame of a huge European research project with more than 40 partners involved: Cost-effective, Sustainable and Innovative Upgrading Methods for Fire Safety in Existing Tunnels – better known under the acronym UPTUN. For the same purpose the European Commission launched a feasibility study for a Large-Scale Underground Research Facility on safety and security under the acronym L-SurF in March 2005. Such a facility would surely contribute to avoid failures in large investments in tunnel safety systems which may at the end not fulfill the expectations.

In general, there are some basic requirements with regard to fixed fire suppression systems [4]. According to the present and still ongoing discussion those systems have to be functionable at any time. They must be and stay reliable even under the rough conditions of the tunnel atmosphere which is normally characterised by high moisture and in the winter time salt content of the air and dust because of steady wear of the road pavement and the tyres as well and additionally particle loaded air because of diesel exhaust fumes. The investment costs must be acceptable and the maintenance costs kept low. The installation as well as the operation of the system should not be too complicated.

There are some very important questions left in connection with the installation of fixed fire suppression systems. Those are for example:

- Is there any economic compensation given with the investment for a fixed fire suppression system for example in form of savings for the layout of the ventilation?
- What is the mutual impact of the various components of safety systems in a modern tunnel additionally equipped with a fixed fire suppression system?

It is still not possible against the present status of knowledge to set up general rules whether to install fixed fire suppression systems in tunnels or not. For a given tunnel a specific risk analysis concerning the appropriateness of a fixed fire suppression system has to be conducted. Such a risk assessment of
a tunnel encountering a fixed fire suppression system should take into account the following aspects:

- Safety of users
- Capacity/possibilities of the fire brigades and rescue services in the area of the tunnel
- Resistance of structure against fire
- Balance between costs and benefits of a fixed fire suppression system
- Interaction between the various safety related components of the tunnel

An important step forward in this direction could be taken by the recently finalised research project SOLIT – Safety of Life in Tunnels sponsored by the Federal Ministry of Economy and Technology, Germany and FOGTEC, a supplier of water mist systems. Numerous tests were conducted in the test gallery San Pedro de Anes in Asturias, Spain. These tests have shown some significant advantages using a fixed fire suppression system based on water mist:

- An improved accessibility of the fire place by fire fighting squads and rescue teams
- Avoidance of fire spreading from vehicle to vehicle
- A clear slow down of the fire development
- Better protection of the infrastructure

All these effects lead to clearly improved conditions for escape and rescue.

CONCLUSION

Summarising and coming back to the basic question formulated by the title of this paper it appears sensitive to combine the advantages of both, the active and passive fire protection measures if ever possible. This has proven to be very effective, useful, and pragmatic in the field of industrial and commercial facilities as shown further above. The combination of active and passive fire protection measures can be easily realised in case of newly built structures. It is much more difficult and significantly more expensive to realise in connection with already existing facilities and to be studied in case by case.

With regard to the application of fixed fire suppression systems PIARC’s view is changing considering the latest findings gained with the remarkable national as well international research work conducted during the last couple of years. But there are still good reasons to be cautious and to weigh the advantages of the installation of a fixed fire suppression system project wise. According to PIARC’s present view 3 absolutely important requirements have to be met when discussing whether to install a fixed fire suppression system in a specific tunnel or not:

- The installation of a fixed fire suppression system is to combine with an appropriate fire detection and fire localising system.
- Great care must be taken into account regarding maintenance and operating costs of such a system.
- During the whole life cycle of a tunnel it must be guaranteed to meet an acceptable cost frame as well as the full capacity and function of the fixed fire suppression system.

It is highly recommended to conduct a risk analysis in the sense of the European Directive Road [5] which was published by the EU in April 2004 as well as a cost-benefit analysis project by project.

In the end it can be stated that without any question we need tunnels in our daily life to ensure a high level of mobility for persons and goods (Figure 7) which is a highly ranked political requirement. Tunnels for road, rail, and mass transit must be safe and for this all necessary efforts have to be taken
while considering an optimum balance between technical solutions, their effectivity and reliability, and a reasonable relation of costs and benefit.

**Figure 7**  Heavy goods vehicle passing through a tunnel

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Security of Tunnels & Underground Space: Challenges and Opportunities

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ABSTRACT

Security of tunnels & underground space seems to be a relatively new issue that our industry must deal with. However, it is not a new subject, nor is the general subject of security for underground public and private spaces as illustrated by a few examples. However, the importance and urgency of the subject are extreme. For convenience, one can divide this subject into two main categories: 1) use of underground space as a safe haven, and 2) the safety and protection of tunnels & underground facilities from natural and man-made hazards. The first category reflects the fact that a major use and quality of underground space is that it is frequently used for protection, storage, or preservation. Our industry should actively promote and stimulate greater use of underground space where appropriate as a safe haven. The second category reflects the fact that special efforts are needed to maintain the security of tunnels and underground space. This paper provides an overview of the background, challenges and opportunities on both of these issues for both natural and man-made hazards.

KEYWORDS: tunnel, underground, security, safe haven, protection, risk, challenges, opportunities

INTRODUCTION

For convenience, one can divide the broad issue of security in tunnels and underground space into two main categories: 1) use of underground space as a safe haven, and 2) the safety & protection of existing facilities. Underground space is often considered as the location of choice for the preservation and storing of anything that you want to protect as well as for the disposal of unwanted materials. This started with our ancestors living in caves for safety and continues today to the use of underground space for an ever increasing variety of purposes that ranges from burial of lifelines for safety from earthquakes, archival storage of art and records, bulk storage of essential products, and disposal of unwanted materials such as hazardous waste and, recently, even disposal of CO₂.

Despite the relatively recent publicity and activity in recent years, protection of existing facilities and security of underground space is not a new subject. Well entrenched in our mind is the case of the London underground. But, we must also remember the following tragedies that occurred not so long ago: 1) Sarin gas incident in Tokyo in 1995; 2) arson incident in Daegu, Korea, in 2003; and the bombing incident in Moscow, in 2004; and several others. Note that most incidents involve public transportation, not some of the many other uses of underground space. There are fewer cases involving underground space but non-transportation facilities also are subject to threats from natural and man-made hazards. An example is the accidental flooding of the freight tunnel system and numerous basements in downtown Chicago in 1992. Also, there was a terrible fire in an underground frozen food storage warehouse in Kansas City in 1991 which burned for 5 months. Accordingly, there is a justified renewed interest of safety and security in all underground spaces but particularly in public transportation systems because of recent events.

There are clearly challenges and opportunities associated with both categories of tunnels and underground space. Our industry must deal with these issues regarding natural and man-made hazards urgently and straightforwardly.
TUNNELS & UNDERGROUND SPACE AS A SAFE HAVEN

Not all aspects regarding security of underground space are negative in nature. There are many cases of “upside” or positive aspects of security of underground space where underground space is used in order to provide security. Various definitions of “haven” generally refer to a location of safety, or a refuge, or a location which offers favorable conditions. Any consideration of security aspects of tunnels and underground space should take into account the fact that, in many instances, underground facilities provide a protection for the user and for the contents in the underground space that can not be obtained elsewhere. Therefore one of the uses of underground space is to provide security. There are many examples where owners and designers have used underground space in order to obtain the degree of security that it offers.

Mankind has depended on underground space since the beginning when existing caves were used for shelter and safety and subsequently when the spaces were modified by man to adapt to changing needs. This intentional positive use of the inherent safety of underground space has developed over time and is still a major factor in society’s use of underground space.

Nature and Type of Safe Haven Underground Facilities

The subject is too complex and far reaching to treat fully in this paper but it should be recognized that whenever society wishes to protect, store, or preserve something, underground space is often the location of choice. For centuries this has been the case. Ancient tombs are excellent examples and they are found all over the world and represent the efforts of a society at many different times. Examples that most often come to mind are the Egyptian tombs in Luxor, the terracotta army in Xian, China but there are many other examples of tombs worldwide. Other ancient underground havens actually include living spaces like Cappadocia, Turkey where the population lived in a complex labyrinth of tunnels carved out of the rock and the underground complex provided security from attacks from enemies.

Underground space generally provides increased protection against the natural elements and from manmade threats. Protection from natural elements includes elimination of adverse temperature and climate or rapid climatic changes; strong protection against adverse weather such as hurricanes, tornados or cyclones; resistance to earthquake effects; resistance to deterioration of structure; reduction of maintenance; isolation from pests and adverse biological characteristics. Protection from manmade hazards stems largely from the isolation of the underground space and the fact that there usually is limited access to the people, product or to the underground space in general. The advantages include increased protection from crime, theft, arson, sabotage, and intentional attacks.

Of course, the degree to which underground space provides these advantages depends upon the type, location, use, function, and operation of the underground space. For instance, public transportation systems and public meeting facilities do not share these advantages as well as, for example, bulk storage of fuel, food & water. Also, permanent archives and permanent storage of hazardous materials are usually well sealed and offer much more protection.

For centuries, food and water have been stored below ground and they still are in various parts of the world. These facilities range from hand-dug pits in rural areas to sophisticated water cisterns and caverns. Other foodstuffs are stored underground including bulk storage of wine. These food storage facilities are designed to be safe and secure and, because of isolation and other inherent qualities of underground space, they generally fall in to the safe haven category with respect to security.

Military and civil defense facilities have historically been placed underground for safety and security reasons. Of course, these range from special foxholes to sophisticated bunkers. World War II and the subsequent cold war spawned numerous civil defense structures which ranged from backyard nuclear
bomb shelters to adapted civil structures such as subways and even sewer systems. It is the author’s understanding that the stimulus for the development of underground sewage treatment plants in Scandinavia stemmed from the desire to protect the facilities in wartime. During the cold war many concepts were developed for military shelters and missile bases over a km deep. Even now, some cities incorporate civil defense functions into new subway structures and stations. Clearly, tunnels and underground spaces have been used extensively in military and civil defense applications and many more, and more sophisticated facilities, can be expected in the future.

Fuel storage facilities are another major use of the underground as a safe haven. This has been particularly well developed in Scandinavia as well as many other countries all over the world. Huge caverns have been excavated from rock for the safe and economical storage of fuel. In other geologic conditions, these huge caverns have been either excavated or solution-mined in salt rock formations. All these fuel storage caverns provide safe havens and they are economical as well as strong contributors to sustainable development at the same time. There are numerous examples of bulk storage of crude oil and other materials in underground space for safety and security all around the world.

Moreover, there are numerous examples of underground space being used for archival purposes. These include document and record storage facilities, libraries, etc. There are many such facilities around the world. In fact, the Swedish Royal Library in Stockholm uses underground space for all of its books and archival records.

There are new concepts being developed every day to take advantage of the special characteristics of safe havens. Recently, there have been proposals to reduce global warming by capturing CO2 and disposing it underground, most likely in geologic formations which have an impermeable caprock which would resist migration back to the atmosphere but which might, under some schemes, involve some underground space.

Underground space has been also been considered and/or used as a safer location for some of society’s less desirable materials or functions. The mode of security for such a facility is just the opposite of most other underground facilities. Rather than prevention of entry from the outside, the security provided by these facilities is the containment of the undesirable features and prevention of undesirable emissions from the facility. The classic example is the storage of nuclear waste where nuclear waste is contained in special capsules which prevent, or at least resist, release of radionuclides and then the capsules are placed deep underground in a remote location to provide a natural containment in order to keep all adverse effects far away from human contact for thousands of years.

Other containment functions of underground space are the disposal of hazardous waste of various kinds. Many facilities have been built and put into operation for this purpose but there are increasing environmental and regulatory restrictions that will reduce the feasibility of such disposal sites.

New concepts for the use of underground and/or underground space to provide security and safety are frequently being proposed all the time. There have been proposals for locating nuclear energy plants underground so that in case of an accident, any release of radioactivity can be prevented or at least controlled.

Finally, on a more positive note, it is not generally known that tunnels and underground facilities normally behave very well in earthquakes. This favorable aspect of underground space is because ground motions at depth are generally very small, certainly smaller than at the surface, and there is no amplification, or whiplash effect, that surface facilities, and especially tall buildings, experience. For instance, after the Magnitude 6.9 Loma Prieta earthquake in October, 1989, it took San Francisco several months to a year to recover but their subway system, BART, was not damaged. BART was inspected and put back into service after a few hours. Similarly, after the Magnitude 6.7 Northridge earthquake in January, 1994, the Los Angeles subway was inspected and put back in to service the
next day yet many freeway overpasses and buildings suffered extensive damage and collapse. Even tunnel sections that were under construction successfully survived the earthquake.

Thus, if one wants to protect a lifeline, such as a water supply, sewer, power, etc from earthquake damage, one should go out of their way to consider the favorable earthquake behavior of tunnels and underground space. One line of life that is now being protected by underground space is the Svalbard Global Seed Vault in Norway. In order to preserve the vast nature of our current population of seeds, an archive was carved out of rock with sufficient space for 2.25 Billion seeds which will be preserved into perpetuity at minus 18 Celsius.

Accordingly, underground space can be designed and constructed to provide security and protection of the public and the contents within. Underground space provides the isolation necessary to provide protection from adverse outside events or circumstances. The underground also provides the necessary containment when underground space is used to dispose of or contain undesirable waste.

Security Challenges and Opportunities Associated with Safe Havens

As will be discussed in the subsequent section on security of existing facilities, those tunnels and underground spaces that are considered safe havens also must be designed and operated with renewed emphasis on security. The advantages safe havens now offer with respect to security must be preserved, enhanced and increased. Moreover, since security threats are always changing, the process will have to be continually updated. This must be an innovative, creative and systematic process.

The challenges and opportunities of traditional underground facilities, which will be discussed in the next section, are also applicable for the segment of our industry considered as safe havens. There are however special aspects and features of safe havens that warrant special consideration and attention. This is particularly true of the non-technical aspects of security although even the technical aspects pose special challenges and opportunities.

Looking at the non-technical aspects, our industry has to preserve the special advantages over surface facilities that underground space offers. In fact we must enhance the strategic advantages of safe havens which inherently involve isolation; containment; favorable conditions; and especially, limited, restricted, and dependable access. Properly-constructed, safe havens generally provide a superior protection against natural and man-made hazards. We must, however, strive to stay ahead of our adversaries who seek to conduct intentional acts against our facilities.

Of course, not all underground spaces, nor are all safe havens universally safe. Those whose functions are related to containment, isolation, or storage and preservation have favorable security properties against both natural and man-made hazards. Those which involve the public can be designed and constructed to be relatively safe against natural hazards such as earthquake and adverse weather but may still be somewhat vulnerable against intentional deliberate man-made acts. As with aboveground facilities, there are degrees of vulnerability. Those where the public can be screened or controlled such as an concert hall or event center are less vulnerable than an open rapid transit system.

Our industry needs to organize and develop a coordinated approach to identifying the threats and vulnerabilities then developing technology and operational methodology to reduce the threats and vulnerabilities. This must start with a program creating increased awareness of this issue and stimulating action and funding. Since 9/11, the broad security industry has responded to the challenge but underground space has not yet benefited sufficiently from research and development directed specifically toward tunnels and underground space. We owe the public to keep ahead of our enemy as much as possible and not to wait until another event or tragedy provides the impetus for additional funding. Let's do it before the next event in ways that will “deter” any and all events.
SECURITY OF EXISTING FACILITIES

Of course, the foremost and most urgent concern regarding security of underground facilities is the protection of existing facilities, their contents and the public. This includes those discussed above that are considered safe havens, for which, although they are inherently more secure, there are still security issues and problems that must be overcome. Underground transportation as well as utilities, communication tunnels, and underground space for public use are likely to be more vulnerable and more difficult to protect. Some of the challenges and opportunities associated with security of tunnels and underground space are discussed in the sections below. Our adversaries are very resourceful and creative and their tactics and strategy will change with time. Thus this will require a long term effort.

One of the challenges is the same that all facilities face; that of the unknown threat and at an unknown time, a so-called “unknown-unknown.” Our industry, and society in general, have been fortunate by the relatively long time between events. So far, this extra time has been put to good use but we must not think that we have the luxury of time. An event or events could occur at anytime. One of our challenges will be to upgrade as best we can with the methods we now have then upgrade these tools in the future. Thus we must identify, stimulate, and conduct urgent broad-based research on security of underground facilities against natural and man-made hazards.

SECURITY CHALLENGES FOR TUNNELS AND UNDERGROUND SPACE

Our industry has similar challenges that we share with other segments of society. We all face increasing challenges to both natural hazards and man-made hazards. It may not yet be scientifically absolutely proven but our weather appears to be more severe and the effects of global warming must also be dealt with.

Fortunately, research, development, testing, and actual deployment of technical and non-technical measures to combat threats from deliberate acts have been under way even before 9/11 and, of course were accelerated subsequent to 9/11. Nevertheless, the author believes these have not been well-coordinated, nor comprehensive enough, nor funded well enough. Moreover there seems to be institutional constraints that prevent us from sharing ideas, successes, and Lessons Learned. Some suggestions will be given in the subsequent section on “Opportunities.”

There is reason for hope. Tunnels and underground space are not necessarily the target of choice and this has given our industry time. However we must use this time wisely because of the unknown-unknown effect. Our industry is very strong and very creative and can respond to any identified need. The challenge is to identify those needs, develop appropriate priorities, provide funding, and respond accordingly.

We have many existing facilities that need upgrading and rehabilitation from a security standpoint. Of course each type of facility must be treated individually and, in fact, ultimately, it is a case by case basis especially when making existing facilities more secure.

So what are some of the technical security challenges facing our industry? Let us look at the traditional time-sequence of threats and our defense and then recovery from any event. It is common sense that security threats and recovery from any event are easier, the earlier our intervention occurs. We all know the sequence but for the sake of completeness, it goes somewhat in the following time sequence: Deter, Deny, Detect, Delay, Defend, Isolate, Shield, Protect, Evacuate, Mitigate, Cleanup, Repair, Rehabilitate, and Restore. Naturally, our goal is to Deter with our backups being Deny, Detect, Delay and Defend. But we must also be prepared for damage control.

Each of these poses challenges depending upon the type of facility although there are common threads throughout. One of the challenges is to provide consistent approach and appropriate methodology at all levels of the time-threat scenarios. One of the major challenges our industry faces is to raise the
level of security for all types of threats and time-threat sequence for all types of threats, not just explosive threats. Explosive threats have received considerable and justified attention by our industry. However, we must not let our guard down to other threats such as chemical, biological, and radiological threats.

Another challenge that needs immediate and considerable attention is that of potential flooding of tunnels and underground space as a result of both natural and man-made hazards. With respect to natural hazards, no one knows what the long-and short-time effects of global warming may be but these effects should be taken into account. Even if sea levels rise slowly, there seems to be a greater number of incidences of local flooding throughout the world which may threaten underground facilities. Many transit systems have already taken this into account by increasing the elevation of the entrances to their stations. However, in view of recent events and floods, all tunnels and underground space, especially public transportation facilities, should be reevaluated to include new data for such issues as a revised size of design storm and for local storm surges. Lessons can be learned from the flooding and recovery of essentially the entire subway system in Prague in 2002 when 17 stations and 17 kilometers of tunnel were completely flooded.

Potential flooding is one of the more serious potential hazards which could result from natural hazards, accidents, or deliberate acts. Flooding is always a potential when working close to existing tunnels and underground space surrounded by a large source of water such as a river or lake. The flooding of the freight tunnels and basements in downtown Chicago in 1992 is a good example caused by a totally unexpected construction accident. Lessons Learned from this event should be incorporated into the design of new tunnel structures and into the operational manuals of existing tunnels with flooding potential. The author is aware of one transit system construction project which used the Chicago experience as lessons learned. Flood gates were installed in one subaqueous tunnel before allowing construction in very close-proximity to the existing tunnel.

The development of temporary barriers, which could be used in flood threat situations, is also underway. This methodology should be researched and tested thoroughly with the goal of making deployment of such systems quick, simple, and reliable. Demonstration and proof testing should be done in as many different tunnel and underground space situations as practical. This development is an important and urgent priority for our industry.

Another challenge facing our industry, and security in general, is the reduction of threats to lifelines such as water, wastewater, energy, etc. Again, transportation tunnels seem to be leading this segment of our industry but none could be more important than the water and wastewater lifelines. Of course, they present entirely different technical and non-technical challenges. This too is an urgent and challenging task that must be done immediately and then continually updated.

Not all challenges are technical. One non-technical challenge is that of providing the right level of security when the construction procurement method is design-build or is as a concession. The Owner must give away much of the decision-making authority when these methods of procurement are used. Since the means and methods of providing security are closely tied to the means and methods of construction, it is difficult for owners to specify the levels of security needed or desired. Moreover, as will be seen in a later section, security technology is advancing at such a fast rate that new technology, which the owner may desire in the future, is likely to become available during the long design and construction period. Contracting documents should make it easy for the latest technology to be incorporated into the design at the latest possible time. Contract documents should allow these changes to be made in a fair and timely manner without unfair financial penalty to either the owner or the contractor. Moreover designs and configurations of security systems should be done so that they can be upgraded easily and cost effectively even when the tunnel or underground space is in service.

Another very important challenge is the design, operation, installation and operation of concepts that mitigate the effects of any chemical, biological, or radiological threat whether natural or man-made;
intentional or accidental. Likely this would take the form of “compartmentalization” of the ventilation and drainage systems. To some degree our new and advanced fire and life safety ventilation systems do this in order to isolate zones of fire and smoke. However, the control or mitigation of chemical, biological, or radiological threats will require even more advanced and creative systems and this could be very expensive.

OPPORTUNITIES FOR IMPROVING SECURITY IN TUNNELS & UNDERGROUND SPACE

Of course, each challenge leads the way to opportunity. Opportunities are also both technical and non-technical. Many of the opportunities that have more potential reward lie in the non-technical categories.

Safe, Meaningful, Communication, and Cooperation

Probably the most challenging aspect of security is potentially the most rewarding opportunity. This challenge and opportunity is to establish meaningful communications and sharing of ideas in a safe, secure manner among those who are trying to protect the public, our facilities, and our industry. Anything less plays into the hands of our enemy. The author is fully aware of the potential legal, compromising, and the emotionally-scary aspects of such communication but our industry and our future safety depends upon such communications. Fortunately, there are examples of increased openness in how our industry shares ideas and solutions but our industry does poorly in this opportunity. The report, “Making Transportation Tunnels Safe and Secure” [1] and other Transportation Research Board (TRB) security-related publications are examples of more open communications.

The industry is in dire need of a means of openly communicating in a secure forum. The current situation is that firms and employees working in tunnel security are asked to sign confidentiality agreements and are not allowed to share experience gained on a project even with known associates working in the same field. This places an undue restriction on those trying to assure tunnel security and plays into the hands of our adversaries.

The author has, in the past, proposed that the International Tunneling and Underground Space Association (ITA) take a lead in this effort internationally. He has also proposed to develop a similar communication system for the United States using the resources of the ITA representative in the USA, the Underground Construction Association (UCA). The format suggested is similar to a simplified version of an Information Sharing and Activities Center (ISAC) [2]. Members of an ISAC would be pre-qualified and pre-certified with security clearances at the levels of security necessary to conduct meaningful communication. It is visualized that there might be several levels of security clearance and security protocols to permit meaningful communications between various parties but preserving the needed levels of protocol for secure communication.

The proposed format would not necessarily be a 24/7 alert facility, which is the format of the ISACs, but rather would collect information, make analyses with respect to their relevance and importance to all tunnels and underground space, identify the relevance to each type of tunnel, then resubmit back to the membership as case histories, facts, suggestions, or guidelines. The importance of such a network would be to facilitate communications and cooperation worldwide among all the different types of tunnels and underground space as well as the mining industry in each part of the world. It is proposed that this network would also liaison with security-related aspects from other types of infrastructure as well as the general security technology industry. It is the author’s belief that our industry can gain from lessons learned in other types of infrastructure including bridges. For instance, many issues regarding protection of bridge piers are the same as those of our industry faces for tunnel portals (deter, deny, detect, defend etc.).
Technology Transfer Opportunities

Our industry needs to improve the ways that we promote and stimulate the transfer of technology. Again, we do not want to re-invent the wheel. As discussed above, adaptations of existing technology from other fields may be just what our industry needs.

One of the advantages of a network of communications as described above would be to facilitate the transfer of technology between various disciplines. There is an exceptional need & value for the transfer of technology among all of these different types of tunnels and underground space. This technology transfer should also include mining since the mining industry also has similar security issues. The IASC, or any other systematic network, could stimulate and facilitate the transfer of such technology.

The author suggests that there be more technology-sharing opportunities at existing conferences to permit and facilitate the transfer of technology. Although Exhibitions offer marketing opportunities to firms with good technology for sale, the author is suggesting a more professional level of technology transfer such as engineering conferences where the overall issues, including pros and cons, can be discussed rather than listening to sales pitches.

Use Risk Management Principles for Security Management

Owners and planners of underground space have now begun to use systematic risk management principles to identify all risks in a way that directs the rest of the planning and construction process to minimize those risks. This is a very powerful method if conducted with the proper attitude and approach. It is the author’s opinion that risk management principles should be used also for security issues.

This systematic procedure must be done as early as possible in the stages of a project (pre-conceptual or idea stage). This risk management work then is systematically carried on and updated all the way through design and construction and, for all security-related issues, into the full period of service.

This process would then put security issues into context with the other risks and opportunities affecting the project. Accordingly, the risks to be considered would be broad and would also include risks and opportunities of security, cost, financing, schedule, environment, public acceptance, adjacent owners & third-party intervention, politics, etc. in addition to the technical risks that always immediately come to mind.

Fortunately, the same concepts and tools can be used to identify value engineering ideas, as well as to identify broad ideas and opportunities including “thinking out of the box” [3]. Even for security issues, it is important to also look at the “opportunities” side rather than just the downside of security risks. An example would be the opportunities that safe havens offer.

Opportunities Associated With Cost of Security

It is a mistake to think of the cost of security as just the initial cost of the security systems. The author recommends that the evaluation of the cost of tunnels and underground space should use life-cycle cost concepts [3]. This concept should be extended for the evaluation of the cost of security aspects of tunnels as well. Ordinarily, the cost of security is not well identified when estimating the cost of a project. This is complicated since security requires not only the system itself but also the long term cost of monitoring, maintenance, upgrading and replacement. Thus the need to consider life-cycle cost principles for evaluating the cost of security.

Tunnels often remain in service for over a century. Accordingly, decisions about whether a certain
infrastructure should be a tunnel, or not, should be made on considerations of Life-Cycle Cost & Benefit and not Initial Capital Cost. This is a difficult concept to implement but it is important for planners and decision makers to avoid the pitfall of decisions based on initial capital cost and this should be true for evaluating the cost of security as well.

One of the values of using risk management techniques to manage security issues is that it permits and facilitates addressing and comparing the cost versus the benefits. It also permits making “What If” calculations in which the cost of various ways of adding or enhancing a security system can be compared to their likely benefits. Again, these are best done if looked at and compared from the standpoint of life-cycle costs.

Obviously, the life-cycle costs should include future operational and maintenance costs and benefits. A special case occurs when the cost of a safe haven is considered versus the cost of the same type of facility above ground. There should be a financial advantage to the underground facility because of the permanent containment and isolation which comes at little to no long-term costs.

As a side benefit, tunnels and underground space are very environmentally beneficial. Accordingly, cost analyses should also include realistic allowances for equivalent financial benefits from environmental and social improvements associated with tunnels which can be substantial.

**Selected Design Opportunities**

There are abundant opportunities with respect to technical design and security methodology most of which are beyond the scope of this general paper. Some have been mentioned in the discussion of challenges in previous paragraphs such as the opportunities offered by improved compartmentalization of ventilation systems. Similar opportunities exist in the compartmentalization of drainage systems. Another opportunity is to take advantage of optimizing security needs and physical systems when upgrading traditional fire and life safety installations. There are many opportunities for synergism between fire systems and security systems and these should be optimized. In fact, improvements in our traditional fire and life safety systems very likely also improve the security of the facility.

There are numerous opportunities for designs against explosive type events as well as against contamination events but explosive events are those that are most often considered. However, our industry must also address security against contamination threats. Regarding contamination events, consideration might be given to reducing the number of places where contamination might be difficult to remove during cleanup and recovery such as minimizing angular corners at intersections perhaps with the use of fillets. Also consideration might be given to sacrificial coatings where appropriate.

Unfortunately, most of these would add to the cost of an already expensive facility. Accordingly the use of risk management methodology together with life cycle costing concepts should be used to evaluate the costs and benefits of such systems.

**Flexible Design, Contracting, & Construction Opportunities**

The rate of development of security systems and methodology is proceeding at an enormously rapid rate. It is almost guaranteed that the security systems considered during conceptual and preliminary design will have been superseded or upgraded by the time construction is complete. Accordingly it is important to have a flexible outlook with respect to security issues throughout the entire design, construction, and service life. The use of risk registers and risk management procedures can assist in this effort.

There may be slightly higher initial costs for providing this flexibility but in terms of life cycle costs and in terms of the absolute requirement of public safety, such initial costs may be acceptable. This is
particularly true if the security design is made so that upgrades and replacements can be made easily and cost-effectively during the service life of the facility.

As noted earlier, some of these provisions for providing easier maintenance and upgrading may be difficult to convey in contract documents especially design-construct documents. Procurement methodologies should be developed to give the public the best technology for security.

**Opportunities in Preparing As-Constructed Reports**

A substantial opportunity exists in the simple act of documenting design details and in preparing detailed As-Constructed Reports (sometimes called As-Built reports). Those of us who have worked on the rehabilitation of underground facilities recognize the great difficulty posed by not knowing what was constructed in the first place. Normally our industry has called for the preparation of as-constructed reports mostly to document what was constructed to provide knowledge for maintenance crews and for future extensions of the facility. Owners frequently do not want to take the time nor pay for such “non-productive” reports. With the renewed importance of security, there are many more of reasons to document exactly what was constructed.

Should some damage occur to a facility, either from natural or from man-made causes, a detailed and accurate as-constructed report becomes invaluable. This is important for many reasons including being able to assess the degree and the extent of damage as well as making the best interface between old and new construction. Usually rehabilitating a damaged facility must be done under emergency conditions and in the least amount of time. This does not leave any time for speculation of what was built in the first place. Although in the past, many owners have not wanted to pay for as-constructed reports, for security reasons alone, they may be invaluable. Naturally there will likely be a need for limited access protocols for such confidential and sensitive documents.

**CONCLUSIONS**

Recent events have increased the challenges and opportunities associated with security of tunnels and underground space. Clearly, security of tunnels and underground space must take into account hazards from both natural and man-made causes. Even environmental and global warming issues increase the security challenges from natural hazards.

Security issues are not all adverse since there are numerous positive aspects of security in tunnels and underground space. Many tunnels and underground space facilities can be considered as safe havens since they offer increased security especially in terms of isolation, containment, and limited access. Our industry should strive to make decision makers recognize and understand the very significant security advantages of safe havens and promote greater use of safe havens for the benefit of society.

Further our industry should continually upgrade the security aspects of safe havens so that they retain their advantage.

Tunnels and underground space behave well in earthquakes providing additional security from natural hazards. Thus, if one wants to protect a lifeline, such as a water supply, sewer, power, etc from earthquake damage, consideration should be given to the favorable earthquake behavior of tunnels and underground space.

Of course the most important and most urgent aspect of security in tunnels and underground space, including safe havens, is that of protecting the public and those facilities from both natural and man-made hazards. The challenges are substantial but not impossible.

Although more attention is needed on security aspects of transportation schemes, transportation facilities have received the bulk of the development of security systems. We must also direct our attention to all other underground facilities, especially those for water and waste water.
These challenges also give rise to abundant opportunities for our industry. One of the most important opportunities is that of developing a network of sharing security issues in ways that will promote open discussions and transfer of technologies for the benefit of society but which preserve improved but sufficient confidentiality protocols.

Another opportunity that our industry should embrace is the use of risk registers and risk management techniques to evaluate the overall risks and opportunities associated with security. Moreover, since most security systems add cost to an already expensive facility, the long-term cost and long-term benefits should also be considered in addition to initial cost.

The rate of development of the technology of security systems is so fast that design and construction projects should adopt a flexible approach that would allow the latest technology to be installed during construction. Moreover the systems should be easy and cost-effective to upgrade in the future. In order to facilitate repair of any damaged facility, detailed as-constructed reports are recommended.

Our industry is very strong and creative so it can meet all the challenges and take advantage of all of the opportunities associated with security.

**REFERENCE LIST**

The methodology for determining traffic flow on motorway sections before and after an expected obstacle – a tunnel

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Abstract

Traffic safety on motorways depends on the intensity and the method of the traffic flow. The method of the traffic flow is changing first of all on the motorway sections with obstacles, expected and unexpected. This exercise will discuss an expected obstacle – a tunnel. Speed of the traffic flow before a tunnel is reducing because of speed limit. Braking and acceleration (before and after a tunnel) negatively influence on traffic safety. This exercise also discusses possibilities for projecting the level of safety of the traffic flow before and after an expected obstacle – a tunnel.

For this purpose, the research introduces new indexes of traffic safety. With help of this indexes we can project the level of the traffic safety on tunnel sections.

KEYWORDS: traffic safety, motorway, tunnel, traffic flow

INTRODUCTION

Traffic safety on motorways and in particular in motorway tunnels enjoys particular attention from their users. In order to provide a higher level of users' trust in safety on motorways, a motorway manager must focus on all factors which in any way have an influence on traffic safety. These also include the area of traffic flow behaviour before and after motorway tunnels.

There are a number of events which may occur as a consequence of expected traffic flow interruptions. The following events before a tunnel may cause a traffic accident in the very tunnel:

- speed limit for a tunnel is introduced already at a certain distance from the tunnel;
- before they enter a tunnel, drivers are trying to take the best possible position for passing through a tunnel – by overtaking slower vehicles;
- a motorway has three lanes before a tunnel, with one lane reserved for slower vehicles, which is discontinued before the tunnel;
- this results in redirection of cargo vehicles from the lane for slower vehicles to a traffic lane;
- since there are vehicles on the traffic lane, they keep driving on the lane without reducing their speed or they brake intensively.

In the area of an exit from a tunnel, the following events occur:

- after a tunnel, the road usually descends, which means that personal and cargo vehicles intensively accelerate when they pass the speed limit sign;
- cargo vehicles usually drive through a tunnel in a line on one traffic lane (keeping the minimum safety distance), and start making dangerous manoeuvres when they exit the tunnel – in order to see who is stronger and quicker – trying to overtake vehicles in front of them;
because of this, personal vehicles cannot continue their course safely when they exit a tunnel, which makes them brake and cause a chain reaction back into the tunnel;

the aim of all drivers exiting a tunnel is to regain the speed with which they were driving before they entered the tunnel.

**PROBLEM DESCRIPTION**

The purpose of this presentation is a short description of the methodology for determining the level of traffic safety considering traffic flow obstructions before and after a tunnel, aimed at answering the following questions:

1. Can the level of traffic flow obstruction before and after a tunnel be determined for the existing tunnels, regardless of the fact that the method of the traffic flow is different for each tunnel?
2. Can the realistic level of traffic flow obstruction before and after a tunnel be estimated for the tunnels being planned considering the expected traffic flow obstruction?
3. Can the measures which project traffic flow obstruction before/after tunnels be projected?

Tunnels are constructed primarily because of the complexity of a road section, so tunnels are constructed in demanding sections. The biggest mistake that can be made in the planning of a tunnel is that the projected traffic flow which is to enter and exit a tunnel is not taken into account [5].

The expected behaviour of the traffic flow for an individual planned tunnel can be projected on the basis of experience and already collected data, so that certain traffic and technical requirements of the tunnel can already be coordinated during the designing of the tunnel.

**METHODOLOGY**

In determining the methodology, I have taken into account

- experience of other countries in the field,
- research and experience of Slovenian expert institutions dealing with the matter,
- previous experience in the field of Slovenian motorway tunnels.

Because of the wide scope of the issue in question, the concept is directed only to the evaluation of traffic and technical elements on which we do not have direct influence during the planning. Therefore, these are the measures taken during exploitation and not during the project designing.

In determining the methodology, it is necessary to take into account traffic/technical and project/technical elements [1] of a primary influence on the safety of traffic flow before and after a tunnel:

- the number of traffic lanes before and after a tunnel,
- canalisation of traffic lanes before and after a tunnel,
- speed of vehicles in the areas before and after a tunnel,
- speed of vehicles in a tunnel,
- intensity of traffic flow in a tunnel.

Traffic flow intensity, expressed in the annual average daily traffic (AADT), traffic flow structure and the prescribed speed of vehicles, expressed in km/h, are from the aspect of the proposed methodology authentic factor of traffic activity before and after a tunnel. AADT, together with speed,
the area of obstructed traffic flow on motorway sections before and after the expected obstacle – a tunnel.

![Speed Limits in Tunnel Area](image)

**Figure 1**  
*Presentation of speed limits in the area of a tunnel*

Input data of the methodology system present the existing situation (traffic flow intensity before a tunnel, location and type of tunnel, traffic and safety situation, road surface, speed limit, axis alignment, level section alignment, transversal inclination, visibility, traffic signalisation, etc.). Input data first must be analysed from the aspect of the existing and planned situation (projected traffic, planned changes in the areas before and after a tunnel, etc.).

The methodology envisages the following scenarios:

- selection of the tunnel before which traffic flows are merged, and selection of a tunnel before which the speed is reduced and after which speed limits end,
- collection of traffic information,
- when the methodology is used to project the value of individual scenarios, we analyse the and decide on the implementation of the proposed solution,
- monitoring of the functioning presents the last phase of the methodology, where an analysis of the situation is used to determine the adequacy of a solution.
Capacity of road section (C) or capacity is the biggest number of vehicles which can drive through a certain road section in a unit of time under the prevailing road and traffic conditions. Capacity does not depend on the actual load on a road sections.

Capacity for motorways, roads with physically separated roads with four or more traffic lanes:

\[ C = C_0 \cdot n \cdot f_1 \cdot \prod_{i=1}^{4} F_i \] (vehicles/h in one direction) [2]

\[ V = V(t) = \frac{ds}{dt} \]
\[ a = a(t) = \frac{dV}{dt} = \frac{d^2s}{dt^2} \]
\[ k = k(t) = \frac{da}{dt} = \frac{d^3s}{dt^3} \]

[3]

Figure 2  Movement of vehicles before and after a tunnel [2]

Figure 3  Diagram of dependence between the traffic flow intensity on a traffic lane and speed on a motorway [4]
Conflict points of traffic flow before a tunnel take place in the area where

- the traffic lane for slow vehicles is discontinued,
- the traffic speed is reduced and the reduction is not registered with systems,
- the traffic speed is reduced and the reduction is registered with systems.

Figure 4  Location – time diagram of congestion of traffic flow. Lines on the diagram represent trajectories of individual vehicles. Formation of a ‘plug’ and its dynamics is clearly visible [3]

Figure 5  Conflict points before a tunnel
ANALYSIS OF RESULTS

During the processing of the input data by means of the proposed measures of the methodology, I have found out that the number of manoeuvres of vehicles - changing of traffic lanes – increases before and after a tunnel. Similarly, the speed of vehicles in the area before and after tunnels changes considerably – it is reduced before a tunnel and increased after a tunnel.

On the basis of the results, it is possible to make an adequate simulation which would present the realistic behaviour of traffic before and after a tunnel.

Video Simulation: Traffic flow before tunnel (Simulation will be presented on the presentation).

CONCLUSION

It would be necessary to deal with the area of traffic flow behaviour in the areas before and after a tunnel already during the concept phase and during the drawing up of the project documentation for tunnels.

Solutions for traffic – safety elements which direct traffic flow in the mentioned area – should be defined.

The main advantage of the proposed methodology is that it enables precise estimate of the level of traffic safety already in the concept phase, therefore before drawing up of the project documentation. The proposed methodology is uniform, which means that it is applicable for all types of tunnels. The methodology will help project designers to make the right choice of project/technical elements of the areas before and after a tunnel.

The result of this research is not a final solution for the improvement of traffic safety in its entirety, but it is only a new approach in the advancement of traffic flow safety before and after the expected obstacle – a tunnel. It presents a possibility of actual determination of traffic flow behaviour in the mentioned area, its management and preparation for the entry into a tunnel. On the basis of these solutions, it is possible to determine the safest construction of traffic safety elements with as less conflict situations as possible.

On the basis of statistical data, it is possible to easily monitor the course of traffic flow before and after a tunnel. The findings may be used for the same types of tunnels, because the method of the
traffic flow in the same types of tunnels does not differ considerably. It can differ from the course of road before and after a tunnel (inclination). The methodology introduces a new term - traffic flow obstruction before a tunnel. This term arises from the project/technical elements, traffic/technical elements, traffic flow intensity and traffic accidents in the area of the existing tunnels. It enables us to compare the common and apparently common characteristics of different types of tunnels. If a mutual comparison of the areas of two same types of tunnels with the same method of the course of the traffic flow before and after a tunnel is considered, parameters which contain the common characteristics should be used for the calculations. If the use of two different types of tunnels and its wider area is considered, it is necessary to apply the apparently common characteristics. In such cases calculations with the common adjustable parameters are used, as in my AADT methodology, and what also can be used is the number of traffic lanes before and after a tunnel.

The degree of traffic flow obstruction before/after a tunnel can also be named relative indicator of traffic safety, because it enables a logical comparison of the degree of traffic safety among different types of tunnels. With this, the methodology enables projections of the level of traffic flow obstruction on motorway sections before and after the expected obstacle – a tunnel.

On the basis of the methodology, I recommend the following measures, which would improve traffic safety in tunnels primarily because of adequate preparation of traffic flow before a tunnel for the very entry to a tunnel:

- gradual reduction of speed before a tunnel
- field of sight before a tunnel should be adequately envisaged during the project designing
- prohibit overtaking for all vehicles in the areas before and after tunnels
- taking into account the proposed methodology in the phases of the project designing of a tunnel.

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Initial Assessment of the Impact of Jet Flame Hazard from Hydrogen Cars in Road Tunnels

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ABSTRACT

As the development of hydrogen cars advancing into the markets, it is unavoidable in the near future that hydrogen cars would become the users of ordinary road tunnels. This paper carried out an initial examination of potential fire scenarios and fire hazards from worst possible cases of hydrogen release in road tunnels and implications on the fire safety measures and ventilation systems in existing tunnels. Due to the low ignition energy and wide flammable range, hydrogen leaks have a high probability of ignition and result hydrogen jet flames. CFD simulations of hydrogen jet flame in a full scale 5m by 5m square cross-section tunnel were carried out. The effect of the ventilation on controlling the upstream backlayering and the downstream flame were discussed. The results showed that the impact of hydrogen flame in the tunnel depended on the hydrogen release rate. The tunnel ventilation system could eliminate the upstream backlayering and fully control downstream flame with a smaller hydrogen release rate. For a larger hydrogen release, the tunnel ventilation system couldn’t provide sufficient air flow into the fire and there is an oxygen deficit hydrogen layer accumulating under the ceiling downstream of the fire. The accumulating hydrogen layer could pose more serious hazards inside the tunnel.

KEY WORDS: jet flame, hydrogen car, road tunnel safety

INTRODUCTION

It is widely anticipated that hydrogen as fuel will be first introduced into the transportation systems. Hydrogen is a very clean fuel and ideal for transportation systems either for direct use in internal combustion engines or for fuel cells to power electrically driven vehicles. Combustion of hydrogen can produce very low emissions of nitrogen oxide together with some water vapour. In fuel cells it only produces water vapour and so far as is known there are no fuel-related health effects. Markets for hydrogen fuel already exist in road transport and a number of development vehicles have been built by the major motor manufacturers to demonstrate their potential and to gain operational experience. Global energy companies are tackling the infrastructure requirements for a substantial hydrogen production and distribution system.

When hydrogen economy takes off, hydrogen cars would be regular users of urban transportation systems. Underground or partial underground tunnels form a very important part of modern road transportation infrastructure. The use of underground space became more and more important all over the world. The volume of tunnelling construction [1] is expected to be around 2,100 km in Europe and 2,350 km in Asian in next 10 to 15 years. The hydrogen economy is predicted to arrive in a similar time scale which is in 15 to 20 years. The sustainability of tunnelling activities requires consideration of impacts of hydrogen cars as the future users of the existing tunnels and new tunnels to be constructed.
Ventilation systems play an important role in fire safety management of existing long road tunnels. In most existing long tunnels, a longitudinal or transversal ventilation system is used to supply air to control smoke movement and to create a safe route, clear of smoke, for people to escape the tunnel and for fire fighters to gain access to sources of fire. For years, the ventilation system has been considered to be an effective and practical measure to control small fires in tunnels. However the series of catastrophic tunnel fires that have occurred since 1999 has raised serious questions about the capability of the ventilation system alone to provide a comprehensive fire safety system in tunnels facing increasing traffic load. The appearance of hydrogen cars in tunnel would no doubt cause more concerns in the safety of the tunnels.

The hydrogen car is still in early development stage. It is not possible to establish the fire scenarios of hydrogen car in tunnel through experimental tests at this stage. The objective of this paper is to carry out a general discussion of the fire hazards of hydrogen cars in tunnels and use CFD simulations to assess the implication hydrogen fire on the tunnel ventilation systems.

TUNNEL VENTILATION SYSTEMS AND SAFETY MANAGEMENT

Historically the mechanical ventilation systems in the long tunnels were mainly designed for providing fresh air into the tunnel and remove pollutants out the tunnel. Only in recent years, the mechanical ventilation systems were considered seriously as measures of controlling the smoke flow movement during a fire and were used to create smoke free zones to aid the evacuation of personnel in tunnels. Nowadays the ventilation systems became an important part of emergency safety procedures.

There are mainly three types of tunnel ventilation systems namely: transverse ventilation, longitudinal ventilation and semi-transverse ventilation.

In fully transverse ventilation systems, fresh air is channeled by fresh air ducts and is supplied to the tunnel through vents at regular intervals along the tunnel length. The pollutants are extracted through exhaust vents and channeled away by the exhaust ducts.

In the semi-transverse ventilation, fresh air is supplied through vents at regular interval; however exhaust air is extracted through a few large vents located in the main portals or the ventilation shafts.

In longitudinal ventilation systems, fresh air is supplied in one end of the tunnel portal and is forced along the tunnel by pressure differences or by aid of jet fans mounted on the tunnel roof. The systems are mainly used in high traffic density tunnel with uni-directional traffic.

All of those three ventilation systems are commonly used in road tunnels. Some of the tunnels have both longitudinal ventilation and transverse ventilation in different sections. When operated in the emergency mode, the transverse ventilation systems are aimed at the maximum extraction of the smoke from the tunnel and the longitudinal system is operated at the critical ventilation velocity that prevents the smoke flow travel against the ventilation and forces the smoke move one direction only, therefore create a clear pass for evacuation and for fire fighters to access the fire seat. Figure 1 demonstrates a tunnel fire under influence of transverse ventilation system and Figure 2 shows the smoke flow in the tunnel controlled by the longitudinal ventilation.

Some modern tunnels are also equipped with water sprinklers fire suppression systems to cool down the area round a fire. The sprinkler systems are commonly installed in long tunnels in Japan and also equipped with intelligent fire detection systems. In European, only a very few tunnels have installed water sprinklers. For fire detection, tunnels usually equipped with temperature sensors, smoke detectors, carbon monoxide (CO) monitor and closed circuit television systems (CCTV).
The design of the emergency ventilation systems are based on the possible fire load of one or several accident scenario. The fire behaviour, duration and the fire load (heat release rate) of a burning passenger car and a HGV in tunnel environment have been established through a series of experimental tests [2-4]. To carry out risk assessment of transporting hydrogen car through the tunnel, it is essential to obtain data on the fire behaviour, duration and the fire load of a hydrogen car.

CHARACTERISTICS OF HYDROGEN CAR FIRE

The characteristics of the fire are largely determined by the method of hydrogen fuel storage on board. In this paper, the discussion is concentrated on cars carrying hydrogen compressed gas bottles. Although there is very little information available at this moment on hydrogen car fire, a video produced by Swain [5] has demonstrated some of the characteristic features of fuel leak and ignition of a hydrogen car in open air. The Swain’s tests showed that the hydrogen car generated vertical high velocity jet flames with very long flame length and high flame temperature. The body of the hydrogen car was not ignited in open air and flame last a few minutes. In contrast, the leak from gasoline car formed a pool fire; the flame engulfed the body of the car and substantial smoke generated from the burning car. This paper therefore concentrated on discussions on jet flame scenarios of a hydrogen car inside tunnel.

The flame length and duration of the jet flame generated from the fuel leak depends on the conditions and the load of the fuel tanks. Currently hydrogen stored on board on a fuel cell vehicle is mainly in high pressure compressed gas form. The current storage pressures were found to be 250, 350 and 450 bars. The common storage capacity of hydrogen on board a fuel cell vehicle is approximate 3 to 5 kg, this could be a few times higher if high storage pressure is used. Two important parameters for hydrogen jet flames are the fuel released rate and jet velocity. Those two parameters were derived with reference from a study in stability of hydrogen flame by Wu et al [6]. It was showed that for a 10 mm diameter nozzle, the velocity could easily reach from 200 m/s up to 860 m/s when the jet reached supersonic flow condition. For a larger release nozzle, velocity would lower accordingly. Figure 3 shows a image of a hydrogen jet flame issuing from a 2 mm diameter hole. This study selected two scenarios with realistic hydrogen release conditions. In the first fire scenario, the hydrogen is released at rate of 0.05 kg/s and at velocity 10 m/s. This would results a 6MW hydrogen fire which would last...
about 1 minute. In the second scenario, hydrogen is released at rate of 0.25 kg/s and velocity of 50 m/s, which would result 30 MW fire for a shorter duration.

![Image of a hydrogen jet flame in day time. (Produced by Wu et al [6]).](image)

**CFD SIMULATIONS OF HYDROGEN CAR FIRES INSIDE TUNNELS UNDER LONGITUDINAL VENTILATION.**

Three-dimensional simulations of smoke flow in the tunnels have been carried out using FLUENT code. The simulated tunnel as illustrated in Figure 4 has a length 102 m and a 5 m by 5 m square cross-section. The hydrogen release source is 40 m away from the inlet and that gives 40 m upstream and 62 m downstream. The first plane of the longitudinal domain was set to be the inlet of the ventilation flow and the last plane was set as the output of the smoke flow to the exhaust.

The k–e turbulence model was selected for the turbulence model and the combustion process has been modelled using the mixture fraction/PDF approach. The k–e turbulence model is based on the model by Launder and Spalding [7] and includes basic modifications for buoyancy effect proposed by Ljuboja and Rodi [8] in the k–e equation. The upstream backlayering is sensitive to buoyancy effect, the current CFD simulations tested suitable values for C3e, which is used to take account of the buoyancy effects in transport equations for k and e. Woodburn and Britter [9] used C3e equal to 0.20 and a previous study by Wu and Bakar [10] found that C3e =0.25 gave the best results in CFD simulations of the smoke flow in tunnel fires. Therefore C3e was set as 0.25 in this study. The ventilation flow has been modelled by setting the flow of air at the tunnel inlet uniformly through out the whole cross-sectional area. The tunnel wall was modelled as an insulation wall therefore no heat loss was considered. In the simulations it is assumed that the flow is symmetrical about the tunnel vertical mid-plane. Radiation from hydrogen flame is much less than flames of other conventional fuels and unlikely to have dominate effect on the hydrogen dispersion inside the tunnel, therefore radiation was not considered in the simulations.
DISCUSSIONS

The temperature and hydrogen distributions inside the tunnel are shown in the Figure 5 for the 6 MW hydrogen fire under 2.5 m/s ventilation velocity and in the Figure 6 for the 30 MW hydrogen fire under 2.5 m/s ventilation.

Critical Velocity

The values of the air velocities required to control the smoke movement in horizontal tunnels have been studied both experimentally and theoretically in a previous study by Wu & Bakar[10]. Both the experimental work and CFD simulations suggested that at low rates of heat release the critical velocity vary as the one-third power of the heat release rate, however at higher rates of heat release the dependence on the heat release rate falls off rapidly. And eventually the critical velocity becomes independent of the heat release rate. Therefore for any specific tunnel there is a super-critical velocity, which could control the smoke, moving downstream only regardless what the magnitude of the heat output from the fire is. For the 5m by 5m square cross-section tunnel, the super-critical ventilation velocity is about 2.5 m/s. In the CFD simulations, the ventilation velocity was set at 2.5 m/s.

The CFD results showed that the ventilation can fully eliminate the backlayering in the situation of 6 MW hydrogen fire at hydrogen release velocity 10 m/s. For the 30 MW fire, the ventilation flow didn’t eliminate the backlayering, however the length of the backlayering was controlled within the length of three tunnel height. The CFD results showed that the flame and the flow features for 6 MW fire are different from the ones of 30MW fire. For the 6MW fire, the flame features are similar to the ones observed in previous studies by Wu & Bakar [9]. The flame length was short and located in lower part of tunnel. However for the 30MW fire, flame reached the tunnel ceiling and spread under ceiling for a long distance (45 m). This might be resulted from the deficit air supply for the fire which will be discussed later in this session.

Jet flame Hazards

The simulation demonstrated that the hydrogen flames inside the tunnel have features of jet flames. The flame length generated from the fuel leak depend on the conditions of the release. The long reaching hydrogen jet directly impinged the ceiling as shown in Figure 5 for the 30 MW fire. The
impinging flow then would spread under the ceiling and considerable amount of hydrogen spread under the ceiling in downstream as shown in Figure 6(c) and reacting flow stretched 45 m long (9 tunnel height length). Obviously the impingement of high temperature flow could pose serious hazard on the tunnel equipment and structures along the ceiling. Hydrogen flame has very high temperature; the adiabatic flame temperature of a stoichiometric hydrogen in air is 2321 k. Equipment and sensors in the tunnel ceiling would not survive even for a very short exposure time. This ceiling flow could spread rapidly and reach long distance in a very short time space. This hot ceiling flow could act as ignition source and ignite fuel vapour and surface on its pass and generate smoky combustion flow under the ceiling. The jet flame resulted from a hydrogen car may not be a problem in open air, however when it occurs inside road tunnel, it could be a serious hazard.

**Hydrogen Flame Features inside Tunnel**

A hydrogen flame inside the tunnel has the feature of long reaching flame in downstream. This feature is unique for hydrogen fuel. For other types of fuels, the flame length is short and usually within two tunnel height downstream. This can be attributed to the nature of hydrogen. Hydrogen combustion demands the highest amount oxygen per unit mass of fuel. Compared with most common hydrocarbon fuels, hydrogen needs four times as much air per unit fuel. Therefore the hydrogen combustion reactions are controlled by the oxygen supply process. For most of the tunnels, the ventilation system has a limited and fixed air supply. Therefore it is possible to have an oxygen deficit hydrogen fire inside the tunnel when the hydrogen release rate is high. For the 30 MW fire, the oxygen deficiency caused the hydrogen spread downstream under the ceiling for a long distance and the reacting flow produced high temperatures under the ceiling. There is no oxygen deficiency in the 6 MW fire. The cross-section average hydrogen mole fraction distribution inside the tunnel shown in Figure 7 clearly demonstrates that the hydrogen is completely consumed within less than one tunnel height distance for the 6 MW fire, but the hydrogen is accumulated inside the tunnel for the 30 MW fire.

**Implication of Oxygen Deficit Hydrogen Fire inside Tunnel**

Figure 6(c) showed that there were hydrogen present in long distance downstream of the fire in oxygen deficit hydrogen fire inside tunnel. This would have more serious implication in tunnel ventilation systems. These oxygen deficit high temperature flows have a risk of develop into flash over if oxygen is supplied from other sources. For ventilation ducts with extraction mode, there might be a risk of transferring the oxygen deficit hydrogen fire into ventilation ducts.

**CONCLUSIONS**

The initial assessment of the jet fire hazards from hydrogen release inside tunnel were carried out. The CFD simulations were carried out for two fire scenarios. It was shown that the super-critical ventilation velocity can completely eliminate the backlayering in normal hydrogen release rate or keep the backlayering under control in very high release rate. It was shown that jet flame hazard could be unique for hydrogen cars. For high release rate, the flame inside the tunnel might be in the status of oxygen deficit. This would result impingement of hydrogen jet flame on the tunnel ceiling and produce high temperature ceiling flow reaching substantial distance and damage tunnel infrastructures. The oxygen deficit hydrogen fire also pose flashover hazard inside tunnel and ventilation ducts.
Figure 5: Temperature and hydrogen mole fraction distribution inside the tunnel with a 6 MW hydrogen fire and 2.5 m/s ventilation.
Figure 6: temperature and hydrogen mole fraction distribution inside the tunnel with a 30 MW hydrogen fire and 2.5 m/s ventilation.
Figure 7. The average mole fraction distribution inside the tunnel.

REFERENCES


L-surF: Large Scale Underground Research Facility on Safety and Security

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SAFETY AND SECURITY IN THE EUROPEAN UNION

Security and stability rank among the most important aspirations in everybody’s life. Mobility of people and reliable transport of goods are key issues in our society. Both economic growth and societal development rely heavily upon safe and secure infrastructure, in which road, rail and metro tunnels besides other enclosed spaces of infrastructures are important elements.

The increasing awareness of safety and security caused by severe heavy accidents with partly enormous damage on health and goods and terrorist attacks in underground infrastructures, led to the necessity of R&D projects that work on safety and security and make an improvement of both existing and projected infrastructure in enclosed spaces possible. This also finds its expression in the description of the 7th Framework Programme of the EC where safety and security is explicitly addressed as an individual topic for R&D activities.

As a result of several research projects of both the 5th and 6th Framework Programme on RDT, a lack of rules and regulations on European level regarding safety and security of underground infrastructure was identified. Furthermore, differences in requirements to underground infrastructure all over Europe led to the need for harmonisation, collaboration and communication in the field research and development covered through L-surF. The L-surF concept which included an inventory of existing Research Infrastructures, facilitating the cooperation between them and also a survey of research needs, was well meeting the European strategy and therefore successfully implemented in the frame of FP6 as a Specific Support Action (SSA).

L-SURF – THE CONSORTIUM AND ITS OBJECTIVES

L-surF, which is the acronym for Large Scale Underground Research Facility on Safety and Security, is a feasibility study in the frame of the Sixth EU Framework Programme for Research and Technological Development implemented as a Specific Support Action. Five European institutes (V-S-H- Hagerbach Test Gallery, SP Technical research institute of Sweden, STUVA e.V., TNO Netherlands Organisation for Applied Scientific Research and INERIS Institut National de l’environnement industriel et des risques) leading in the field of safety and security research of underground spaces are collaborating in order to find an answer to open questions, problems and shortcomings identified during several FP5 projects in this research area.

The main objectives of L-surF are fourfold and include firstly carrying out a feasibility study for the establishment of a pan European research facility for large scale test in underground spaces. The development and design of the constructional layout goes hand in hand with the identification and definition of R&D activities based on research needs which are screened in the frame of an own Work Package. Additionally, potential clients and partners strongly influence the development of the design study as a whole.

L-surF’s second main objective covers scientific and technological research on both the constructional properties of the infrastructure and the measurement equipment to guarantee technical equipment
according to the latest state of the art and based on the newest technology available. As far as constructional properties of testing areas are concerned L-surF is developing an entirely new system called CCSS (Convertible Contour and Shape Scheme) to ensure best possible flexibility regarding cross sections, contours, slopes, in other words to provide test areas with every geometrical property required by the clients. Depending on the test activities carried out in the corresponding areas, the properties of the surface will exactly meet the specific requirements, i.e. fire resistance up to several degrees in the locations for fire tests according to special needs, stability and resistance against dynamic loads to allow research on and with explosives, air tightness for ventilation and smoke distribution tests etc. As far as the measurement equipment of the test areas is concerned, the technology transfer is thought to facilitate the development of innovative 2D and 3D measurement sensors as an important issue. In some parts large scale testing for tunnel safety and security requires measurement of similar parameters or even the same (but maybe in another range or with different accuracy) as in aeronautic research. As mentioned above, the measurement of air velocity distribution with PIV (Particle Image Velocimetry) or 3-dimensional measurement of pressure distribution with PSP (Pressure Sensitive Paint) are available technologies from other fields of research which might be transferred and adapted for the use in the scope of L-surF. Besides these scientific aspects environment protection has to be dealt with in a very careful way, too. Caused by the fact that large scale fire testing in tunnels always goes together with tunnel ventilation, it is easily imaginable that enormous amounts of smoke resulting from the test have to be treated besides the waste water from the fire mitigating or extinguishing system.

L-surF’s third main objective is a business plan comprising information about users, customers, markets and of course financial issues for the realisation of the research facility. In the frame of “Work Package 5 - Research, Training and Experimental Activities” the consortium has been working on a definition of R&D activities carried out in the scope of L-surF in the future, based on a survey of research and market needs (Work Package 2) and its our own capabilities and knowledge. But at the same time an integration process (Work Package 1) is developed for both existing and projected national facilities with their competences and researchers thus restructuring and improving the relevant EU competence while simultaneously showing ways for using R&D funds more economically. From the consortium’s point of view, added value to the European research community is compulsory and absolutely necessary to enable the realisation of L-surF.

Consequently, one or more legal entities will be established in the course of the L-surF project which is stipulated in the contract and therefore L-surF’s fourth main objective. The kind of entity and the location of its head office will depend on the business scenario. So this might be a specialty of L-surF that the end of the project itself is definitely not the end of L-surF but actually a starting point for a new era of research and development on safety and security of confined and subsurface spaces.

FOUR BUSINESS SCENARIOS AS A RESULT OF THE DESIGN STUDY

A European infrastructure for large-scale experimental research on safety and security has to fulfil many activities. More than 'only' carry out large scale tests, it is important to take into account the necessary technical fields that have to be covered, the logistic of the tests, the safety of the tests, the services to offer to the end-users, etc…

Well aware of the various kinds of activity that a large scale research facility has to fulfil, the L-surf consortium has proposed to the European Commission to analyse within a design study the activities and services that the L-surf European Infrastructure should 'ideally' and 'sustainably' offer.

As a result a full set of activities and services has been identified to be very important and useful for the sustainable development of the European Research Area in the domain of safety and security of underground and confined spaces.

To carry out these activities various options are possible to set up the L-Surf European Research
Infrastructure which will manage the development of the identified activities and services. These possible options (scenarios) are presented hereafter.

**Scenario A: A European coordination and harmonisation organisation.**

The purpose of the L-surF Scenario A is to coordinate and harmonise research and knowledge between existing networks of large-scale experimental facilities. This L-surF European organisation would be the European coordinator of research & development related to large scale experiments in the field of safety and security for underground and confined spaces. The large-scale experimental facilities existing in Europe would be partners of the L-surF organisation and the L-surF would offer the following services with the help of its partner network:

- Harmonize and develop the best experimental practices (test conditions, results requirements, logistic and planning requirements…) for large-scale test leading to the "L-surF Class Quality Services" label,
- Provide services for the design and execution (proper and safe) of large-scale experiments,
- Manage test results and knowledge transfer to industry and end-users (for examples on safety and security systems, equipment and products, vehicles/coaches hazard library, heat sources, fire design…),
- Translate research questions and requests into research programs and coordinate the strategic research agenda, …
- Initiation and co-ordination of important large scale experimental research and demonstration,
- EU advisor for the large-scale experiment facilities development,
- Addressing questions related to emergency response training (safety & security) and requests related to the design and execution of such large-scale experiments,
- Offer a large set of services to end-users by validating R&D results and translating them into tools, learning and training courses…

In the Scenario A, no supplementary facility (in addition to those already existing) would be built but the coordination of knowledge of existing facilities would be developed in order to enhance competitiveness of the European Research Area.

**Scenario B: Structuring the use of existing European large-scale research facilities**

In this scenario the L-surF organisation is responsible for test design and test conduction, but also for analyses and conclusions from test results by using existing large scale experiment facilities. Specific agreement with the L-surF partner large-scale facilities are concluded to do so and the tests would be performed in these facilities.

The main added value of this scenario, making use of the existing facilities, is the integrated approach of safety and security and the possibility to offer to the end-users a one stop shop for large-scale experimental services in relation with all the necessary facilities.

This organisation would ensure the efficient use sustainability and development of the facilities within the European Research Area and would avoid duplication of research to the profit of new and important R&D questions to be solved in the field of safety and security of underground and confined spaces.

In addition to the knowledge management services offered by the Scenario A, the Scenario B is leading the L-surF organisation partly into responsibility for the efficient use of the L-surF partner facilities. By this way the L-surF European research infrastructure would build up sustainable and good relations between the existing research facilities and thus use them more efficiently.
Scenario C: Completing existing facilities with new Gap Facilities

It is obvious that the existing facilities have been built to answer a given set of R&D questions and therefore have been developed with a 'limited' set of experimental characteristics. It is clear that in the field of underground safety the majority of the existing large-scale facilities are "fire tunnel shaped" facilities. Consequently the existing facilities are not well prepared to answer the new R&D questions induced by the major changes of our society in the fields of city development, energy, mobility, terrorism etc.

As a result, the Scenario C is devoted to complement the 'Scenario B facilities' by building the identified lacking large-scale experimental tools to faces the new questions asked to the research. The L-surF consortium identified more than five large-scale new gap facilities that are necessary to answer the present and coming R&D questions to answer to the end-user needs.

Scenario D: Developing the new L-surF European research infrastructure

In this scenario the construction and running of the “ultimate groundbreaking” large scale experiment facility is the main objective. Such a facility does not exist at present time. In this facility new research and tests will be possible which neither existing facilities are able to offer nor potential completing gap facilities would be able to do.

By this way the new facility will be unique in Europe and will serve all the European research community and end-users to tackle problems that cannot be solved in the existing or gap large-scale facilities.

For example, the new and unique facility shall solve problems related to:
- the geometry and shape characteristics when these parameters will be of prime importance to carry out realistic demonstration and training (see CCSS concept),
- complex underground infrastructures that are not simply a tunnel tube but maybe hubs, gallery connections and vertical structures,
- human behaviour research and exercises under realistic conditions will be supported by the
efficient training of emergency and rescue services. This will be possible by simulating whatever existing infrastructure without any need for disruption of operation of the real infrastructure,

ill willed acts and terrorism involving explosives and toxic dispersion by allowing safe and secure experimentation in high respect to a high confidentiality level.

Around this infrastructure all the necessary high skilled personnel for tests design, measuring equipment and visualization, test results and analysis in the total field of safety and security in underground spaces will be available. In that scenario the L-surF European infrastructure will put in place really new, realistic and dedicated training capabilities for safety and security and users might perform dangerous exercises in a highly controlled and qualified environment.

CCSS CONCEPT

CCSS is an acronym for Convertible Contour, Size and Shape. The CCSS concept covers the objective to design, to build and to operate a new experimental tools for large scale experiments that is able to adapt its geometry, size and shape to each given underground infrastructure geometry case.

For the development of the CCSS concept, the L-surF consortium has started to design this new tool on the basis of required geometry characteristic and all the necessary measurement characteristics. The CCSS will focus on targeted research and training needs where the added value of such a new tools is the highest. To this end the CCSS could be used for the development of the above explained Scenarios C and D.

OUTLOOK – IMPLEMENTATION OF SCENARIOS

Meanwhile, the last term of the L-surF design study has started and the time has come to establish an organization in charge of L-surF’s objectives. For that purpose and to offer third parties participation in L-surF activities, L-surF has launched its 2nd Call for Expression of Interest in autumn last year (2007). Up to now, more than 50 applicants showed reaction and submitted their application form fed with information about their organization and indications of what future collaboration could look like.

At the present stage L-surF has submitted a proposal for an I3 project (Integrating Infrastructure Initiative) in the frame of the 7th FP to the theme Capacities / Research Infrastructures. If the proposal is successful, this will be the first activity embedded into Scenario B. The legal frames for this
scenario as well as for the other Scenarios are in preparation and will be presented to interested organisations soon in order to give all interested parties the opportunity to join these L-surF organisations and to contribute and participate actively in the future development of the European Research Area in the field of Safety and Security in underground infrastructures.
Fire Testing of Concrete and Concrete Protection Systems for Tunnels in Sweden - An Overview

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ABSTRACT

The paper presents an overview of fire resistance tests conducted in Sweden on concrete and concrete protection systems for tunnels. The database of published tests drastically increased after publication of a recently completed project. The major objective of the project was to compile and publish experience gained in Sweden from fire protection of tunnel lining systems. Three main areas were covered: codes and regulations, research and testing, and technical solutions used in some recent tunnel construction projects. The review of tests conducted on concrete and concrete protection systems, resulted from acceptance by clients to publish a large amount of test results previously covered by client confidentiality. This data is summarised in a SveBeFo report. This article presents basic information concerning which test series are included in the full report and an illustrative example of the type of data contained in the full report. The length of this article does not allow inclusion of all data available in the full report.

KEYWORDS: fire resistance; spalling, tunnel concrete, test methodology, fire protection systems

INTRODUCTION

During a tunnel construction project, authorities require fire safety of tunnels to be considered from several aspects, such as fire detection, ventilation, escape routes and the construction’s resistance to fire. One aspect of the construction’s resistance to fire is the risk of spalling of concrete used in the tunnel linings [1]. If spalling occurs, the load bearing capacity is reduced due to a reduction of the material supporting the load, but also due to an increase in temperature in the remaining structure with a change in mechanical properties as a consequence. Concrete qualities used in tunnels are often of a high density to attain good durability. Unfortunately, high density concrete often brings a higher risk of spalling.

There are several methods used to reduce the risk of spalling. The easiest is to use a concrete quality that does not spall during a fire. If that is not possible, different protection systems could be used, such as adding polypropylene (PP) fibers in the concrete or by attaching a thermal barrier to the concrete surface. Examples of such barriers are spray-on materials or panels with high insulation capacity. Another approach is to increase the concrete thickness to compensate for the effect of spalling by including a certain “sacrificial” spalling depth.

The physics behind spalling is not yet fully understood [2] and the risk of spalling is difficult to predict. Consequently, many fire tests have been carried out on different concrete qualities for tunnel applications, as well as together with different protective systems for the concrete. Unfortunately, most tests are carried out for specific tunnels, and thus generally not available to the public due to secrecy constraints. The experience and knowledge obtained from tests conducted for one tunnel...
construction project is not accessible to other tunnel projects, researchers or others involved in fire safety of tunnels.

A project has recently been completed with the objective to compile and publish experience gained in Sweden in the area of fire protection of tunnel lining systems [3]. The project has been lead by SP Fire Technology in cooperation with the fire consultant company Brandskyddslaget. Three main areas were covered; 1) codes and regulations, 2) research and testing, and 3) technical solutions used in some recent tunnel construction projects. The project focused on experience from Sweden but in the case of research and testing, some information from work published from other European countries has been included. As the data from the research and testing part of the project has been published elsewhere [ref], this article focuses on the proprietary testing data included in the report.

The full report represents a unique body of data that will be useful when designing future tests.

SUMMARY OF TESTING CONDUCTED IN SWEDEN

A large number of tests (both fire tests and general characterisation tests) on concrete and concrete protection systems have been conducted at SP Fire Technology. Some are tests conducted as research projects and consequently available to the public. Others are conducted as commercial tests for specific tunnel constructions by the authorities or private companies. The clients for the commercial tests, i.e. the owners of the test reports, were contacted and asked if they were willing to contribute to a database of tests available to the public. The majority of the clients was positive to releasing test data due to the advantage of being a part of a test data base, and did contribute by giving acceptance for their results to be published. Examples of some of those tests are presented in Table 1. In a few cases the clients had restrictions on what information about the tests could be published. Full data on the various tests is available in the full SveBeFo report. An example of the type of data available for each project (i.e., each “P-number”) is given in the next section for project P502334, conducted as part of the evaluation of alternative material for use in the Malmö City Tunnel.
<table>
<thead>
<tr>
<th>Project</th>
<th>Purpose/ Tunnel project</th>
<th>Test method</th>
<th>Test sample</th>
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<tr>
<td>Hallandsås Tunnel</td>
<td>Fire resistance tests to study spalling tendencies and temperature profile in concrete (16 tests)</td>
<td>Large scale ISO 834 with the RWS-curve for 120 min</td>
<td>Elements (1800 x 1200 x 540 mm³) Traditional vibrated concrete (5 formulas), with different quantities of PP-fibre and stress level.</td>
<td>Internal concrete temperatures. Spalling depth.</td>
</tr>
<tr>
<td></td>
<td>Fire resistance testing to test adhesion, and capability of shotcrete to protect concrete elements. (8 tests)</td>
<td>Large-scale ISO 834 with the RWS-curve for 120 min.</td>
<td>Shotcrete on concrete elements (1800 x 1200 x 540 mm³) with different quantities of PP-fibre, thickness and anchoring systems.</td>
<td>Spalling depth. Internal temperatures.</td>
</tr>
<tr>
<td>Malmö City Tunnel</td>
<td>Fire resistance testing to test spalling tendencies and temperature profile in concrete. Pre-tests to subsequent large-scale tests. (6 tests)</td>
<td>Small scale SP Brand 119 with the Malmö City Tunnel-curve for 60 min</td>
<td>Small scale elements (600 x 500 x 200 mm³), post-stressed. Traditional vibrated concrete with PP-fibre (3 formulas).</td>
<td>Spalling depth</td>
</tr>
<tr>
<td></td>
<td>Fire resistance testing to test spalling tendencies and temperature profile in concrete. (10 tests)</td>
<td>Large-scale EN 1363-1 with the Malmö City Tunnel-curve for 300 min.</td>
<td>Elements (3600 x 1200 x 590 mm³), post-stressed. Traditional vibrated concrete with different quantities of PP-fibre (10 formulas).</td>
<td>Internal concrete temperatures. Spalling depth.</td>
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<tr>
<td></td>
<td>Fire resistance testing to test spalling tendencies and temperature profile in concrete. (8 tests)</td>
<td>Large-scale EN 1363-1 with the Malmö City Tunnel-curve for 300 min.</td>
<td>Elements (1800 x 1200 x 400 mm³), post-stressed. Different quantities of PP-fibre (8 formulas).</td>
<td>Internal concrete temperatures. Spalling depth.</td>
</tr>
<tr>
<td>Citybanan, Stockholm</td>
<td>Fire resistance testing to test adhesion, and capability of shotcrete to protect sealing layer/insulation on elements of concrete or rock. (23 tests)</td>
<td>Large-scale EN 1363-1 with the STD-curve for 90 min or the HC-curve for 180 min.</td>
<td>Shotcrete with PP-fibre on different types of sealing layer/insulation on concrete elements (3600 x 1200 x 280 mm³) or elements made of rock (1800 x 1000 x 300 mm³).</td>
<td>Adhesion, spalling</td>
</tr>
</tbody>
</table>
Together with tests conducted in research projects run at SP, as well as published results of some tests conducted in Europe, the report [3] presents a collection of close to 200 small or large scale fire resistance tests of tunnel lining materials or systems. Today the collection of tests has expanded even more. Including recently finalized research projects, the database of tests available for research now contain up to 400 tests.

The collection of tests included in this compilation span from large-scale fire tests according to EN 1363 and ISO 834 to small scale furnace tests [4]. The fire curves represented include the standard fire curve, the hydrocarbon (HC) curve, the RWS curve and the Malmö City Tunnel curve (see Figure 1).

<table>
<thead>
<tr>
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<tr>
<td>P602418</td>
<td>Fire resistance testing to test adhesion, and capability of shotcrete to protect sealing layer/insulation on elements of concrete or rock. Pre-tests to subsequent large-scale tests. (8 tests)</td>
<td>Small scale SP Brand 119 with the HC-curve for 60 min.</td>
<td>Shotcrete with PP-fibre on sealing layer/insulation on mineral wool sheets or elements made of rock (600 x 600 mm²).</td>
<td>Temperatures behind shotcrete. Spalling depth.</td>
</tr>
<tr>
<td>P602418</td>
<td>Fire resistance testing to test adhesion, and capability of shotcrete to protect sealing layer/insulation on elements of concrete or rock. (4 tests)</td>
<td>Large-scale EN 1363-1 with the HC-curve for 180 min.</td>
<td>Shotcrete with PP-fibre on sealing layer/insulation on concrete element (3600 x 1200 x 280 mm³).</td>
<td>Temperatures behind shotcrete. Spalling depth.</td>
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<td><strong>Generic Tests</strong></td>
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<tr>
<td>P404443</td>
<td>Testing of thermal resistance and attachment systems of calcium silica boards. (4 tests)</td>
<td>Large-scale EN 1363-1 with the RWS-curve 120 min followed by the Malmö City Tunnel-curve 280 min (total exposure 300 min)</td>
<td>Calcium silica boards on concrete elements (3400 x 1200 x 600 mm³).</td>
<td>Attachments. Temperature behind boards.</td>
</tr>
<tr>
<td>P700779</td>
<td>Testing of thermal resistance of cement based material (6 tests)</td>
<td>Small scale SP Brand 119 with the ISO 834 standard-curve for 60 min.</td>
<td>Elements of cement based material (600 x 500 mm²)</td>
<td>Internal temperatures. Spalling depth.</td>
</tr>
</tbody>
</table>
The risk of spalling and the thermal insulating capacity have been studied for a wide range of concrete qualities for tunnel applications, of which several contained different amounts of polypropylene fibres as additives. In several tests different systems functioning as thermal barriers for the protection of concrete, granite, thermal insulation or drainage systems, have been investigated. Among those systems, examples of different shotcrete qualities, spray-on insulation and insulation plates and their anchorage systems could be found. The full body of data found in the SveBeFo report is too comprehensive to include in this paper. Therefore an illustrative example from fire testing conducted during the planning phase for the Malmö City Tunnel is included in the next section.

ILLUSTRATIVE EXAMPLE

As seen in Table 1, numerous tests have been conducted for the Malmö City Tunnel. A summary of the results for the test series conducted as a part of project P502334 are presented below to illustrate the type of data included in the full report. This data has not been presented previously as prior to the project it was governed by a confidentiality agreement and not available to the public.

The project included the fire test of eight (8) different concrete elements containing PP-fibres to investigate the propensity of the concrete formulations to spall and their thermal insulation characteristics. The test was conducted in general accordance with EN 1363-1 using the Malmö City Tunnel fire curve for 300 minutes.

The concrete elements were 1800x1200x400 mm³, molded as wall elements and manufactured with different concrete formulations. The concrete recipes are presented in Table 2. The elements were post-stressed using 36 mm DYWIDAG bars to a pressure of 5.4 MPa. In those cases where the concrete contained PP-fibres in its formulation ADfil Ignis (dimensions 6 mm x 18 μm) was used. The test objects were manufactured 2,5-3 months prior to testing and conditioned under water for 2 months.
The temperature was measured at different depths in the concrete elements and the spalling from the surface measured. The spalling results of the tests are summarised in Table 3.

The results of this test series can be summarized as follows:
- All test objects exhibited spalling during the fire test
- Test objects B3(I), B3(II), B4 (I) and B4(II), all spalled less than 40 mm on average or a maximum of 100 mm
- An increase in the addition of fibers resulted in a reduction in the overall spalling
- All test objects exhibited several vertical cracks during the test.
- When manufacturing the test elements, it was noticed that the workability of the concrete was significantly reduced due to the addition of fibers.
SUMMARY OF FINDINGS AND DISCUSSION

The work of collating the tests did not incorporate an analysis of the results, however some general findings are summarized below:

- There is a high risk of spalling in many concrete qualities, especially for dense concrete, such as self compacting and high strength concrete.
- A relatively small addition of PP-fibers reduces the risk of, or amount of, spalling in all types of concrete.
- In the majority of the large tunnel construction projects currently in progress in Sweden, PP-fibers will be added to concrete to some extent.
- For shotcrete, other spray-on products and different types of boards, it is very important to have an accurately designed and tested anchorage system. Otherwise there is a high risk of collapse during a fire, with a large reduction on functionality of the protective layer as a consequence.
- The concrete protection systems are tested during a limited time period, e.g. ISO 834 for 60 minutes. Real tunnel fires often have longer duration. The functionality of some protection systems is based on vaporization of bound water or other substances, and their functionality at longer exposure to high temperatures is unknown.
- Experience from industry shows that mixing concrete with PP-fibers has a large influence on the concrete rheology. For example concrete with PP-fibers requires higher slump flow than concrete without PP-fibers, if traditional vibration methods are used during molding.
- When adding PP-fibers to shotcrete, it is important to adjust the formula and have good control of all the ingredients. The shotcrete can otherwise easily exhibit a layered structure with large variations in quality.

ACKNOWLEDGEMENTS

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REFERENCES

Comparison of Road Tunnel Design Guidelines

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ABSTRACT

In the light of the recent catastrophic fires in tunnels much effort has been put into the work of preventing fires in tunnels and limiting the consequences of fires when occurring. This study describes the level of fire safety of road tunnels at the tunnel design stage, as given in guidelines, standards, regulations, directives, etc. A number of road tunnel guidelines from different countries and organizations have been compared to each other. The main focus of the comparison is the application criteria of guidelines and installation spacing. The comparison provides several interesting discussion topics, including similarities or differences between detailed requirements and the popularity type of each fire safety equipment or facility. The work can be divided into three parts. First, how tunnels are categorized in the different guidelines is described. Secondly, a description and comparison of different safety measures and how these relate to different tunnel categories is given. In the paper, the requirements for hand held extinguishers and the resistance to fire for different equipment are given as examples. Finally, the work includes some recommendations for specific improvement to Korean guidelines.

KEYWORDS: fire safety guideline, tunnel category, annual average daily traffic, fire safety equipment, fixed fire suppression system, hand held extinguishers, resistance to fire.

INTRODUCTION

Many road tunnels are built worldwide each year for various reasons. Some drivers may enjoy the reduction of travel time or the convenience of driving. On the other hand, for those who are engaged in fire safety, an increase in the number of road tunnels presents another problem at the same time because accidents (e.g. fires) often become more severe when occurring inside a road tunnel. The Korean economy has advanced briskly since the 1970's coupled to development in civil engineering. Many road and tunnels have been built nationwide to speed up the transportation of resources and people. In 1996, the number of road tunnels was 170. In 2005, this number had increased to 817, with a steady increase as shown in Table 1 and in Figure 1 [1]. Building a road tunnel can contribute to the decrease of environmental pollution and enhance the convenience for passengers. On the other hand, it poses safety problems to be solved and safety in road tunnels is emerging as a major issue.

In 2003, a significant fire occurred in the Hongjimun tunnel which is located in Seoul. All traffic around the tunnel was stopped for more than 2 hours and many tunnel users were frightened by this incident. Moreover, this accident was televised throughout the nation and people realized the seriousness of fire safety in road tunnels. In 2005, another tunnel fire attracted the public’s attention. A truck carrying a missile propellant caught fire and subsequently exploded. This fire accident caused the government to investigate whether existing fire safety guidelines of road tunnels are acceptable to ensure tunnel users’ safety. A large number of engineers, scientists and government officers started examining the actual condition of road tunnels and tried to find reasonable solutions. As the result of their efforts, some guidelines for road tunnels have been revised in 2004 and 2005 to strengthen their requirements for fire safety equipment. However, it is not easy to evaluate to what extent revised
requirements represent improvements or whether they can be accepted as reasonable guidelines when they are compared to those in other countries.

In this study, tables of comparisons have been compiled from various guidelines and recommendations for countries and organizations, in order to compare the fire safety level in each country. More details are found in the report by Kim et al. [2]. The countries included in this study include: some European countries with many tunnels, USA, Australia, Japan and Korea. Further, recommendations from EU, UNECE (United Nations Economic Commission for Europe) and PIARC (World Road Association) were reviewed for more information. This work can contribute to the evaluation of standard levels of fire safety and improve the requirement of future tunnel guidelines.

**Table 1 Increase in total number and length of road tunnels in Korea [1].**

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</tr>
</thead>
<tbody>
<tr>
<td>Total no.</td>
<td>170</td>
<td>184</td>
<td>312</td>
<td>351</td>
<td>397</td>
<td>528</td>
<td>583</td>
<td>603</td>
<td>667</td>
<td>817</td>
</tr>
<tr>
<td>Total length (km)</td>
<td>136</td>
<td>150</td>
<td>174</td>
<td>212</td>
<td>240</td>
<td>339</td>
<td>378</td>
<td>390</td>
<td>432</td>
<td>551</td>
</tr>
</tbody>
</table>

**Figure 1 Increase in total number and length of road tunnels in Korea [1].**

**Fire safety guidelines for road tunnels studied**

Numerous fire safety guidelines for road tunnels have been compared in this study. Table 2 lists their titles, ID, type of document, publishers and publishing year. The structures and administrative status of guidelines differ depending on their nature or purpose. However, the word "guidelines" as used in this study also indicates regulations, standards, and directives. The definition of the document status related to design of road tunnels can be defined below [3];

- **Regulation documents** contain specific mandatory requirements and are produced by a legal government entity.
- **Standard documents** contain mandatory language, and they are usually produced by a technical entity such as an association or society. These documents by themselves have no legal standing except where they have been adopted by or on behalf of a government agency by legislative action.
- **Guideline documents** provide, to the reader, recommended practices which can be applied in the design, construction, installation, operation and safety of the fire life safety and fire protection systems in a road tunnel. These documents are usually prepared by technical associations, however some have been prepared by governmental agencies.

A legislative document such as a directive has another status than a guideline and this is important to remember when comparing the different documents.

There are two guidelines concerning the fire safety of road tunnels in Korea. One is NFSC and the
other is GIST. NFSC is an acronym for National Fire Safety Codes. It is under the jurisdiction of NEMA (National Emergency Management Agency). GIST is an acronym for Guideline for Installation of Safety facility in road Tunnels. It has been established by the Ministry of Construction & Transportation of Korea. The relationship between the two guidelines appears to be complementary. GIST adopts many of the NFSC requirements as their provisions although some specific application limits and installation spacing may differ between the two. However, GIST is a stricter guideline concerning fire safety for tunnel than NFSC at present. NFSC gives tunnel designers or owners more freedom, which lets them decide the safety level of the tunnel depending on risk analyses and performance criteria.

Table 2  Guidelines of different countries included in the comparison [2, 4, 5, 6].

<table>
<thead>
<tr>
<th>Country</th>
<th>Title</th>
<th>ID</th>
<th>Type</th>
<th>Publisher/Year</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>Fire Safety guideline for road tunnels</td>
<td>-</td>
<td>Guideline</td>
<td>Australasian Fire Authorities Council (2001)</td>
<td>7</td>
</tr>
<tr>
<td>Austria</td>
<td>Guidelines and Regulations for Road Design</td>
<td>RVS</td>
<td>Guideline</td>
<td>Transportation and Road Research Association (2001)</td>
<td>8</td>
</tr>
<tr>
<td>Germany</td>
<td>Guidelines for equipment and operation of road tunnels</td>
<td>RABT 02</td>
<td>Guidelines</td>
<td>Road and Transportation Research Association (2002)</td>
<td>10</td>
</tr>
<tr>
<td>PIARC</td>
<td>Fire and Smoke Control in Road Tunnels</td>
<td>PIARC</td>
<td>Guideline</td>
<td>PIARC (1999)</td>
<td>19</td>
</tr>
</tbody>
</table>

a) New regulations dealing with the fire safety in road tunnels has been established in July 2007.

ESTABLISHMENT OF REQUIREMENTS

When specific requirements of fire safety equipment are established, two approaches can be found in most countries studied: a tunnel length system and a combination system based on tunnel length and
other parameters, mainly traffic volume (flow).

Tunnel length systems determine the requirements or recommendations according to the length of the tunnels. They consist of a few length intervals which have a certain range of values. It is occasionally found in some tunnel length systems that some parameters such as traffic volume (flow) and traffic types of tunnels affect the application of the guidelines. However, their influences are limited and the related requirements should be regarded as an exception for principles. A typical example of a tunnel length system is presented in the table given in Figure 2.

![Figure 2](image)

**Figure 2** Summary of requirements for Germany [10].

The combination systems are based mainly on the matrix of the tunnel length and traffic volume. Each parameter is considered for elevation to the upper categories which require more extensive safety measures. The tunnels with heavy traffic volume or long length are elevated into the higher categories. In general, the traffic volume is given in AADT (Annual Average Daily Traffic, unit: no. of vehicles) which is the estimated average daily traffic volume in both directions of a tunnel bore after opening. In addition to traffic volume, risk analyses are adopted for the formation of matrix in some countries. A typical example of a combination system is shown in Figure 3. This system is applied for road tunnels in the UK [16].

![Figure 3](image)

**Figure 3** Road tunnel categories of UK [16].

TUNNEL LENGTH SYSTEMS

Tunnel length systems are established in five tunnel countries/regions: France, Germany, Korea
There are large differences in length intervals and the minimum length of application between the countries. France has more divided length intervals and more supplement factors than NFSC of Korea and NFPA 502 of USA which has only three length intervals. Comparisons of the tunnel length systems are shown in Table 3.

**Table 3 Comparisons of the tunnel length systems in different countries**

<table>
<thead>
<tr>
<th>Country</th>
<th>No. of length interval</th>
<th>Boundary values for length interval (m)</th>
<th>Minimum length of application</th>
<th>Supplement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>7</td>
<td>300, 500, 800, 1000, 1500, 3000, 5000 m</td>
<td>300 m</td>
<td>Location, traffic type, traffic volume</td>
</tr>
<tr>
<td>Germany</td>
<td>4</td>
<td>All tunnels, 400, 600, 900 m</td>
<td>All tunnels</td>
<td>Traffic volume</td>
</tr>
<tr>
<td>Korea (NFSC)</td>
<td>4</td>
<td>All tunnels, 500, 1000, 2000 m</td>
<td>All tunnels</td>
<td>-</td>
</tr>
<tr>
<td>USA</td>
<td>3</td>
<td>90, 240, 300 m</td>
<td>90 m</td>
<td>-</td>
</tr>
<tr>
<td>EU</td>
<td>3</td>
<td>500, 1000, 3000 m</td>
<td>500 m</td>
<td>Traffic volume</td>
</tr>
</tbody>
</table>

**COMBINATION SYSTEMS OF TUNNEL LENGTH AND TRAFFIC VOLUME**

Among the countries/organisations studied here, combination systems are adopted in six of them: Austria, Japan, Korea (GIST), Sweden, Norway and the UK. The categories of Japan, Sweden, Norway and the UK are decided by a matrix of tunnel length and traffic volume. This means that the basic parameters for the design are the tunnel length and the traffic volume. This is not the case for the guidelines given in Table 3.

Beyond using the tunnel length and traffic volume, Korea (GIST) carries out risk analysis for determining the elevation to upper categories which is based on the evaluation of six risk factors. Traffic volume is one of these six factors. In particular, Austrian classification is determined by traffic volume per hour, not AADT and other factors such as mean directional split and number of dangerous goods transports. All tunnels appear to be considered for use in Austria.

The specific criteria of two parameters (length and traffic volume) which determine the categories vary among the countries; the minimum lengths of tunnel for application of guideline are all tunnels (Korea), 100 m (Japan and Sweden), 150 m (the UK) and 500 (Norway). The minimum values of AADT are 100 (Sweden and the UK), approximately 250 (Norway), and 500 (Japan). The numbers of the categories are three (Sweden), four (Austria and Korea), five (Japan and the UK) and six (Norway). In addition, the years for estimation of AADT are different in five countries: 10 (Japan), 15 (UK) and 20 (Korea, Norway and Sweden) years after opening. The comparison of the combination systems studied is presented in Table 4.
### Table 4 Comparisons of the combination systems in different countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>The number of categories</th>
<th>Minimum lengths of tunnel for application of guideline (m)</th>
<th>Minimum values of AADT</th>
<th>Estimation year of AADT after opening (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>3</td>
<td>100</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>Japan</td>
<td>5</td>
<td>100</td>
<td>500</td>
<td>10</td>
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<tr>
<td>UK</td>
<td>5</td>
<td>150</td>
<td>100</td>
<td>15</td>
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<tr>
<td>Norway</td>
<td>6</td>
<td>500</td>
<td>250</td>
<td>20</td>
</tr>
<tr>
<td>Korea</td>
<td>4</td>
<td>All tunnels</td>
<td>All AADT</td>
<td>20</td>
</tr>
<tr>
<td>Austria</td>
<td>4</td>
<td>All tunnels</td>
<td>Traffic volume per hour</td>
<td>-</td>
</tr>
</tbody>
</table>

It is known that there are advantages to adopting a combination system to decide the basic safety facilities to be installed for the safety of road tunnels. However, care should be taken when such a system is selected and used, as each tunnel has its own nature and environment and some of the differences are not considered by the combination systems.

### COMPARISON OF ESTABLISHMENT OF REQUIREMENTS

It is interesting that Korea adopts different application systems in two governmental documents dealing with fire safety issues for road tunnels: tunnel length system in NFSC and combination system in GIST. Each system has its own advantages and disadvantages and preference for which system should be adopted is solely up to each country. However, an optimal balance between tunnel length and traffic volume seems to be the best method for ensuring the fire safety.

For a clear understanding and distinction, a comparison between a tunnel length system and a combination system is presented in Table 5.

### Table 5 Comparison between tunnel length system and combination system.

<table>
<thead>
<tr>
<th>Comparative Items</th>
<th>Tunnel length system</th>
<th>Combination system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key factor</td>
<td>Tunnel length</td>
<td>Tunnel length and traffic volume (AADT)</td>
</tr>
<tr>
<td>Supplementary factor</td>
<td>Traffic volume, tunnel location, types of traffic etc.</td>
<td>Risk analysis, elevation to upper classes etc.</td>
</tr>
<tr>
<td>Advantage</td>
<td>Easy to understand. Simple application of guideline.</td>
<td>Reflection of both traffic volume, tunnel length and in some cases risk.</td>
</tr>
<tr>
<td>Disadvantage</td>
<td>Underestimate of the importance of traffic volume. There is nearly no consideration of risk.</td>
<td>Difficult to estimate the expected traffic volume.</td>
</tr>
<tr>
<td>Country</td>
<td>France, Germany, Korea (NFSC), USA, EU</td>
<td>Austria, Japan, Korea (GIST), Sweden, Norway, the UK</td>
</tr>
</tbody>
</table>

### COMPARISON

In Table 6, detailed requirements concerning different fire safety equipment have been compared for a number of countries and organizations. Among all available fire safety equipment given in Table 6, only two types of equipment will be studied in detail. It is not possible to do this type of analysis for all the listed equipment. It was, however, thought that these two equipment categories, hand held extinguisher and equipment resistance to fire, could serve as a good examples of how these guidelines work.
### Table 6 Matrix of guideline contents

<table>
<thead>
<tr>
<th>Fire safety equipment</th>
<th>Australia</th>
<th>Austria</th>
<th>France</th>
<th>Germany</th>
<th>Japan</th>
<th>NFSC</th>
<th>GIST</th>
<th>Korea</th>
<th>Norway</th>
<th>Sweden</th>
<th>UK</th>
<th>USA</th>
<th>EU</th>
<th>PIARC</th>
<th>UNECE</th>
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<tr>
<td>Fire fighting facilities</td>
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<tr>
<td>Hand held extinguishers</td>
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<td>Water supply and hydrants</td>
<td>● ● ● ● ● ● ● ● ● ● X ● ● ● ●</td>
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<td>Fire department connections</td>
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<tr>
<td>Fixed fire suppression system a)</td>
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<td>Fire detection and communication</td>
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<tr>
<td>Manual fire detection system</td>
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<tr>
<td>Automatic fire detection system</td>
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<td>Loudspeakers</td>
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<td>Emergency telephones</td>
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<td>Radio communication systems</td>
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<td>Emergency cross-passage</td>
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<td>Emergency access for rescue staff</td>
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<tr>
<td>Separate gallery for emergency vehicles</td>
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<tr>
<td>Cross-passage for rescue vehicle</td>
<td>X ● ● ● ● ● ● X X X X X ● X ●</td>
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<td>Emergency services parking</td>
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<td>Lighting</td>
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<tr>
<td>Emergency lighting</td>
<td>X X ● ● ● ● ● ● ● ● ● ● ● ● ●</td>
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<td>Smoke control ventilation</td>
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<td>Emergency exit sign</td>
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<td>UPS and emergency generator</td>
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<td>Fire brigade power tool sockets</td>
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<td>Drainage of flammable liquids</td>
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<td>Inclination (scope) of tunnel</td>
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<td>Liquid sump</td>
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<td>Response of structure and equipment to fire</td>
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<tr>
<td>Structural fire resistance</td>
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<tr>
<td>Equipment resistance to fire</td>
<td>X X ● ● ● ● ● ● X</td>
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</table>

Note: symbol “●” shows that the information on the application length and installation interval is provided, symbol “▲” indicates that general information is given and symbol “X” indicates that no relevant provisions are found in the examined guidelines.

a) The symbol “●” in the section for fixed fire suppression systems indicates that relevant provisions are prepared or the installations of fixed suppression systems are reported.
Hand held extinguishers

Hand held extinguishers are included in all guidelines studied. This indicates that a portable extinguisher is one of the basic pieces of equipments in road tunnels. The application criteria do not show significant differences between guidelines. The minimum length of targeted tunnels varies from all tunnel lengths to 500 m; i.e., all tunnel lengths in Korean regulations, 100 m in Japan, 240 m in USA, 300 m in France, 400 m in Germany and 500 m in Sweden and the EU with some exceptions. Norway and the UK have minimum application classes: Category B in Norway and Class B in the UK. However, the installation spacing varies considerably; the maximum spacing is from 50 m (Korea, Japan and the UK), 60 m (Australia), 90 m (USA), 150 m (Germany, Sweden, and EU), 200 m (France) and 62.5–250 m (Norway) and 250 m (Austria). It is common that the extinguishers are provided in emergency recesses with other facilities such as emergency phone and hydrants. For that reason, the spacing of extinguishers corresponds to that of emergency recesses or emergency call stations.

Almost all countries/organizations (Austria, France, Germany, Japan, Norway, Sweden, USA and PIARC) in this section require at least two, 6 kg-extinguishers. In Austria and the USA, 9 kg-extinguishers are recommended. Further, CO₂ extinguishers, installed adjacent to all electrical switchboards, control panels etc. are mentioned in the Australian guidelines. Korea requires two extinguishers which have three unit-capacity as the minimum capacity. In general, a 3.3 kg-extinguisher is regarded as having three unit-capacity and used as a home fire extinguisher in Korea. Unit-capacity indicates the extinguisher’s ability to suppress fires. When an extinguisher can extinguish two types of wood cribs which consist of 144 and 90 wooden sticks respectively, it is designated as a three unit-capacity extinguisher. It seems to be doubtful whether two 3.3 kg-extinguishers with three unit-capacity each have sufficient abilities to suppress tunnel fires effectively. Almost all fires which occur in tunnels are vehicle fires or vehicle related fires. Vehicles contain a certain amount of flammable fuels and in particular trucks often carry heavy loads of flammable goods. In addition, typical tunnel environments such as existing air flow and restriction of access make it difficult for tunnel users to control fires. For these reasons, extinguishers installed in road tunnels should have more capacity than those used in houses or general buildings.

The provision of automatic alarms on equipment can be found in the guidelines of Austria, France, Germany, Norway, the UK and PIARC. However, there is no provision in NFSC of Korea concerning extinguisher removal alarms which would enable tunnel operators to be informed of the use of their equipment should an extinguisher be removed. For quick response in tunnel fires, efficient equipment removal alarm systems are necessary.

Equipment resistance to fire

The minimum resistance temperature and time is given in most guidelines. However, the figures differ significantly: 200 ºC for 120 minutes (ventilation fans, France), 250 ºC for 45 minutes (all installations, Sweden), 250 ºC for 1 hour (all electrical and structural components relating to ventilation fans, Korea), 250 ºC for 1 hour (tunnel ventilation fans etc, USA), 316 ºC for 1 hour (materials manufactured for use as conduits etc, USA), 250 ºC for 2 hour (all electrical components relating to ventilation fans, the UK), 400 ºC for 1.5 hour (fans and electrical connections, Germany) and 750 ºC for 1.5 hour (fire-proof cables, Norway). The guidelines of Australia and EU do not give detailed temperature and duration time requirements. Compared to the requirements of Germany, which require 400 ºC for 1.5 hour for fans, and electrical connections and the requirements of the UK, which require 250 ºC for 2 hour for all electrical components relating to ventilation fans, Korean counterparts have lower fire resistance temperatures and shorter resistance time. It is difficult to judge which criteria are more appropriate because it is a matter of cost-benefit issues.

The requirements of equipment resistance to fire in different countries are shown in Table 8.
### Table 7 Hand held extinguishers in different guidelines.

<table>
<thead>
<tr>
<th>Country</th>
<th>Application criteria</th>
<th>Capacity &amp; Spacing</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korea</td>
<td>NFSC</td>
<td>All tunnels</td>
<td>Two 3.3 kg (≥ 3 Unit capacity). &lt;50 m spacing.</td>
</tr>
<tr>
<td></td>
<td>GIST</td>
<td>All tunnels</td>
<td>Two 3.3 kg (≥ 3 Unit capacity) extinguishers. &lt;50 m Spacing.</td>
</tr>
<tr>
<td>Australia</td>
<td>-</td>
<td>Dry chemical extinguishers (equipment niche, 60m spacing) and CO₂ extinguishers a).</td>
<td>a) adjacent to all electrical switchboards, control panels etc.</td>
</tr>
<tr>
<td>Austria</td>
<td>&gt;500 m</td>
<td>6 l and 9 l extinguishers, 250 m spacing (at each fire fighting equipment recess and emergency telephone station)</td>
<td>Automatic alarm on opening door to extinguisher.</td>
</tr>
<tr>
<td>France</td>
<td>≥300 m</td>
<td>Two 6 kg (unit capacity) and at least 13A and 183B performance. 200 m spacing (emergency recesses)</td>
<td>Extinguisher removal alarms may be provided.</td>
</tr>
<tr>
<td>Germany</td>
<td>&gt;400 m</td>
<td>Two 6 kg (net) extinguishers, &lt;150 m spacing (at emergency call station).</td>
<td>Automatic alarm on equipment.</td>
</tr>
<tr>
<td>Japan</td>
<td>Class D (&lt;100 m)b)</td>
<td>Two 6 kg extinguishers, 50 m spacing.</td>
<td>b) It means that the minimum length of Class D is 100 m.</td>
</tr>
<tr>
<td>Norway</td>
<td>Category ≥B</td>
<td>Two (Category D and F) 6 kg extinguisher (NS EN 3) Category B: 250 m spacing c), d) Category C, D: 125 m spacing c), d) Category E: 125 m spacing c) Category F: 62,5 m spacing c)</td>
<td>c) Additionally installed outside each tunnel entrance. d) Mounted on one side at given spacing and located with emergency telephones on the opposite side. Extinguisher removal alarms should be provided.</td>
</tr>
<tr>
<td>Sweden</td>
<td>All classes (≥500 m)</td>
<td>Extinguishers should be at each portal and at least every 150 m. They should contain 6 kg ABC-powder and manage the test fires 34A and 183B.</td>
<td>The extinguisher should fulfill SS-EN 3-7.</td>
</tr>
<tr>
<td>UK</td>
<td>Class AA, A and B</td>
<td>Two extinguishers (13A fire ratings of BS EN 3 Part 1). 50 m spacing (emergency point)</td>
<td>Class C tunnels can be applied.</td>
</tr>
<tr>
<td>USA</td>
<td>≥240 m c)</td>
<td>9 kg (maximum) extinguishers (2-A: 20-B: C). ≤90 m spacing</td>
<td>e) ≥240 m where the maximum distance from any point within the tunnel to a point of safety exceeds 120 m, otherwise ≥300 m.</td>
</tr>
<tr>
<td>EU</td>
<td>≥500 m with exceptions</td>
<td>Two extinguishers. ≤150 m spacing (≤250 m in existing tunnels)</td>
<td>At emergency stations with a telephone.</td>
</tr>
<tr>
<td>PIARC</td>
<td>-</td>
<td>The minimum content of 6 kg when the traffic includes mainly passenger cars. The maximum of 9 kg when heavy goods vehicles are numerous.</td>
<td>Extinguisher removal alarms recommended.</td>
</tr>
<tr>
<td>UNECE</td>
<td>-</td>
<td>-</td>
<td>Fire extinguishers should be installed systematically in tunnels and at their entrances.</td>
</tr>
</tbody>
</table>

Note: In the table, *Italics*: Hoj [21], *underline*: KTA [4], normal font: original guideline.
Table 8 Equipment resistance to fire in different guidelines.

<table>
<thead>
<tr>
<th>Country</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korea</td>
<td><strong>NFSC</strong> Air supplier and auxiliary equipment of ventilation systems exposed to a fire shall be able to operate for more than one hour under 250 ºC.</td>
</tr>
<tr>
<td></td>
<td><strong>GIST</strong> All electrical and structural components essential to the continued operation of ventilation fans shall, in the event of a fire, be suitable for operating in smoke-laden air at a temperature of 250 ºC for 1 hour.</td>
</tr>
<tr>
<td>Australia</td>
<td>Consideration should be given to emergency doors, communication systems, ventilation system and other equipment located between two tunnel tubes, the tunnel and the escape route or located on the walls or ceiling of the tunnel.</td>
</tr>
<tr>
<td>Austria</td>
<td><strong>Cables for emergency lighting must be inflammable and corresponding to F90 (90 minutes functionality).</strong> <strong>Cable for normal lighting, ventilation and door steering must correspond to E30 (30 minutes functionality) and FE180 (180 minutes isolation).</strong></td>
</tr>
<tr>
<td>France</td>
<td>The main arteries ensuring connections between electricity supply points and transmission cables can function under the conditions of Level N3 (CN 240 HCM 120). Where fans are installed in order to ensure massive extraction, these must be capable of operating for 120 minutes at a temperature of 200 ºC. Extraction fans located at each end of a duct must be capable of operating at a temperature of 200 ºC for 120 minutes.</td>
</tr>
<tr>
<td>Germany</td>
<td><strong>Extraction fans and dampers must be designed minimum for resistance to a temperature of 400 ºC during 90 minutes.</strong> <strong>Jet fans and electrical connections shall withstand a temperature of 250 ºC during 90 minutes and (in some case) up to 400 ºC in 90 minutes.</strong></td>
</tr>
<tr>
<td>Norway</td>
<td>For open ducts a distinction is made between cables which supply power to equipment which shall function in a fire situation (Cable class 3), and cables for non-critical equipment (Cable class 2). Cables in Class 3 shall function for a period of 90 minutes in a flame temperature of 750 ºC.</td>
</tr>
<tr>
<td>Sweden</td>
<td>Installations should endure 250 ºC for at least 45 minutes.</td>
</tr>
<tr>
<td>UK</td>
<td>Light, lighting diffusers, cables and tunnel linings above shall be non-flammable. Heavy items such as fans, subject to temperatures of 450 ºC, should not fall during the fire fighting period. All electrical and structural components essential to the continued operation of ventilation fans shall, in the event of a fire, be suitable for operating in smoke-laden air at a temperature of 250 ºC for 2 hours.</td>
</tr>
<tr>
<td>USA</td>
<td>Tunnel ventilation fans, their motors, dampers and all related components shall be designed to remain operational for a minimum of 1 hour in an air stream temperature of 250 ºC. Materials that are manufactured for use as conduits, raceways, ducts, cabinets, and equipment enclosures and their surface finish materials shall be capable of being subjected to temperatures up to 316 ºC for 1 hour.</td>
</tr>
<tr>
<td>EU</td>
<td>The level of fire resistance of all tunnel (≥ 500 m) equipment shall aim to maintain the necessary safety functions.</td>
</tr>
</tbody>
</table>

Note: In the table, *italics*: Høj [21], _underline_: KTA [4], normal font: original guideline.

**DISCUSSION**

When all detailed comparisons are reviewed, some important issues should be highlighted. A list of the most important issues is given below. More details can be found in the report by Kim et al. [2].
• Most requirements depend on the tunnel length. This means that the installation of required facilities for road tunnels are decided mainly based on the length of the tunnel. However, some countries consider other criteria as well, e.g., traffic volume is adopted as a key parameters in Japan, Norway, Sweden and the UK. Danger potential is considered in Austria and risk analysis is carried out in Korea. The French guideline is established mainly according to the location of the tunnel, using supplementary parameters such as traffic type and traffic volume. In conjunction with the criteria given above, risk of congestion, ventilation type, and human supervision can also influence the ultimate decision concerning the application of provisions.

• The minimum length of tunnel for application of guideline varies from country to country. The figures are 90 m (USA), 100 m (Japan and Sweden), 150 m (the UK), 300 m (France), and 500 m (Norway and EU). Germany and Korea do not have a minimum value so all road tunnels are potentially applicable. The minimum value is useful as safety facilities may be useless in very short tunnels. There is also a cost-benefit issue.

• Further study is needed on the relationship between the capacity and spacing for firefighting equipment. In Korea, extinguishers, hydrants and fire department connections have lower capacity than that of other countries included in this study. However, the installation spacing in Korean guidelines are shorter than that of European countries and USA. It is not known which approach is better or whether these two aspects (i.e., capacity versus spacing) compensate for each other so that the requirements are essentially equivalent.

• The minimum values of AADT adopted by guidelines vary. They are 100 AADT in the UK and Sweden, approximately 250 AADT in Norway and approximately 500 AADT in Japan. In addition, the years of estimated AADT are different in five countries: 10 (Japan), 15 (the UK) and 20 (Korea, Norway and Sweden) years after opening.

• More attention has been drawn to the installations of fixed fire suppression systems worldwide. It is reported that fixed fire suppression systems have been installed in Australia, Austria, Japan, Korea, Norway, Sweden and USA. In Japan, the use of sprinkler systems is mandated for certain types of tunnels and traffic volume. In Australia, the installation is not mandatory but new tunnels are routinely equipped with sprinkler systems.

• Recommendations for each country can be proposed resulting from the requirement comparison. For example, key recommendations for Korea are the improvement of fire fighting facilities and emergency power supply, establishment of requirements dealing with the drainage of flammable liquids and structural fire resistance and the accordance between two Korean tunnel safety design guidelines. In the same manner this study contains tips for each country included in the comparison for better requirements and develop their safety measures.

CONCLUSION

In this study, numerous guidelines from countries and organizations have been compared to identify their differences and similarities. Some fire safety equipment has been described frequently or similarly in various guidelines while some are mentioned rarely or differently in the countries. Based on the comparison, recommendations for Korean fire and road authorities could be proposed. It is also hoped that this comparison and recommendations will provide meaningful information from which beneficial conclusions can be derived for improvements to future tunnel safety worldwide. The aim of this work is to support existing requirements or develop more useful provisions.

As the results of this study, the necessity for further research is demonstrated. The topics of the research will be a screening process through which recommendations should be verified and supported before they are applied to real tunnels. An analytic approach is needed, e.g. a performance-based approach and relationship between capacity and spacing.
It is practically impossible to construct a perfect tunnel safety guideline, ensuring absolute fire safety in road tunnels. However, we must make every effort to decrease the risks associated with the use of tunnels to the greatest extent possible. Also, cost-benefit issues should always be considered in the development of a new or revision of existing guidelines. It is only through continuous research on this topic that we will ultimately limit the effects of tunnel fires.

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The Burnley Tunnel Fire – Implications for Current Design Practice

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Arup Fire
Melbourne, Australia

ABSTRACT

The major fire that occurred in the Burnley Tunnel in Melbourne, Australia provided the first real test of the current fire safety design approach generally applied to road tunnels in Australia.

This incident occurred in March 2007 in the Burnley Tunnel which forms part of the CityLink toll road system, which resulted in the deaths of three car drivers and a significant fire. The tunnel operator activated the water based deluge system and the hybrid smoke control system. The tunnel was able to be re-opened in 4 days.

In Australia, the design of fire protection for road tunnels has generally followed the Australian Fire Authority Council (AFAC) Guidelines for fire safety of road tunnels and the more recent Road Traffic Authority of NSW Guideline, although a new Australian Standard for tunnel fire safety is currently in preparation.

Australia and Japan appear to be the only countries to consistently require water based suppression systems in road tunnels, although it is recognized there are examples in other countries. It is recognized also that PIARC, NFPA and European regulators are examining the question of provision of water based suppression systems for road tunnels. For these reasons, it makes an investigation of the sequence of events in the Burnley Tunnel fire most interesting.

Discussion on safety issues since the Burnley Tunnel fire have largely concentrated on measures to prevent further accidents, including consideration of reduced traffic speeds, limiting trucks to the left hand lanes, restricting vehicles passing and provision of breakdown lanes or bays. Ongoing investigations by road research and traffic authorities are examining these issues. However, it has also re-focussed attention on fire protection measures.

In summary, this paper utilizes the events of the tragic Burnley Tunnel fire to examine the key design elements of road tunnel fire safety as currently practiced in Australia. It also provides insights into the ongoing debate about the value of water based suppressions systems in protecting life, property and tunnel operations that may be useful in a global context.

KEY WORDS: road tunnels, fire safety design, standards, suppression systems
INTRODUCTION

The major accident and fire which occurred in the Burnley Tunnel in Melbourne has provided a major opportunity to evaluate the adequacy of the current design approach generally applied to road tunnels in Australia. Other fires have occurred in Australian road tunnels over recent years, but generally they have been small.

This incident occurred on 23 March 2007 in the 3.4 km Burnley Tunnel which forms part of the CityLink toll road system in Melbourne. A HGV had stopped in the left lane of the tunnel, a second HGV collided into three cars waiting to go around the stopped HGV. Other vehicles were involved. A significant fire immediately followed the crash, resulting in manual activation of the water based deluge system and the hybrid smoke control system by the tunnel operator to control the fire and the smoke. The Burnley Tunnel re-opened to traffic in 4 days.

More recently, a somewhat similar road accident and fire occurred in a road tunnel on the Interstate 5 Freeway near Santa Clarita in California, USA. On this occasion there were few if any fire protection systems and the fire burned intensely for over 4 hours, with flames extending out the portals some 25-30 metres into the air. Again, three people were killed, and the tunnel was so damaged that it was expected that it would be many months before the damaged tunnel could be repaired and re-opened. A comparison between the Santa Clarita I-5 and the Burnley Tunnel fires is of international interest.[1]

In Australia, road tunnels have generally followed the guidance from the Australian Fire Authority Council (AFAC) for fire safety of road tunnels[2]. More recently, the Road Traffic Authority of NSW have developed and published a Road Tunnel Design Guideline[3], the principles of which have largely appeared in Scope of Work and Technical Requirements (SWTC) documents for major tunnel projects around Australia. An Australian Standard Committee FP-023 has been formed to prepare a new Australian Standard for tunnels, including road tunnels.

Common practice in Australia requires road tunnels of significant length to meet a number of key requirements, including fire detection, CCTV, cross passages at 120m centres, a water based zoned deluge system, and some form of smoke control. In tunnels in excess of 4 to 5 km, a hybrid longitudinal/semi-transverse smoke extraction system is required which not only provides a critical velocity to prevent backlayering, but incorporates a roof level duct system to extract smoke in a zone downstream of the fire.

The Burnley Tunnel fire has attracted a good deal of media, community and industry attention. For fire safety professionals, particular interest has focussed on the apparent success of the water deluge system in preventing fire spread and major tunnel damage.

This paper highlights the major design features of the tunnel, its fire protection measures and the sequence of events which led to the fire and its subsequent control. The paper traces the development of fire safety measures in road tunnels in Australia, and highlights the role that water suppression systems play in Australian tunnels. This leads into the implications for current design in Europe and the Americas, where PIARC and NFPA are considering the adoption of such suppression systems. A brief comparison between the Burnley and Santa Clarita Tunnel fires is made to illustrate the effectiveness of a comprehensive approach to tunnel fire safety.

The details in this paper are gleaned only from media reports and other publicly available information that have been assembled by the authors into a tunnel fire summary[4] on which this paper is based. The sequence of events and their timing are therefore speculative, and will only be confirmed once official investigations and the coronial enquiry into the incident are completed.
**BURNLEY TUNNEL**

**Tunnel Details**

The Burnley Tunnel forms part of the CityLink toll road system and is one of the pair of tunnels which carries traffic under the Yarra River and part of the city in Melbourne, Australia. The CityLink tunnels were opened in 2001.

The two tunnels, namely the Burnley Tunnel and the Domain Tunnel are both three lanes, but have different alignments, lengths, and depths below grade. They run in parallel only for part of their length as illustrated in Figure 1 below. Each tunnel has no breakdown lane or stopping bays.

![Figure 1: Tunnel Location](image1.png)

The Burnley Tunnel which takes traffic from west to east around the city has a length of approximately 3.4km, and at its deepest point is some 65m in below grade, as illustrated in Figure 2. The grades in the Burnley Tunnel are significant, with a 6.2 degree downhill slope starting at the entry and 5.2 degrees on the upgrade toward the exit portal.

![Figure 2: Longitudinal Tunnel Section](image2.png)

The tunnel cross section clear of equipment at roof level is approximately 4.9m high, with three lanes each 3.5m wide. This is illustrated in Figure 3.
The tunnel carries high traffic volumes with substantial numbers of freight vehicles along with cars and buses. Latest figures indicate usage of over 100,000 vehicles/day, of which 14,000 are trucks. The normal speed limit is 80km/hr, but in times of lane closure, minor accidents or maintenance periods, the speed limit is usually reduced to 60km/hr. During peak hours, traffic can be congested and travelling at less than the signed speed limits.

The tunnels, together with the associated toll road system, is managed by CityLink on behalf of the ultimate owner Transurban, who own and operate other toll road systems in Australia and the US.

**Fire Safety Features**

The Burnley and Domain Tunnels were considered to have the state-of-the-art fire protection when constructed. In part, this was due to investigations conducted by the CityLink design team and fire authorities into the results of the Mont Blanc fire, and the design of the Harbour Tunnel in Sydney, as reported by Nicholson[5].

The key fire safety features for the Burnley Tunnel include:

- A water based deluge system, with 30m long zones, normally activated remotely from the control room.
- A combined longitudinal and semi-transverse smoke control system, with a central duct at tunnel roof level with extract dampers at 80m intervals, plus sets of jet fans to control critical velocity. The duct extract is vented through exhaust stacks at the ends of the tunnels.
- A linear heat detection system set at 68°C.
- Cross passages to the adjacent tunnel and exits to an emergency egress tunnel for part of the Burnley Tunnel. In addition, there are three safe havens and one lift to the surface.
- An elevated walkway about 750mm high and 750mm wide on the right hand side (inside lane) of the tunnel.
- “Fire boxes”, consisting of hydrants, hose reels, and portable extinguishers at approximately 60m centres.
- A CCTV system, with cameras at 150m centres, with stopped vehicle alarm provisions.
- A radio ‘break in’ system with AM/FM rebroadcasting to transmit traffic control or emergency messages.
- Overhead variable message signage at 120m intervals to indicate lane closure, and other emergency messages. Also speed limit signs.
- Exit signs to cross passage/exit doors.
• A public address/emergency warning system, and emergency telephones at 120m centres.
• DISPLAN communication points for emergency services direct communication to their control rooms.
• Emergency lighting systems.
• An emergency incident management plan, which has been regularly rehearsed by CityLink staff with the emergency services.

The Incident

The traffic accident which triggered the fire occurred at approximately 10am on Friday 23 March 2007, a little after the peak hour rush but at a time of relatively heavy traffic volumes. The accident occurred about 1.4km into the Burnley Tunnel at the end of a long downhill grade.

Media accounts[6][7] suggest the following sequence of events:

• A truck travelling through the tunnel suffered stopped in the tunnel’s left hand lane.
• The stopped truck was detected by the CityLink’s control room.
• Routine response was implemented by the Control Room. This includes tunnel signs to tell motorists that the left-hand lane was closed, the speed limit was reduced and an incident response truck was dispatched.
• Within some minutes of the truck stopping, the traffic accident occurred. Cars were waiting behind the stopped truck, to merge right and change lanes to get past the stopped truck.
• A second semi-trailer truck (HGV), apparently travelling in the centre lane, struck these cars. Other vehicles were affected to a lesser degree.
• It appears at least one of the cars burst into flames, and people reported a number of “explosions” and a “fire ball”, with flames reaching the tunnel roof. It is unclear whether the “explosions” were the noise of the impacts, tyres bursting, or petrol or LPG from vehicle fuel tanks actually exploding.
• The resultant fire led to the deluge and the smoke exhaust systems being activated. Cars ahead of the accident, and subsequent fire, drove out of the tunnel. However, some 200 cars and 400 people were stopped by the accident and fire, and were instructed to leave their cars and evacuate.
• Some people walked back through the incident tunnel to the tunnel entrance. The remainder evacuated using the cross passages and exit stairs linked to the Domain Tunnel which was closed soon after the accident. Media reports indicate there was “no sign of panic or alarm”.
• The tunnel entrances became staging points or assembly areas for persons evacuated, where they were given identifying wrist bands, provided with food and water, and given instructions by police and CityLink emergency personnel.
• The deluge system appeared to control the fire, and the fire brigade attended with 30 fire trucks and 84 fire fighters, as well as 10 special police crash investigators.
• The fire was finally extinguished at approximately 11am, about 1 hour after the accident occurred.
• Disabled people were assisted in evacuation by able bodied people apparently quite successfully.
• The final toll was three dead (all drivers of the cars involved), plus one or two persons with minor injuries taken to hospital.
• Cars belonging to evacuees were removed by mid afternoon.
• The non-incident Domain Tunnel was re-opened to traffic at approximately 2:30pm on that day, Friday 23 March 2007.
• The Burnley Tunnel was re-opened to full traffic operations at 10am on the following Tuesday, 27 March 2007, four days after the incident, following system testing and checks of essential fire protection measures.
Fire Performance

Although not confirmed by authorities, it appears that the deaths and injuries were due to the traffic accident and not the subsequent fire, although this is certain to be a major area of investigation for the coronial enquiry.

The water deluge system, which was zoned with open deluge heads and not a closed head sprinkler system, seems to have operated as intended and prevented fire spread from the immediate incident area. It appears to have been activated manually from the control room. There was some relatively minor damage to electrical systems in the immediate vicinity of the fire, but these were reasonably easily repairable.

The tunnel linings and exhaust duct appeared not to be damaged and were cleaned prior to the tunnel re-opening. The asphalt road surface suffered some minor damage but was repaired within three days.

According to media reports, the total asset damage and repair bill has been estimated at AUD$1.5 million and loss of toll revenue at AUD$3.0 million. Some temporary reduction in daily toll revenues might have been expected in the weeks following the incident, due to driver concerns with travelling through the tunnels after such an incident.

The CCTV also appears to have worked satisfactorily to provide an alarm to the control room to allow control room staff to make appropriate emergency management decisions.

The smoke extraction system appears to have worked satisfactorily, although it is unclear how much smoke was extracted downstream of the fire by the duct system, and how much smoke continued down the tunnel. However, given only some 100m of the tunnel needed to be cleaned, and there were reports of substantial smoke flowing out of the exhaust stack from the duct system, it indicates that heavy smoke was probably confined to this area near the fire. It also appears that the jet fans and exhaust duct operated to prevent “back layering” and smoke travelling uphill towards the tunnel entrance in the direction of evacuation.

The radio interrupt system and the signage telling drivers and passengers to stop their vehicles, begin evacuation and walk back towards the tunnel entrance, seems to have been heeded. Reports by evacuating people and the emergency services all seem to indicate that the pre-planning, fire drills and other training contributed significantly to the success of the entire emergency management system. This is acknowledged in the following quote by Metropolitan Ambulance Operations Manager, Paul Holman, who said at the scene, “If there are any positives out of such a tragedy, it is that the emergency response worked like clockwork today. It was an horrific scene, but more importantly, it was safe…we could have had many more people injured or hurt.”

Further investigations

Since the incident, attention has centred on traffic management issues and avoidance of future accidents.

CityLink incident data gleaned again from media reports\(^6\)\(^7\) has indicated that in 2006, there were 412 tunnel incidents attended to by the CityLink emergency response team. These included:

- 11 banned prohibited users (errant vehicles)
- 17 accidents involving cars or trucks (5 causing minor or serious injuries)

The key issues to improve traffic safety and reduce the likelihood and severity of accidents which have been discussed in the media\(^6\)\(^7\) are:
• Reduction in the speed limit for trucks to 60km/hr
• Trucks restricted to the left hand lane, and limited to use of the middle lane for overtaking
• All trucks banned from the right hand lane
• Provision of an emergency lane or breakdown bays in the tunnel (an expensive option)

It is clear that these issues will also be canvassed further in the forthcoming official incident investigations.

Burnley Tunnel Summary

The key observations from the information available publicly to date are:

• The Burnley Tunnel traffic accident and subsequent fire was a major incident, resulting in three deaths and considerable damage.
• It appears that all the fire safety systems worked as intended.
• The emergency management and evacuation and response appear to have ensured the safety of all those not directly involved in the initial accident.
• Major questions are being asked about tunnel design and traffic management in relation to future accident prevention.
• Overall, in fire safety terms, the provision of the water based deluge and smoke control systems appear to have contributed most significantly to life safety and minimisation of asset damage and operational interruption.

SANTA CLARITA AND OTHER INCIDENTS

The Santa Clarita tunnel incident which occurred in a road tunnel on the Interstate-5 Freeway in California on 12 October 2007 has some startling similarities and some major differences to the Burnley Tunnel incident. Wittasek has compiled a summary of the incident, again based on media reports and other publicly available information[1].

In this incident, traffic slowing to avoid another earlier accident came into collision within the 165m tunnel, starting a huge fire which burned intensely for over 4 hours, with flames extending 25-30 metres out of the tunnel portals. Three drivers were killed, some 30 trucks were destroyed, and an important part of the major north-south arterial highway linking Canada with Mexico through the US is expected to be closed for many months. Very extensive damage occurred to the tunnel wall and roof linings as well as to the road surface, with very substantial concrete spalling, requiring the tunnel roof to be propped to avoid collapse.

It appears that few if any fire safety measures were installed in this tunnel. Following the fire, the LA County Fire Department made a series of recommendations for retrofitting this (and other) tunnels with measures including the following:

• A ventilation system for smoke exhaust
• A water supply and appliances near each tunnel portal for fire fighting
• A zoned, manually operated water or foam suppression system throughout the tunnel
• An emergency lighting system
• A traffic control system to stop traffic when an incident occurs.

These systems look very much like those installed in the Burnley Tunnel which were successful in limiting the tunnel interruption to 4 days.

Major tunnel incidents worldwide have led to some 713 deaths in the period 1995 to 2006[8]. This has included the major fires in the Mont Blanc Tunnel in 1999 (39 deaths), the Tauern Tunnel in Austria
in 1999 (12 deaths) and the Gotthard Tunnel in 2001 (11 deaths). As a result, organizations like PIARC, NFPA and the EU continue to support research such as the UPTUN program, fire test programs such as the Runehamar Fire Tests and initiatives such the Fire Detection in Road Tunnels project (for the Fire Protection Research Foundation) as a means of trying to find better solutions for tunnel fire safety.

In particular, the Burnley Tunnel incident and the apparent success of the water based deluge system in controlling the fire and minimizing damage has given some impetus to the considerations of PIARC and the NFPA 502 Committee in their considerations of the need or not for changing their recommendations on suppression systems in road tunnels.

CURRENT DESIGN PRACTICE IN AUSTRALIA

The early major road tunnels in Australia, such as the Sydney Harbour Tunnel, the Northbridge Tunnel in Perth and the Citylink (Burnley and Domain) Tunnels in Melbourne created the need for a standard or some guidelines for tunnel fire safety.

While designers and fire authorities around Australia looked to the PIARC and NFPA documents for guidance, there was considerable concern by the fire authorities that an increased level of safety was required that could be best obtained by including water based deluge systems as part of the design. This led to the development of the AFAC Fire Safety Guidelines for Road Tunnels, first published in 2001[2].

The AFAC Guidelines stressed a risk based approach, and gave particular attention to, amongst other things:

- Design fires
- Fire detection systems
- Manually operated deluge systems
- Smoke Management (longitudinal and semi-transverse systems)
- Communication systems
- Emergency Management
- Testing and Commissioning, including Hot Smoke Tests[9]

While the AFAC Guidelines were reasonably comprehensive, they certainly did not provide a full set of prescriptive requirements. Nor did they provide overall performance requirements such as design fire sizes, or criteria like deluge system water density or smoke extract rates. Nevertheless, the industry practice started to evolve along fairly consistent lines, with deluge systems provided for all tunnels, with jet fan longitudinal smoke control systems for shorter tunnels, and semi-transverse smoke control systems for longer tunnels. These latter systems were often hybrid systems with a requirement to extract smoke from a defined zone downstream of the fire using a ducted arrangement, while jet fans maintained a critical velocity of approximately 3 m/s.

In order to provide an even more consistent level of fire safety and a more standardized design and approval process, the Road Traffic Authority of NSW released their Road Tunnel Design Guideline[3] in 3 parts in December 2006. While strictly only applicable in NSW on RTA funded projects, it has helped to set the standard in the absence of other documents.
This Guideline contained a number of important characteristics, viz:

- A definition of a “tunnel”, meaning an underground or covered roadway of 120m or greater in length.
- A set of generally required fire safety measures for all tunnels up to 360m in length, and additional requirements for those tunnels over 360m in length.
- The need to use AS/NZS4360:2004: Risk Management[10] as part of the process for establishing the “concept design” and adopt risk analysis techniques.
- The need for the design team to engage with a wide range of stakeholders though risk workshops.

The fire safety measures to be considered under this Guideline, and provided unless agreed by the stakeholders, include:

- Fire detection and alarm systems
- Traffic detector loops*
- CCTV/tunnel operator*
- Fire suppression system*
- Smoke control system* (longitudinal, semi-transverse, transverse)
- Cross passages and their intervals
- Fire resistance of tunnel linings
- Emergency lighting and signage
- Fire separation of tunnel bores (if twin tunnels)
- First aid fire fighting equipment
- Fire telephones, radio re-broadcast and other communication systems
- Fire brigade access and intervention
- Traffic management in fire emergencies*
- Flame traps for drainage

The items marked with an asterisk* may not be required for tunnels under 360m in length, again subject to the fire risk analysis and stakeholder agreement.

While the RTA Guideline does provide some requirements such as the fire resistance requirements for tunnels linings (4hr FRL ISO; 2hr HC for critical areas), exits at 120m centres and 60m spacing for CCTV cameras, it does not specify design fires or deluge system densities. In current practice, these are often spelt out in the Scope of Work and Technical Specification (SWTC) document for the project or left to the tunnel design team. It is common practice to design to a 50MW design fire, regardless of the provision of a suppression system, and to provide a zoned deluge system with a water density of 10mm/min which is able to operate simultaneously over 3 zones of 30m length, with manual activation.

The latest initiative in Australia is the development of an Australian Standard for tunnels, including road, rail and other tunnels, which will enshrine requirements in a performance and risk based context for use across Australia. This standards writing process is seeking to capture best practice from across Australia, and also recognize other international experience.
IMPLICATIONS FOR INTERNATIONAL PRACTICE

The implications of the Burnley Tunnel Fire and the current design practice in Australia is that it appears that if life loss in road tunnel fires is to be minimized, especially after major truck accidents such as occurred in Burnley and Santa Clarita, then some or all of the current practice in Australia will need to be considered in other countries. In particular, further consideration will have to be given to provision of suppression systems.

This represents major challenges for many countries, especially those with far more mountainous terrain than Australia, and with heavier road volumes and many more tunnels. The costs of installing all of these fire safety provisions in all tunnels would be prohibitive. The answer must lie in fire risk assessment linked to cost-benefit analysis as the best way that governments as well as tunnel developers, owners, and operators can evaluate their fire safety options. Such a risk framework best serves the interests of all stakeholders. It provides a balanced, objective way of assessing all fire risks, including likelihoods and consequences, in order to find the most cost-effective solution for any particular tunnel.

For private and toll operators of road tunnels, and for public–private partnerships (PPP) projects in particular, owners and their funding agencies must weigh up the capital and recurrent costs over a period against not only the potential life losses and resulting litigation and loss of reputation, but also the asset damage and business interruption (revenue) losses which can eventuate.

CONCLUSIONS

The major conclusions to be drawn from the Burnley Tunnel fire and other incidents in terms of current design practice are as follows:

- The provision of a comprehensive package of fire safety measures in the Burnley Tunnel ensured that the further loss of life was prevented and damage and interruption to operation was minimized.
- The water based deluge system together with the hybrid semi-transverse smoke control system played a major role in ensuring the fire was controlled.
- The Burnley Tunnel fire contrasts strongly with the more recent Santa Clarita fire in California where a lack of fire protection measures meant that damage was much greater, and the length of tunnel interruption will be much longer.
- The practice of tunnel fire safety design has evolved in Australia over a number of years, which is culminating in the preparation of an Australian Standard.
- The use and effectiveness of water based suppression systems, and their success in the Burnley Tunnel fire, has created a body of evidence that is of interest to tunnel fire authorities and designers worldwide as PIARC documents and NFPA standards are being considered for revision.
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Safety Requirements & Transport of Dangerous Goods through the 53 Kilometer Railway Tunnel through the Alps between Lyon and Turin

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KEYWORDS: transport of dangerous goods, tunnel safety, railway tunnel

1 INTRODUCTION

The Lyon-Turin rail link between France and Italy, crossing the Alps, is one of the major projects in Europe. This high speed link is an important connection in the pan-European railway network. In 2015 the first trains will run. The link will be used by high speed passenger trains, freight trains and “Autoroute Ferroviaire” (trucks on the train) and will consist of a 53 km long tunnel crossing the border between France and Italy as well as the 12 km long Bussoleno tunnel. For such a project, the safety expectations are very high. Before starting the detailed design of the tunnel, it is therefore of importance which safety measures are to be integrated in the tunnel to meet the defined safety principles.

2 INCIDENT TREATMENT PRINCIPLES

Different kinds of incidents have to be potentially treated on the LTF section. They have to be identified and the specific constrains of the project have to be considered, in order to face them. The topic of “Incident treatment principle” specific study is a global one which includes a lot of parameters and hypothesis coming from other studies. The following paragraph details only the principles. Specific topics concerning equipment, dangerous goods and railway motorway are described below.

2.1 Reminder of the project previous phases conclusions

The two single-track tubes will be linked by cross passages every 400 m. A safety station will be provided at each extremity of the link (in the open air), in the middle of the tunnel (underground space close to Modane) and also on the Val Cenischia viaduct between the main tunnel and the Bussoleno tunnel. These emergency stations will be able to receive every type of train (AF, freight or passenger) and will be built for dealing with the possible incidents. Three additional underground intervention stations will be situated in the main tunnel for dealing with the incidents concerning the railway motorway and freight trains only. These emergency and intervention stations are to be designed and equipped to ensure the safety of users, even in the case of an incident.

2.2 Events to take into account

The identification of the events to take into account has been carried out in collaboration with the studies in charge of the global risk analysis of the project called “Safety principles”. The main elements for identifying the potential incidents are:

- The infrastructure has to be designed for several kind of trains (passengers, freight, railway
• The infrastructure will consist of a 53 km long tunnel crossing the border between France and Italy as well as the 12 km long Bussoleno tunnel and a viaduct;
• The freight train and the railway motorway may carry dangerous goods.

Consequently, the following events have been studied:
• Breakdown of each type of train in different locations;
• Fire on a passenger train in several locations in the tunnel or in the open air;
• Fire or explosion on a freight train or a railway motorway in several locations in the tunnel or in the open air.

2.3 Major elements concerning incidents treatment
In case of an incident, the goal for the concerned train is to reach an adapted place in order to treat the event (emergency station or intervention station). However, in case of a breakdown in the current section of the tunnel, the safety concept has to also allow the treatment of this incident.

The trains behind the stopped train will have to stop and to reverse. The trains in front will have to continue their route with an adapted speed. The behaviour of the trains in the other tube will depend on the nature and the position of the incident train.

2.4 Use of ventilation means
In case of a fire on a train, there are two possibilities:
• All people on board are on the same side of the train;
• People on board are separated by the fire.

In the first case, the ventilation system is used in order to push all the smoke on the side where nobody is present. The minimal distance between two trains has been calculated in order to maintain the following trains free of smoke. In the second case, the ventilation system is used in order to provide an environment compatible with an evacuation of the train passengers.

2.5 Procedure in case of a fire on a freight train
In case of a fire on a freight train, the driver has to stop the train in a safety or intervention station. The ventilation system and the fire mitigation system are switched on in order to protect the train driver. He goes down the train and waits emergency services in a safe place. In case of stop inside the tunnel, he waits in a cross passage.

2.6 Procedure in case of a fire an a railway motorway train
In case of a fire on a railway motorway train, the driver (located in the “Sonia” with all the truck drivers on board) has to stop the train in a safety or intervention station. The ventilation system is switched on in order to protect the “Sonia”. The driver start the diesel propulsion and separate the “Sonia” from the rest of the train in order to drive away from the burning convoy and exit the tunnel.

2.7 Procedure in case of a fire on a passenger train
In case of a fire on a passenger train, the driver has to stop the train in a safety station. In the open air, users are directly taken care of by rescue teams. In the tunnel, the train passengers wait for an evacuation train in the not-affected tube, which will bring them outside.

2.8 Elements concerning rescue teams
Elements concerning rescue teams are specific to the infrastructure:
• First line of intervention, with a very rapid response, because they are located permanently nearby the access to safety and intervention stations;
• Second line of intervention, which is organized by the public services.

Their vehicles will be both “road-rail”-vehicles together with traditional rolling stock for the more heavy logistics. The road-rail engines are rapidly put on rail and can operate in bad conditions (presence of smoke or high temperatures).
3 EQUIPMENTS

In order to provide for the required level of safety in the tunnel, several security systems and security equipment has been foreseen in both tunnels (Tunnels du base and the Tunnels du Bussoleno).

3.1 Emergency philosophy
The emergency philosophy for trains with a fire onboard has to, if possible, continue to a ‘safe haven’ and to evacuate all passengers there. For all other trains not directly involved in the incident the rule is to a) leave the tunnel(s) as quickly as possible or to b) stop before entering the tunnel.

3.2 Emergency installations and equipments
The following emergency installations are used in the tunnel and connected areas:

- **Detection equipment for:**
  - Smoke and fire
  - Derailment
  - Train stop
  - Gage
  - Fumes and gasses

- **Containment and extinguishing equipment in case of fire:**
  - Ventilation systems in tunnels, inter tube tunnels
  - Ventilation of safe areas
  - Ventilation of technical rooms

- **Control systems:**
  - Lighting system
  - Video system (CCTV)
  - Central command post (PCC)
  - Communication equipment
  - Telephone system
  - HF communication system

The following equipment is foreseen in the tunnels, intervention stations and safety stations and surrounding elements:

- **Evacuation of passengers:**
  - Emergency platforms:
  - In the tunnels (min. 1.2 m width)
  - In the emergency stations and station (3.0 m width, 750 m length)
  - Cross passages (every 400 m, in Modane station every 50 m)
  - Collection rooms for the injured in every intervention and emergency station
  - Directions signs for emergency escapes
  - Audio system

- **Accessibility and equipment for emergency services:**
  - Emergency accesses at the highest point of every emergency tunnel, connecting to local infrastructure. The accesses are provided with a helicopter platform, parking space, and a command post
  - Emergency tunnels
  - Fire extinguishing equipment:
  - Hydrants (6 – 10 bar, every 133 m, French and Italian system)
  - Fire mitigation system in every intervention station and in the safety station
  - Automatic fire extinguishing system in technical rooms
  - Emergency water reservoirs (with a capacity of 120 m3) in each station.
  - Central command post (PCC), one in France and one in Italy.
  - Drainage system liquids (alpine water, extinguishing water)
  - Storage tanks for dangerous liquids (6 in total, storage capacity 240 m3 per tank)
Three systems in particular will be described in following paragraphs, namely the foam water system, the emergency tunnels and the drainage system.

### 3.3 Fire mitigation system
Fires with a capacity of 50MW can occur in the tunnel, due to the properties of transported goods and air speeds in the tunnel. These fires cannot be reached physically by fire fighters and therefore cannot be put out in a traditional way. For this reason, all goods trains will have to make a safety stop at an intervention station or safety station when exiting the tunnel is not an option. Each intervention and emergency station in the tunnel is provided with a sprinkler like system, using a specific mixture with water onto the fire from nozzles located on either side of the tunnel roof. Two systems have been modelled and tested: a Foam Water system and a high pressure Water Mist system. With a ventilation speed of 2 m/s, the following results are found.

![Figure 1 Test results from Foam Water and high pressure Water Mist systems to a 50MW fire.](image)

The figure shows that the FW system reduces a fire to 20% of its original intensity within 70sec and to 10% within 150sec. The WM system mitigates a fire to 40% and 35% for the same time intervals respectively. These results are obtained when the system is called into action immediately after the start of a fire. There are however scenarios in which it takes up to 15 min before a train is located in an intervention station provided with a FM or WM system and the system is switched on. This way, 100MW fires cannot be excluded.

### 3.4 Emergency tunnels
The intervention stations of Saint-Martin, La Praz and Venaus, as well as the emergency station of Modane are connected to the outside world by means of emergency tunnels. In total there are 4 emergency tunnels, with a diameter of 10m and lengths varying from 500 to 4,500m. The emergency tunnels will be used by emergency services in case of an emergency. The enormous length of the emergency tunnels led resulted in a one-way regime for traffic, with passage sites every 400m, dividing each emergency tunnel into sections. The passage sites have a length of 200m and a width of 20m. Traffic lights will be used to indicate a free passage per section.
3.5 Drainage system
In the tunnel, a drainage system is applied to drain the alpine water from the tunnel the slope of the system is 2%, following the tunnel slope. In case of fire in a goods train leaking dangerous liquids, extinguishing efforts with water will result in a pool fire, possibly increasing the capacity of a fire. Therefore, the drainage system consists of lateral and longitudinal canals that collect in central collection points with siphons, to prevent progression of a fire in the closed drainage system. The liquids are collected in storage tanks, located at every station and at the heads of the tunnel.

4 DANGEROUS GOODS

One of the reasons the tunnels are being constructed is the transport of freight. From current transport of freight we know that a substantial part of the international transport can be classified as dangerous goods. Effects of an incident with dangerous goods in the tunnel may be serious for both persons present and the structure of the tunnel. Before allowing transport of dangerous goods in the tunnel, it has to be determined whether the possibility of an accident in relation to the effects is acceptable.

4.1 The methodology

The UN working group WP15 on the transport of dangerous goods has been developing a methodology to categorize tunnels. Through tunnels of different categories, different groups of dangerous goods are allowed for transport. For the LTF project this methodology has been the base to define safety measures and to determine whether transport of dangerous goods can be allowed in the tunnels. For each group is determined whether the possibility of an accident in relation to the effects is acceptable and if safety measures can be taken to ensure that the required safety level is reached.

4.2 Possible effects and proposed safety measures

4.2.1 Group A

Dangerous goods in this group are prohibited for transport and are therefore not analyzed in the studies for the project Lyon Turin Ferroviaire.

4.2.2 Group B

4.2.2.1 The effects

Dangerous goods in this group can provoke a big explosion. LPG is the product most transported good within this group. For this reason the effects of an accident with LPG are taken as normative to analyze the effects of a possible incident with goods of this group.

Two types of incidents have been considered: a leak of limited size leading to a vapour cloud explosion after ignition and a catastrophic failure of a LPG vessel leading to a BLEVE (Boiling Liquid Expanding Vapour Explosion).

A combination of a steady leak and steady ventilation flow may result in a homogeneous cloud in the tunnel downstream of the leak. For stoichiometric clouds of 10, 20, 50 and 100 meter length (it is never certain when a cloud may be ignited), the blast effects up to a distance of 5000 meters on either side of the cloud have been modelled.
Figure 2 The blast effects after ignition of a cloud with a length of 100 meter

A vapour cloud explosion as simulated can generate a blast that can cause victims up to 4200 metres.

Figure 3 Possible blast after a BLEVE of a vessel of 100m3.

The blast of the simulated BLEVE can cause victims up to a distance of 4200 meters in the tunnel on both side of the incident.
4.2.2 Proposed safety measures
The prognostics show a large amount of possible transport of flammable gases. For this reason, both protective and preventive measures are proposed for the tunnel.

Since effects of an explosion reach up to 4200 meters in the tunnel, the first measures is to keep a distance of at least 4200 meters between a train carrying this products and a train with passengers. Furthermore the truck train combination is not allowed for this group since there are too many drivers present in the train, thus within the 4200 m range.

4.2.3 Group C
4.2.3.1 The effects
Dangerous goods in group C are goods that can provoke an explosion or a toxic leak in the tunnel. To analyse possible effects of possible incident with goods in this group, dispersion of ammonia and chloride in the tunnel is modelled.

![Figure 4 Dispersion of chloride in the tunnel after a leak (50mm) of a vessel (ventilation speed 3 m/s).](image)

With the probit function (probit functions give the mortality rate depending on concentration and exposure time) for chloride it is calculated the toxic cloud reaches up to 3500 meters from the incident after 16 minutes.
Figure 5 Dispersion after a leak (50mm) of ammonia (taken ventilation speed 3 m/s).

The lethal concentration of ammonia will not reach as far as the chloride cloud.

Toxic vapour clouds from toxic liquids have also been analysed. Since evaporation from a liquid pool is a lot slower than evaporation of a pressurized gas, effects will not carry as far as the effects of pressurized gases.

4.2.3.2 Proposed safety measures
Since some of the goods in this group can provoke an explosion, a distance of at least 4200 meters (3500 m for truck-trains) between a train carrying this products and a train with passengers is introduced.

To reduce toxic effect of gases, the ventilation system should be able to influence the velocity and the direction of a toxic cloud.

To reduce the effect of toxic liquids it is proposed to limit the surface of a possible pool to minimise evaporation. As for the flammable liquids a maximum of 100m2 is proposed (see above). The evacuation system has the possibility to separate toxic liquids and water (they can provoke a chemical reaction in some cases).

Further on, the ventilation systems of trains passing through the tunnel should be closed unless toxic clouds can be detected before trains with groups of passengers enter the tunnel. The Sonia vehicle does also have this possibility to ensure that drivers of the trucks can get away in this vehicle.

4.2.4 Group D
4.2.4.1 The effects
Dangerous goods in groups D are those that can provoke a major fire. To analyse possible effects of possible incident with goods in this group, the effects of a fire of 100 and 200 MW in the tunnel have been modelled.
Furthermore the effect of a fire in case of another train present was analysed.

It has been concluded that the temperature reaches up to 50 °C at 3500 meter after 15 minutes. Since the air in the tunnel will be moist, this the level which can be dangerous to persons present in the tunnel.

4.2.4.2 Proposed safety measures
Since temperature and smoke can reach dangerous levels up to a distance of 3500 meters, this distance
should be kept between a train carrying flammable products and a train with passengers. The interdistance of 4200 m caused by group B makes this one oblivious.
To prevent a fire from growing to fast and to limit effects, the ventilation system should be able to influence the velocity and the direction of the air in the tunnels.
To make sure a pool fire will be limited in magnitude, the surface of a possible pool should be limited to a maximum of 100m² (gasoline generates about 2 MW/m²).
The Sonia vehicle must be able to leave as fast as possible after an incident, before the effects of a fire reach the vehicle where the drivers are present.

4.2.5 Group E
Since the products in group E are either less dangerous or transported in smaller quantities this group has not been analysed. Measures taken to reduce risks for the other groups are supposed to be efficient enough to take away the risks of this group.

5 CONCLUSION

- The safety studies have been carried out in order to determine the Functional Requirements Specifications of all safety measures and precautions in the tunnels to minimize the risks.
- The outcomes are input for further technical studies of the project as well as for the definition of the layout and design of the tunnel. It is up to the design engineers to incorporate all proposed measures in the tunnel.
Implemention of Water Mist Systems in Road Tunnels

Project Case Studies

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ABSTRACT

Fixed fire suppression systems for tunnels increase safety by suppressing and controlling the special solid and liquid fires that occur in tunnels. Typically, these systems are designed according to customer specifications which include many details about the tunnel conditions, fire loads, required system performance, system functionality, acceptance criteria, reliability and so on, which should all be evaluated before the selected system is accepted for installation. Some of the technical requirements can be verified in full-scale fire tests, which then form the basis of the system design. Performance-based parameters such as the required water flow rate, operating pressure, spray head and sprinkler spacing, zone sizing etc. can be defined properly only as the result of a complete understanding of the tunnel conditions and specified fire types.

This paper describes the effectiveness of high-pressure water mist technology as used for tunnel fire protection. Experience drawn from fire testing and field installations shows that water mist technology can provide an excellent level of fire protection with modest water consumption. Marioff’s water mist fire protection system has been installed in Spain in the Madrid M30 road tunnel, and it is currently being installed in the Paris A86 road tunnel and the elsiniki city service tunnel. The HI-FOG® water mist system as installed in the Paris A86 tunnel and Madrid M30 tunnel are described.

KEY WORDS: Water mist system, full-scale fire tests, A86 tunnel, M30 tunnel, flow rate, system dimensioning

INTRODUCTION

In Europe as a whole, the fire protection of tunnels is still largely inadequate although significant improvements have been made in the latest tunnel projects. In the planning stages of these projects, knowledge gathered from a number of tragic tunnel fires has been taken into account as well as the cumulative results of international research into tunnel fire safety.

Resources and money need to be made available for the basic upgrading of old tunnels still in service. European regulations governing tunnel safety are now in force, and the general belief is that they will improve the situation. This is far from sure, however. European Directive EN54 [1] requires the most basic level of fire protection for tunnels longer than 500 meters, and it leaves a host of issues open and undecided. The responsibility for tunnel fire protection lies squarely with the tunnel operators, who are left to ensure that the fire protection of their tunnels is at a level commensurate with the particular fire risks associated with them. The evaluation of these risks, in the best of all possible worlds, would be carried out by acknowledged tunnel fire protection experts. They would recommend the appropriate level of fire protection and, where possible, also how to go about achieving the required level. On this basis, the analysis and intercomparison of different fire protection systems would begin.
WATER MIST FIRE PROTECTION IN TUNNELS

This paper describes the effectiveness of water mist technology for tunnel fire protection in terms of the accumulated experience of one water mist system supplier during a number of full-scale tunnel fire tests. It also describes the development and implementation of a water mist system for tunnel fire protection based on these tests. This subject matter may be useful for decision-makers concerned with the whole spectrum of tunnel safety, and specifically inform the thinking surrounding new tunnel fire protection projects.

The discussion in this paper is based on one water mist system, the HI-FOG® Water Mist Fire Protection System, particularly on the HI-FOG® system variants developed specifically for tunnel fire protection. The observations made in this paper are unlikely to cover all water mist systems. This must be stated explicitly because the water mist systems of different suppliers have their own unique technical characteristics which are difficult to compare accurately outside the test laboratory. That said, a number of general observations on water mist system performance can be made, especially in relation to conventional “deluge” systems. Water mist system performance is substantially different, in a positive sense, from that of conventional deluge systems.

This paper presents real-world experience gathered in two different tunnel fire protection projects: the A86 tunnel in Paris and the M30 tunnel in Madrid. Both tunnels are equipped with the HI-FOG® Water Mist Fire Protection System — the A86 completely, the M30 in part. There are no standards or general recommendations governing the use of water mist technology for tunnel fire protection. Therefore, the customer must rely greatly on the water mist system supplier’s professional skill, installation experience and understanding of the system’s effectiveness and reliability. It is very advisable to use analyses contributed by an objective, third-party expert during the evaluation phase in order to avoid problems later.

GENERAL DESIGN ISSUES

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

1) System performance
   “System performance” comprises categories such as e.g. water flow rate in l/min/m² (or in l/min/m³)¹, spray head type, microdroplet size, system pressure and the distance between spray heads. These can only be defined reliably as the result of full-scale fire tests in real tunnel environments. When the basic tunnel system has been thoroughly tested it can be adapted for use in other tunnel types as is or with small adjustments, as long as the central performance parameters are not substantially altered.

2) System technical design
   By “system technical design” we mean the placement of pump units and associated systems, possible back-up pumps, water sources, the water intake system, the electrical power intake system, the placement of zone valves, the types, placement and size of pipes, the system’s reliability and life-span, and so on. These parameters must all be thoroughly analyzed and designed for each tunnel. The fundamental technical and structural characteristics are different from tunnel to tunnel, and need to be reflected in the requirements of the customer and local authorities.

3) System interaction
   By “system interaction” we mean the possible interactions and connections between the tunnel fire protection system and other tunnel systems such as the fire detection system, the central control

¹ The measurement l/m/m³ is the three-dimensional measurement of flow rate known as “flux density”. Flux density is a particularly relevant measurement for water mist systems.
system, the ventilation system, the smoke evacuation system, and the traffic monitoring, control and alarm system. Achieving seamless interaction with these systems, delivered by different system providers and having different operational priorities, is one of the greatest tunnel fire protection challenges.

It must be kept in mind that there are very few tunnels in Europe in which all the various systems are connected in a seamless operational whole. Tunnel operators and the risk management and operational experts of local fire brigades play the central role in ensuring that a tunnel’s technical systems work to suppress fire in the best possible way. In this area, independently held opinions can greatly affect decision-making — it would be important to rely as much as possible on research data and experience drawn from successful projects.

THE A86 TUNNEL

We will now deal with the three main categories of requirements from the point of view of a water mist system provider and its experience of two large tunnel projects, starting with the A86. The A86 tunnel is located in Paris, France. It connects the northern section of the A86 ring-road from Rueil-Malmaison to the Pont Colbert zone in the southern section, close to the Palace of Versailles and its wide-ranging parkland. The total length of the tunnel is approximately 10,300 metres. If we include all the connecting tunnels, there are about 24 km of tunnels requiring fire protection. Over this distance, the difference in height from the lowest point to the highest point is ca. 135 metres. The tunnel is of a special type: a large bored pipe that is structurally divided into two levels of traffic. This solution, with its ceiling of 2.55 metres, accommodates light traffic only (the effective ceiling is 2.15 metres). There are three lanes on each level. Two are reserved for traffic, the third is the emergency lane. Traffic flow is uni-directional at each level. The levels are connected to each other by stairwells at 200-metre intervals and there are escape exits to the surface at 1000-metre intervals.

The tunnel is equipped with a modern ventilation system which distributes fresh air through both levels via dedicated air ducts. The smoke evacuation and fresh air ducts run along the ceiling and under the road surface. Construction of the tunnel has been organized in two phases, with the first now nearing completion. The tunnel’s first phase will open to traffic this year, the second will be finished in the second half of 2009.

*Figure 1. An indoor photo of A86 tunnel.*
Fire tests

The importance of fire protection is magnified in this type of tunnel, which will carry very dense traffic (to relieve the traffic congestion of the Paris metropolitan area). The ceilings are very low: even small quantities of smoke may be difficult to evacuate. The heat given off by a fire will also very quickly affect the low-lying ceiling structure. Although the fire size to be expected is quite small, in the region of 5 MW per automobile, the project-related fire tests conducted at Hagerbach included fires of 20-25 MW that resulted from burning three automobiles simultaneously. This test simulated a situation where activation of the water mist system was delayed on purpose, in order to allow motorists to evacuate upstream of the smoke to a clean area. Given the possibility of delayed activation, the water mist system must be able to effectively suppress large combined-automobile fires. The deluge-type system tested, featuring open spray heads, fulfilled all the fundamental requirements of the customer including temperature reduction, heat flux and heat release rate [2].

System dimensioning

The A86 HI-FOG® system’s water flow rate is 1.3 l/min/m² (0.5 l/min/m³ as flux density) according to the tests. This flow rate is realized with spray heads located longitudinally on the tunnel ceiling along three pipes of 20 mm in outer diameter (OD). The spray heads are placed longitudinally in staggered formation at ca. 4-metre intervals and laterally at 2.8 metres. Each zone of coverage is 33 metres long with a few zones of slightly different length. There are also a few places in the tunnel with higher ceiling heights — of up to 6 metres. On the basis of fire tests conducted in tunnels with ceilings of similar height, an open spray heads of higher k-factors were chosen to protect these A86 “high spots”. The A86 tunnel’s wider and higher areas are all associated with the tunnel openings and connected areas, therefore the associated HI-FOG® system zones were divided to ensure adequate protection. In practice, the maximum available volume of water is the basis for dimensioning the water mist zone coverage including the areas associated with the tunnel openings, taking into account the requirement that it must always be possible to activate three zones simultaneously.

From the point of view of water flow, it is quite a challenge to protect a tunnel over 10 km long. Over this distance, pressure loss in the pipes becomes significant. The choice of main feed pipes is based on careful hydraulic planning. In the A86 tunnel, the natural and most effective solution was to place the high-pressure HI-FOG® pumps and other technical systems in three different locations at approximately the same distance from each other. In the tunnel’s first phase, the HI-FOG® pumping stations are approximately 4.5 km from each other. In the second phase, they will be 5.5 km from each other. The overriding principle in this configuration is the following: wherever in the tunnel a fire starts, the HI-FOG® system will activate in the fire zone along with the two immediately adjacent zones.

2 An open spray head is a spray head that does not have a thermal activating bulb. It simply discharges water mist when the system activates.
Figure 2. Pumping stations’ arrangement of A86 tunnel.

Pumping stations

The three A86 HI-FOG® pumping stations are technically identical. They comprise feed pumps and high-pressure pumps along with the required support systems. There are two feed pumps in each pumping station: one feeds water to the high-pressure pumps, the other acts as back-up. There are three high-pressure pump sets in each pumping station. In normal fire situations, two are activated. If one of these malfunctions, the third in reserve activates automatically. All of the pumps are electrically powered, fed by two independent electrical power sources. If one electrical power source cuts out, the system switches automatically to the other one. Two water reservoir of 60 m³ capacity is located close to the pumping stations, although not all water is for water but also for a stand pipe fire hose system. Water is drawn from the reservoir through a 100-micron filters. Its design also accommodates maintenance and malfunction episodes. The water held in the reservoir is constantly cycled through a water treatment unit by a pump dedicated to this job, so that it is kept as free as possible of bacteria and dirt.

The water treatment unit comprises UV lamps which prevent the growth of legionella bacteria. It also comprises a stand-by pump unit which maintains 25 bar pressure throughout the main pipes. This arrangement ensures that water can be discharged immediately through the zone valves and spray heads upon system activation. When the pipes are filled with water on activation, system pressure reaches the maximum level almost instantly when the pumps are switched on. In practice it is not possible to wait for the water flow to reach the activated zones if the main pipe is dry. Even under high pressure, the system water flow rate in the main pipe is less than 4 m/s, so supplying water over a distance of 2,500 m would take over 10 minutes.

Figure 3. Water mist hardware in one of the pumping stations of A86 tunnel.
Hydraulic calculations

The hydraulic calculations for the A86 project were made using the Darcy-Weisbach calculation methods for high-pressure flows according to the latest edition of the NFPA 750 handbook. The software used for hydraulic calculation is called “Fluid Flow”, specially designed for pipe dimensioning. The software calculation results were verified by third-party calculations. The system design calls for nominal pressure at the spray heads of 70 bar as verified in the fire tests. The high-pressure pumps operate at a pressure of 140 bar. The difference in pressure between the pumps and spray heads is 70 bar, allowing for quite high pressure losses in the distance between the pumps and the furthest spray heads.

Hydraulically, the most demanding area to cover is near the A13 junction, at the end of the longest slip road. Although this area is close to the A13 pumping station, supplying it with half of the needed water flow as distributed from the Pont Colbert pumping station gives rise to the system’s highest pressure loss. The detailed hydraulic studies undertaken during the design phase showed that the lowest system pressure was 72 bar and the highest 105 bar. Measurements taken on-site, however, showed much higher system pressure at the spray heads. In the theoretical calculations, safety margins were factored in to ensure that the real system pressure would coincide with the tested pressure. Hydraulic calculations were also made to study a number of different “degraded mode” scenarios, where some of the pumps were assumed to have failed. This was done to gather data for defining the system operation modes.

Piping materials

All the A86 HI-FOG® system pipes are made of AISI316-grade stainless steel, for two reasons: first, to ensure that the effects of water (corrosion in all its forms) do not adversely affect the system’s performance and reliability; second, to ensure that exhaust emissions, substances such as road salt used in the tunnel to combat icy conditions, and tunnel humidity do not adversely affect the lifespan of the system piping. All the system parts vulnerable to corrosion are made of stainless steel.

Antifreeze

The A86 HI-FOG® system specifications require the system to operate at a maximum low temperature of -15 °C. To ensure the system meets this requirement, the coldest sections of the main feed pipes are locally warmed and insulated. The local warming system engages automatically when the temperature as measured inside the pipe insulation reaches 5 °C. A notable fact about the piping design of this high-pressure water mist system is that the main feed pipes measure only 76 mm in diameter. Also, the pipes supplying each tunnel level are independent of each other. This is possible thanks to the system’s modest water flow requirement, high pressure, and double pumping station design. With main feed pipes of such small diameter, it is not possible in practice to implement a water-based fire protection system that has a higher flow rate — not even a water mist system.

Thermal expansion

Installing piping in a tunnel as long as the A86 requires careful monitoring of temperature variations in the pipes, especially of the main feed pipes. The highest tunnel temperatures were measured first: their influence on pipe temperature variations is largest at the tunnel openings. This was relatively simple. It was much more difficult to gain a clear understanding of the temperature variations at the tunnel openings considering the influence of traffic entering the tunnel. Exact data was unobtainable, so the calculations were based on “best practice engineering”. On the one hand, we know that the piping in the tunnel opening areas is protected from low temperatures by the local warming system and insulation, over quite a long distance from the openings. On the other hand, we must take into account the cold air entering the tunnel during winter. We must also take into account the fact that the temperatures experienced in the tunnel during the system installation are different from those that will
be experienced when the tunnel is finished and open to traffic. The tunnel temperatures will even out a few years after it is completed. Of course, the piping temperature variations must always be measured according to the largest temperature gradient. The A86 HI-FOG® system features thermal expansion loops designed for 30 °C in the central tunnel areas and 35 °C in the tunnel end areas. These loops are installed at 100 m intervals.

**Zone valves**

The zone valves play a very important role in system activation: it must be certain that they will function correctly under all conditions. The A86 tunnel does not have wall recesses in which to place valves and pipes safely away from traffic, therefore they are installed on the tunnel ceiling. The results of the fire tests show that temperatures during a fire are highest at the tunnel ceiling, therefore the valves have been protected by installing them in special fire-proof cabinets. The customer specifications require the fail-safe operation of the valves at 400 °C for a full hour. To ensure that this requirement would be met, Marioff also tested the valve cabinets at 800 °C for a half hour. These tests were carried out at the VTT testing laboratory (the Technical Research Centre of Finland) in Otaniemi, Helsinki with the customer present. VTT issued its own reports on the tests [3, 4]. The tests subjected the valves to the required temperatures for the required times, after which the functioning of the valves was fully evaluated. The valve cabinets protect the valves from dust and dirt, and, if equipped with locks, from possible unauthorized access as well. The valve electrical cables must also be fire-proof and tested to the temperatures required in the specification. The valves are equipped with a manual activation mechanism. The valve cabinet is equipped with a maintenance valve in addition to the solenoid valve. It is kept open in normal circumstances, but can be closed in order to carry out maintenance. The cabinet is also equipped with a test valve which, when closed, allows the main valve to be opened and closed without releasing water into the zone.

![Figure 4. HI-FOG® zone valve cabinet and “mini-loops” for thermal expansion.](image)

**Control systems**

The control system of the A86 HI-FOG® installation is implemented over groups of six valves connected to the local control cabinets. These cabinets are installed in the stairwells at 200 metres intervals. From each control cabinet, fire-proof control cables run to the six closest zone valves. The central control system is connected to the local control cabinets. A 230 VAC electrical feed also runs to the local control cabinets, which distributes 24 VDC power to the valve solenoids. The valves are monitored from the local control cabinets, and from there to the central control system. Each zone valve is assigned a unique address in the tunnel which corresponds to a fire detection cable zones. When a fire is detected requiring activation of the system, the fire location is provided by the central
control system. The system is activated by an electrical signal from the central control system which starts the pump units in the correct pumping stations and opens the correct zone valves: water is then discharged from the spray heads in the zone corresponding to the fire.

**Interaction with other systems**

Responsibility for ensuring the correct interaction of all the tunnel safety systems lies squarely with the customer. The customer needs to collect all the required operational information from the system designers and suppliers and consult with the tunnel operator, local fire brigades, fire engineers and the local authorities. This is critical to the success of the whole project: care should be taken to devote sufficient resources and know-how to the job. In the A86 tunnel project, this work is being done for the customer by special consultants who have made significant contributions. The A86 tunnel is equipped with a modern ventilation system and smoke evacuation system (a semi-transversal ventilation system). Under normal conditions, the collective effect of these systems and vehicle traffic amounts to an air flow velocity of 6 m/s. If a fire is detected, the air flow velocity is decreased to 3 m/s in the space of five minutes. This is sufficient to prevent the backlayer phenomenon from occurring and to evacuate the smoke in the direction of vehicular traffic, out of the traffic tunnel. The aforementioned air flow rates were used in the A86 fire tests, which showed that water mist performed effectively at the 3 m/s flow rate.

The A86 tunnel fire detection system is equipped with a heat detection cable that indicates fire at an early stage of its development, and pinpoints its location for the purposes of HI-FOG® system activation. The tunnel also has a CCTV system which monitors traffic flow. It is programmed to flag aberrations in traffic flow. In case of fire, the CCTV system can be focused on the fire location and zoomed in for close inspection. In addition, there is a 24/7 emergency and rescue patrol unit which can reach the fire location relatively quickly to help motorists evacuate and evaluate the situation. In addition to the HI-FOG® system, the A86 tunnel is equipped with fire stations (hoses) at regular intervals. Tunnel temperature and exhaust emission levels are monitored continuously.

The HI-FOG® system is activated remotely as part of the operator’s 24/7 operational monitoring system, as a result of information gathered at the fire location. In normal conditions, HI-FOG® activation in one zone of coverage automatically involves activation of the two zones adjacent to the fire zone. Additional zones cannot be activated until the initial zones of activation are shut down. This is designed to ensure that the operator does not activate too many zones simultaneously, resulting in a precipitous drop in pressure and water flow. It also helps the operator’s decision-making in a chaotic fire alarm situation in which there are multiple tasks to handle. Zones can also be activated manually in the tunnel, either at the local control cabinet or at the zone valves.

At the time of writing, it has yet to be decided whether the A86 HI-FOG® system will be activated manually or automatically. Final hand-over testing is now underway. The question can be raised whether it is always wise to activate three zones simultaneously considering the relatively small fire loads of the light traffic allowed in the A86, the length of the zones (33 m) and the tunnel’s low ceiling. When deciding whether to activate the system, it must be remembered that water mist decreases visibility to a certain degree in the zones of activation — but not to a point where it becomes difficult to move and evacuate. Meanwhile, the HI-FOG® water mist cools the area very quickly and blocks the radiant heat, a great aid to rescue operations.

**Notes**

All water-based fire protection systems share a downside when dealing with fire: they mix the stratified hot gases and smoke. Water mist does this with particular effectiveness. That said, one must keep in mind that the fire may already have produced a lot of smoke, which is likely filling the tunnel and moving in the direction of air flow. The most important thing is to get the fire and temperature under control; delaying activation may allow the fire to spread. At the moment of activation, the
people should have evacuated and destratified smoke should not be a problem to them.

From the beginning it has been clear that the A86 tunnel project is one-of-a-kind, involving many more design parameters than the average tunnel project. This has been true from the day system design commenced, through to system commissioning. The A86 HI-FOG® system was designed and quoted based on the specifications and tender as defined by the customer. The customer selected HI-FOG® as its fire protection system and Marioff as its system supplier on the basis of a detailed evaluation carried out by an expert consultant. The selection was partly the result of a reasonable price and the advanced technology it brought, but it also took into account Marioff’s long experience as a water mist system developer — including over 6,000 fire tests and successful water mist system design for many different applications. At some point in the customer’s selection process, Marioff’s credibility and reliability must have made a decisive impression.

This paper has given a general overview of the design and implementation-related aspects of the A86 HI-FOG® system. In addition to the matters already discussed, Marioff also carried out a quality analysis of the available water supply which was used to implement water quality control measures. The “water hammer” phenomenon was simulated [5], also the dynamic analysis of the piping was done [6], pipe fixture corrosion was studied, and so on. Pump station and individual pump unit performance were simulated during the factory acceptance test, before deliveries began. Every aspect of the system design was documented with care, accepted by the customer, and saved in the project design database. Techniques were developed to speed installation — pipe installation was made more efficient by maximizing pre-assembly, for example. When completed, the A86 tunnel will be the world’s largest water mist fire protection system with 16,000 spray heads distributed over 850 zones. Altogether, 24 km of tunnel will be protected by 120 km of AIS316 stainless steel piping.

**THE M30 TUNNEL**

Madrid’s M30 tunnel is the largest urban road tunnel ever built. The southern section of the M30 ring road alone has about 36 km of tunnels. The northern extension of the M30 will contain almost as much. When it comes to fire protection, the M30 tunnel is completely different from the A86 tunnel in terms of tunnel dimensions and traffic allowed. The project schedule and construction arrangements were also entirely different, and there are no restrictions on the type of vehicle allowed.

The tunnel’s average height is 6 metres and for most of its length it is rectangular. In many places traffic moves in two levels but, unlike the A86 tunnel, the levels are separate tunnels with no connections between them. The tunnel contains many junctions of various widths, ranging between 7 and 25 metres. A quick inspection of the tunnel’s width measurements, height measurements and possible large fire loads (HGV) makes it clear that some compromises have to be made when dimensioning a water mist system to protect it from fire.
In 2006 Marioff carried out full-scale tunnel fire tests of the HI-FOG® Water Mist Fire Protection System in Spain. These were specially designed to deal with the dimensioning issues associated with the very wide tunnel areas described above. The tests showed that the three types of HI-FOG® system tested (deluge, hybrid and sprinkler) performed almost equally well given the fire loads and pre-burn times involved. Since the performance and dimensioning parameters of the three HI-FOG® systems were established in the fire tests, it was possible to design and offer a system that would protect the extra-wide tunnel areas, deal with the large possible fire loads (HGV) and still use modest amounts of water. A hybrid-type HI-FOG® system was proposed with dimensioning consisting of three zones of simultaneous activation — with a measured flux density of at least 0.4 l/min/m³ in two of the zones, and 0.8 l/min/m³ in the third. Zone length was set at 24 metres to cover the full length of a tractor-trailer truck. HI-FOG®’s powerful cooling effect allowed Marioff to set the three-zone length at 72 metres [7].

During the offer stage, the customer reduced the tunnel length to be protected with HI-FOG® from 36,000 metres to 2,400 metres — the total currently protected by HI-FOG®. The tunnel widths protected are 8 m, 12 m and 17 m. Where the tunnel height is 6 m and the tunnel width 17 m, the total water flow rate is 3,917 l/min over the three zones.

If a deluge-type HI-FOG® system had been installed, with a flow rate of 0.8 l/min/m³ over each three-zone section, 5,875 l/min would have been required. The water consumption of the installed system is almost 2,000 l/min or about 33% less, representing significant savings. It also requires fewer and smaller pumps, smaller pumping rooms and waste water sewers, smaller pipes and valves, a smaller water intake system and less electricity. Put together, these add up to very significant savings with no penalty in protection: the fire tests proved that the system can handle large fire loads. We can confidently say that the hybrid-type HI-FOG® system is the right system for tunnels requiring a high level of fire protection — a level that becomes too expensive when provided by a deluge-type system which requires much more water to cover e.g. extra-wide tunnel areas.

Project experience

The M30 HI-FOG® system protects a special 1,000-metre section of the tunnel that comprises two separate tunnels and a number of slip road connections. The implementation of the system in this special section was based on recommendations made by fire engineers and technical studies carried out by the customer. Two pumping units were installed in this section, one at each end, the first with a capacity of 2,600 l/min and the second with a capacity of 1,740 l/min. This uneven distribution is due to the fact that a smaller technical space was available for the second pump unit. All the pumps in this section are electrically driven: both pumping stations are equipped with back-up pumps of the single failure type.

Pipes of 76 mm outer diameter are used for the main feed pipes, as in the A86 tunnel. This choice came down to necessity, because the project timelines were extremely tight and larger stainless steel pipes carry delivery times of many months. To ensure the required pressure at the spray heads, these small-diameter pipes had to be installed in two rows for the length of the tunnel. The installation and material costs rose considerably. It was definitely not economical to install two pipes side-by-side where one, slightly larger, would have done the job.
The main feed pipes were installed on the tunnel ceiling, connected to piping leading down to the valves. The valves were installed in fire-proof cabinets. These were placed in recesses in the tunnel walls such that the cabinets and the pipes leading into them are entirely hidden. Thanks to this, they are also fairly well protected against damage from traffic accidents. The spray heads are installed on the ceiling at the intervals established in the fire tests. In this hybrid HI-FOG® system, every second nozzle is a spray head and every other is a water mist sprinkler. At activation, the designated valves open and high-pressure water mist is discharged both through the spray heads and water mist sprinklers3. The water mist sprinklers are protected by a cap which prevents them from activating too early. The activation of this system is based on activation of the fire detection system. If necessary, zones can be closed and then opened again depending on the fire location.

Notes

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

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

CONCLUSIONS

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

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

3 Water mist sprinklers have thermal bulbs which break when the ambient temperature reaches a pre-defined level. Sprinklers for tunnel applications are equipped with a protective cap.
Marioff’s HI-FOG® Water Mist Fire Protection System for tunnel fire protection has been extensively fire-tested with various fire loads over the years 1999-2006. The results of these tests enable Marioff to offer the system for tunnel fire protection with known levels of performance and established dimensioning expertise.

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

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Design fires for tunnel water mist suppression systems

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Edinburgh, Scotland

ABSTRACT

Water mist systems are unable to suppress or control large fires, therefore the ‘design fire’ for a water mist system in a tunnel should not be specified in terms of peak heat release rate, but rather in terms of the characteristics of a growing fire which such a system is designed to suppress. This paper reviews the growth rates of a number of fire experiments carried out in tunnels and makes observations regarding the influence of tunnel ventilation on these growth rates. Further experiments will be required to validate these observations. It is suggested that tunnel ventilation of the order of 3 ms\(^{-1}\) may provide the optimal conditions for rapid fire growth and that both higher and lower airflows may result in slower growing fires. Three ‘design fires’ for water mist systems are proposed.

KEYWORDS: Water mist systems, ventilation velocity, fire growth rates

INTRODUCTION

There has been some debate regarding the issue of ‘design fires’ for tunnels in recent years. These design fires have been used for purposes such as estimating times to failure for structural elements and adequately dimensioning ventilation systems for smoke control. As a consequence of these emphases, discussion has focused more on the peak heat release rate (HRR) of a fire rather on the growth phase or any transient effects. Historically, design fires with peaks of between 20 and 50 MW have been commonly used for tunnels. However, experimental tunnel fires carried out in the past two decades have shown that peak HRRs between 100 and 200 MW may be more realistic.\(^{[1,2]}\)

At present, there is a significant interest in water based suppression systems for tunnel environments. In Europe, particularly, the emphasis seems to be on water mist systems rather than traditional sprinkler systems. Water mist systems have been and are being installed in a number of tunnels in Austria and the tunnel sections of the new M30 Madrid ring road and the A86 near Paris. Other road tunnel operators are considering the use of such systems in their existing facilities.

Water mist systems, by their very nature, are unable to suppress large fires, thus they are only effective in the incipient stages of a fire involving a large vehicle. Therefore, the design fire for a water mist system for a tunnel should not be defined by the peak heat release rate which such a fire could attain, but rather by the characteristics of the growing fire which the system is designed to suppress or control. At present, the upper limit of fire size for operability of water mist systems has not yet been determined, but it is clear that it will be significantly lower than the possible peak HRR of a goods vehicle fire.

In order to adequately define a ‘design fire’ for vehicle tunnels is it therefore necessary to look at the growth characteristics of real fires in tunnels and define the ‘design fire’ on the basis of this.
VEHICLE FIRES IN TUNNELS

Despite a significant amount of research into tunnel fire phenomena in recent years, the number of well instrumented, actual vehicle fire tests carried out in tunnels remains quite small. Indeed, to date, only one fire test of an actual heavy goods vehicle (HGV) has been carried out [3]. Other large scale fire tests have been carried out on solid fuel loads taken to be representative of HGV trailers or HGV cargoes [1,2,4], generally consisting of loads of wooden pallets, sometimes with additional plastic materials and coverings of various types.

The majority of experimental tunnel fire data that are available in the literature are from tests involving fuel pans and passenger cars. However, when designing a fixed fire suppression system for a tunnel, the scenario considered to be the ‘design fire’ by most parties involved is that of a HGV, not a pool fire or a passenger car.

Thus, in order to specify a realistic design fire for a water mist system (or other fire safety system), it becomes necessary to look at the data from tunnel fire experiments that are at least similar in fuel load and size to real HGV and their cargoes.

![Graph showing fire tests in the 2nd Benelux Tunnel, 2002. HRR in the growth phase (approximate representation). The inset graph is the data for the HGV load with canvas cover and no longitudinal airflow, which did not grow significantly until about 12 minutes after ignition.](image)

**Figure 1** Fire tests in the 2nd Benelux Tunnel, 2002. HRR in the growth phase (approximate representation). The inset graph is the data for the HGV load with canvas cover and no longitudinal airflow, which did not grow significantly until about 12 minutes after ignition.

The following experiments may be taken to share characteristics with real HGV fires:

- HGV fire test, Hammerfest tunnel, 1992 [3]
- Three HGV load tests with canvas cover, 2nd Benelux Tunnel, 2002 [4, 6] (see Figure 1)
- Two HGV load tests with aluminium cover, 2nd Benelux Tunnel, 2002 [4, 6] (see Figure 1)
- Large pallet load test (no cover), 2nd Benelux Tunnel, 2002 [4, 6] (see Figure 1)
- Four HGV trailer load tests, Runehamar Tunnel, 2003 [2] (see Figure 2)
These tests are discussed elsewhere and will not be described in detail here. Representations of the HRR data from the 2nd Benelux Tunnel tests and the Runehamar tests are shown in figures 1 and 2.

![Figure 2](image)

Figure 2 Fire tests in the Runehamar Tunnel, 2003, ignition and growth phase. The longitudinal ventilation in the tunnel was approximately 2.5ms$^{-1}$ for each of these tests during the growth phase. Thanks to Haukur Ingason & Anders Lönnermark [2] for the experimental data.

**OBSERVATIONS**

Fires in compartments have often been modelled using a ‘$t^2$’ fire [7], that is, the HRR of a fire is assumed to grow proportionally to the square of the time after ignition. Such fires are commonly classified as ‘slow’, ‘medium’, ‘fast’ or ‘ultra fast’ fires, with the constants of proportionality being approximately 3, 11, 44 and 178 Ws$^{-2}$ for these classifications.

None of the experiments listed above is adequately modelled using a $t^2$ fire. In most instances the initial growth rate is similar to a ‘medium’ rate fire, but then there is a transition to a faster growth than an ‘ultra-fast’ fire. Indeed, rather than a parabolic relationship between HRR and time, all of these experiments would be better represented by a two-step linear approximation; the first step would be the slow growth from ignition to one or two MW in size, the second step would be the rapid growth from only a few MW to tens of MW.

Approximate representations of the data from the 2nd Benelux tunnel tests and the Runehamar tunnel tests, using this two-step approximation, are shown in Figure 3.

Two things may be observed when presenting the data in this manner:

1. There appears to be a correlation between the ventilation rate and the time between ignition and the onset of rapid growth, and
2. There may be a correlation between the ventilation rate and the rate of fire growth in the second step.
Certainly, in the Benelux fire test series, those tests with no or low (1ms\(^{-1}\)) forced ventilation have the longest delay between ignition and the onset of rapid growth; over six minutes. The two tests at high ventilation (6ms\(^{-1}\)) had ‘delay’ times between five and six minutes, while the test with medium ventilation (3ms\(^{-1}\)) had by far the shortest ‘delay’ time of less than two minutes. The four tests from the Runehamar tunnel, with airflow velocities of about 2 to 2.5ms\(^{-1}\), also fit the same pattern with delay times of less than five minutes.

Considering the gradients of the graphs also suggests that there is a similar correlation with fire growth rates; the tests with low ventilation rates have a smaller gradient than those with high ventilation rates. The Runehamar tests with medium ventilation rates have much steeper gradients than both the low and high ventilation tests, although this pattern is not borne out by the Benelux test with 3ms\(^{-1}\) airflow. However, as that test was suppressed by a sprinkler 3 minutes after ignition, it is hard to make any judgement as to what the rate of growth might have been had it been allowed to burn.

These observations suggest that ventilation rates of the order of 3ms\(^{-1}\), might actually provide the optimal conditions for rapid fire growth, that is, the worst conditions for fire safety, whereas higher (or lower) ventilation rates might actually tend to delay the onset of rapid fire growth and reduce the rate of rise of this growth phase.

Unfortunately, for many years now, the results of smoke control studies \([8, 9, 10]\) have proposed ventilation rates of between 2.5 and 3ms\(^{-1}\) as the critical velocity required to control smoke in tunnels and prevent backlayering. Obviously more research is required here, but if these observations are validated by future experimental testing, then the whole area of emergency ventilation response needs reassessed: which is worse, backlayering or rapid fire growth?
DISCUSSION

With the exception of the 1992 HGV fire test, all the tunnel fire experiments described above involved only a representation of the trailer of a HGV. They therefore only model the scenario where the point of ignition of the fire is within the cargo of a HGV. In reality, the majority of HGV fires start in either the engine compartment of the tractor unit (overheating, fuel leak, etc.) or at the rear axle (brakes overheating). A real fire will therefore take some time, perhaps several minutes, to spread to the cargo. In the 1992 HGV fire test, the fire was started on the driver’s seat and was confined to the cab for the first ten minutes.

Based on this observation it may be assumed that the initial ‘delay’ phase of the fire would be longer in reality than in many of the experimental tunnel fires presented here.

The delay times and gradients of the observed rapid growth phases of these experiments are summarised in Table 1, below.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Summary of experimental observations.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel</td>
<td>Fuel</td>
</tr>
<tr>
<td>Hammerfest</td>
<td>HGV &amp; Furniture</td>
</tr>
<tr>
<td>Hammerfest</td>
<td>Wood &amp; Tyres</td>
</tr>
<tr>
<td>Benelux</td>
<td>Wood, canvas</td>
</tr>
<tr>
<td>Benelux</td>
<td>Wood, canvas</td>
</tr>
<tr>
<td>Benelux</td>
<td>Wood, canvas</td>
</tr>
<tr>
<td>Benelux</td>
<td>Wood, aluminium</td>
</tr>
<tr>
<td>Benelux</td>
<td>Wood, aluminium</td>
</tr>
<tr>
<td>Benelux</td>
<td>Wood</td>
</tr>
<tr>
<td>Runehamar</td>
<td>Wood &amp; plastic</td>
</tr>
<tr>
<td>Runehamar</td>
<td>Wood &amp; mattresses</td>
</tr>
<tr>
<td>Runehamar</td>
<td>Furniture</td>
</tr>
<tr>
<td>Runehamar</td>
<td>Plastic cups in boxes</td>
</tr>
</tbody>
</table>

The observations that can be made from such a limited pool of source data should not be considered in any way as authoritative, but may be of some use in defining design fires or in some other engineering calculations. The observed trends in the data are summarised in Table 2.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Summary of observed trends.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation rate</td>
<td>Delay phase</td>
</tr>
<tr>
<td>Low (less than 1ms⁻¹)</td>
<td>6 minutes or longer</td>
</tr>
<tr>
<td>Medium (about 3ms⁻¹)</td>
<td>5 minutes or less</td>
</tr>
<tr>
<td>High (about 6ms⁻¹)</td>
<td>5 or 6 minutes</td>
</tr>
</tbody>
</table>

In a real vehicle fire scenario it is likely that the fire will be subject to a number of different ventilation conditions. It is likely that the vehicle will be moving when the fire is in its initial stages, thus the airflow relative to the fire will probably be small in the ‘upstream’ direction (assuming that the dominant airflow is driven by the traffic flow). Once the fire is detected and the vehicle is stopped, the ventilation (still being driven by the traffic flow) will switch to a significant ‘downstream’ flow. Under normal ventilation control, the emergency ventilation will also operate in the ‘downstream’ direction, possibly greatly increasing the ventilation velocity. Unfortunately, if the observations above
are correct, this scenario will probably result in conditions which will lead to a short ‘delay’ phase after the vehicle has stopped and a rapid linear growth rate. This is frequently observed in real tunnel fire incidents, witnesses report seeing a very rapid increase in fire size very soon after the vehicle is brought to a halt.

This may have consequences for recommended actions to be taken in the event of a fire in a tunnel. If stopping the vehicle may lead to a much faster fire growth rate, might it be better to continue to the portal (assuming this is not many kilometres away) or a designated fire point rather than stopping when the fire is first discovered? Of course, this depends on many factors, requires more research and is outwith the scope of this discussion.

But these observations do have consequences for design fires for suppression systems.

TOWARDS A DESIGN FIRE

When defining a design fire, the times for detection, fire growth and system activation must be carefully considered. It is vital to have a clear understanding of the capabilities of the detection system and the lead-in times for activation of the emergency ventilation and suppression systems. In many cases, the delay between detection and activation may be a few minutes. If this is the case, it is essential that the detection system is capable of detecting a small fire (perhaps of the order of 1 MW) during the ‘delay phase’. If this is not achieved and the fire is not detected until it enters its rapid growth phase, the resulting fire will, in all likelihood, be well beyond the capabilities of a water mist system once it is activated.

Thus, the assessment of performance of a water mist system is entirely coupled with the performance of the detection system. This means that the required detail in the performance assessment of the detection system has to be comparable to that of the water mist system.

On the basis of the observations above, when defining a design fire it is also necessary to take account of the likely ventilation conditions that a real fire in the tunnel will experience.

Three example scenarios are presented which may be used to define a design fire:

1. The ventilation is initially low and remains unchanged, leading to a delay phase of about six minutes and a low growth rate of 5 MW/min.
2. The traffic-induced airflow, about 3ms⁻¹, remains unchanged, leading to a delay phase of only three minutes followed by a high linear growth rate of 15 MW/min.
3. An emergency ventilation of 6ms⁻¹ is activated quickly, extending the delay to five minutes and slowing the growth rate to about 10 MW/min.

These scenarios are shown in Figure 4. For example purposes, we assume here that the detection system is unable to detect the fire within the first two minutes of growth and that there is a four minute delay between detection and full system activation. These two times are indicated using dotted lines.

Of these three scenarios, the largest fire at the point of activation of the suppression system would be a 30 MW fire growing at a rate of 15 MW per minute. If the emergency ventilation could be activated very swiftly, the scenario might be more like a 12 MW fire growing at a rate of 10 MW per minute. Of course, if the time lag between detection and activation is more than four minutes, then the fire growing at 15 MW/min could be significantly larger than any water mist system is capable of suppressing.
The third case of a 2 MW fire growing slowly is trivial. However, it should be noted that this case is similar to a number of fire experiments which have already been carried out to test or demonstrate water mist systems for tunnel applications (although the majority of such tests have been carried out with liquid fuel pool fires, which respond in a different manner to the influence of longitudinal ventilation).

**CONCLUSIONS**

- It has been observed that there is an apparent relationship between the rate of growth of a solid fuel fire in a tunnel and the tunnel ventilation velocity.
- It may be that the fastest fire growth occurs at about 3ms$^{-1}$ airflow velocities, leading to ‘worst case’ fire scenarios.
- Both higher and lower ventilation rates may result in slower growing fires.
- Tunnel fires are not adequately modelled using a $t^2$ fire curve, a two-step linear curve gives a more accurate representation.
- Design fires for water mist systems should be based on the characteristics of a growing fire and should take into account the time delay between detection and system activation.
- These observations are made on the basis of only a few experiments. More research is needed to confirm (or otherwise) the validity of these conclusions.

**ACKNOWLEDGEMENTS**

Many thanks to my colleagues at the University of Edinburgh, particularly Dr Guillermo Rein and Prof. José Torero. Thanks also to Jacobs Engineering and various tunnel operators for interesting discussions on the subject of design fires. Finally, thanks to SP and TNO for the tunnel fire data.
REFERENCE

The Influence of Tunnel Cross Section on Temperatures and Fire Development

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ABSTRACT
During a fire in a tunnel, the temperature is a crucial parameter for the occupants of the tunnel, for the ability of the rescue service to approach the fire, and for the tunnel structure. Therefore, it is of importance to be able to derive information on temperature development and the maximum temperature for different fire scenarios and tunnels with different heights and widths. Fire tests in a model-scale tunnel have been performed to study the effect of the width and height of a tunnel on the gas temperature inside a tunnel during a fire. The model-scale tunnel was 10 m long. The widths used were 0.3 m, 0.45 m, and 0.6 m and the heights 0.25 m and 0.4 m. Fire tests with heptane and wood cribs, respectively, were performed. There was an effect on the gas temperature of the tunnel dimension, generally decreasing temperature with increasing dimensions, even if the effect varied at different positions in the tunnel and the effect in some positions was relatively small. Also, the effect in the vicinity of the fire was opposite to the effect further downstream of the fire.

KEYWORDS: gas temperature, tunnel fire, cross section, tunnel height, tunnel width

INTRODUCTION
As a consequence of the recent catastrophic fires in tunnels and results from large scale fire tests in tunnels during the past few years, the interest and importance of representative design fires has increased. Fires in vehicles in tunnels can lead to fast growing fires with high heat release rates (HRR). It has also been shown, both from investigation of real fires and from fire tests, that these fires can mean a severe thermal load with very high temperatures as the result. Ingason and Lönnemark summarized a large number of different kinds of vehicles or scenarios, showing the wide variety of HRRs and maximum temperatures that can be reached during these types of fires [1]. Different types of fires and types of fire scenarios have been assigned different temperature load on the structures. For testing of construction materials a number of different temperature-time curves are used [2, 3]. The main difference between the curves is the rate of increase and the maximum temperature where the more severe curves most often are connected to petroleum fires.

One problem with trying to draw general conclusions from real fires and fire experiments is that the conditions can vary considerably between the different cases. The fire scenario might not be exactly the same, the ventilation conditions might vary, and the tests may have been performed in tunnels with significantly different height and width.

This is the situation with real tunnels, i.e., the height and width varies between different tunnels. The cross-sections can also be of different shapes. This has lead to the question whether and in what way the tunnel dimensions affect the conditions (e.g. gas temperature) inside a tunnel during a fire. During the large-scale tests in the Runehamar tunnel in Norway, where simulated cargos of heavy goods vehicles were used as fuel, very high gas temperatures were registered [3]. This emphasized the importance of the temperature and the influence of the tunnel dimensions. The temperature is a crucial parameter for the occupants of the tunnel, for the ability of the rescue service to approach the fire, and
for the tunnel structure. Therefore, it is of importance to be able to derive information on temperature
development and maximum temperature for different fire scenarios and tunnels with different heights
and widths.

For HRR, the effect of the tunnel itself [4, 5] and the influence of the tunnel dimensions [6] have been
studied and presented previously. The aim of this paper is to present a study on the influence of cross-
sectional dimensions on the gas temperatures measured during fires in tunnels.

**TEST SET-UP**

To study the influence of different parameters on the fire development and size of a fire inside a
tunnel, free burning tests and fire tests inside a model-scale tunnel were performed. The tunnel was
10 m long (see Figure 1). The width and height of the tunnel were varied during the test series. The
widths used were: 0.3 m, 0.45 m, and 0.6 m, and the heights were: 0.25 m and 0.4 m. The scale of the
tunnel was assumed to be 1:20 and therefore the widths correspond to 6 m, 9 m and 12 m in real scale,
while the heights correspond to 5 m and 8 m, respectively. The different cross sections used are
presented in Figure 2. The ceiling, floor, and one of the walls were made of 15 mm thick
PROMATECT®-H boards. One of the walls was comprised of 15 windows of 5 mm thick fire
resistant glass set in steel frames.

In most of the tests a longitudinal flow was established inside the tunnel using a fan. The air velocity
was varied between the tests. Mass loss of fuel, gas temperature, heat flux, gas velocity, gas
concentrations, and heat release rate, were measured during the tests. In the present paper, the focus is
on the gas temperature and the effect of the tunnel dimensions. The other measurements and results
from these tests are presented elsewhere [6-8].

The fuel load was centred in the width and the length directions. This means that the fuel load was
placed 5 m from the inlet and 5 m from the outlet of the tunnel. Two different types of fuel were used:
pools of heptane and wood cribs. For the heptane fires an almost square pan (0.155 m × 0.160 m) was
used with a 0.05 m thick layer of heptane.

The wood cribs were constructed of four layers of long sticks (0.5 m) with four sticks in each layer
and three layers of short sticks (0.15 m) with three sticks in each layer (see Figure 3). The cross
section of the sticks was 0.015 m × 0.015 m for both the long and the short sticks. This gave a total
height for the wood crib of 0.105 m. The porosity of this wood crib was 2.1 mm [7, 9]. The wood
cribs were placed on four 0.05 m high piles with pieces of PROMATECT®-H standing on a 0.34 m ×
0.55 m × 0.010 m PROMATECT®-H board connected by metals rods to a digital balance beneath the
tunnel floor. The top of the board was 0.02 m above the floor. This means that the bottom of the wood crib was 0.07 m above the tunnel floor. In the heptane tests, the fuel pan was standing directly on the PROMATECT®-H board. The initial fuel surface was in these cases 0.07 m above the tunnel floor. This means that the distance between the ceiling and (initial) top of the fuel was 18 cm and 33 cm, respectively, for the heptane tests, and 12.5 cm and 27.5 cm, respectively, for the tests with wood cribs. The values correspond to the two different tunnel heights used.

![Figure 2](image2.png)

**Figure 2** The different cross sections (A to F) used during the test series. Dimensions in mm.

![Figure 3](image3.png)

**Figure 3** A wood crib used as fuel.

The tests presented and discussed in this paper were part of a larger test series. Most of the tests presented in the Results section were performed with a longitudinal air flow velocity of 0.67 m/s. These tests are presented in Table 1, but note that two tests (Test 31 and Test 33) had a lower longitudinal air flow velocity, 0.5 m/s.
A parameter often convenient to use is the hydraulic diameter, especially when establishing how various parameters depend on dimensions. The hydraulic diameter, $D_H$, is defined as

$$D_H = \frac{4A}{P} \tag{1}$$

where $A$ is the cross-sectional area and $P$ is the perimeter of the tunnel. The three length parameters $W_T$ (width), $H_T$ (height), and $D_H$ are used when describing the effect of the tunnel dimensions on the temperature distribution.

**Table 1** Description of conditions for the tests reported.

<table>
<thead>
<tr>
<th>Test no</th>
<th>Fuel</th>
<th>Initial fuel mass [kg]</th>
<th>$W_T$ (m)</th>
<th>$H_T$ (m)</th>
<th>$D_H$ (m)</th>
<th>$H_{c-f}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Heptane</td>
<td>0.856</td>
<td>0.45</td>
<td>0.25</td>
<td>0.321</td>
<td>0.18</td>
</tr>
<tr>
<td>15</td>
<td>Heptane</td>
<td>0.852</td>
<td>0.60</td>
<td>0.25</td>
<td>0.353</td>
<td>0.18</td>
</tr>
<tr>
<td>19</td>
<td>Heptane</td>
<td>0.852</td>
<td>0.30</td>
<td>0.25</td>
<td>0.273</td>
<td>0.18</td>
</tr>
<tr>
<td>22</td>
<td>Heptane</td>
<td>0.868</td>
<td>0.30</td>
<td>0.40</td>
<td>0.343</td>
<td>0.33</td>
</tr>
<tr>
<td>27</td>
<td>Heptane</td>
<td>0.872</td>
<td>0.45</td>
<td>0.40</td>
<td>0.423</td>
<td>0.33</td>
</tr>
<tr>
<td>33a)</td>
<td>Heptane</td>
<td>0.876</td>
<td>0.60</td>
<td>0.40</td>
<td>0.480</td>
<td>0.33</td>
</tr>
<tr>
<td>9</td>
<td>Wood crib</td>
<td>0.806</td>
<td>0.45</td>
<td>0.25</td>
<td>0.321</td>
<td>0.125</td>
</tr>
<tr>
<td>12</td>
<td>Wood crib</td>
<td>0.808</td>
<td>0.60</td>
<td>0.25</td>
<td>0.353</td>
<td>0.125</td>
</tr>
<tr>
<td>16</td>
<td>Wood crib</td>
<td>0.782</td>
<td>0.30</td>
<td>0.25</td>
<td>0.273</td>
<td>0.125</td>
</tr>
<tr>
<td>20</td>
<td>Wood crib</td>
<td>0.862</td>
<td>0.30</td>
<td>0.40</td>
<td>0.343</td>
<td>0.275</td>
</tr>
<tr>
<td>23</td>
<td>Wood crib</td>
<td>0.806</td>
<td>0.45</td>
<td>0.40</td>
<td>0.423</td>
<td>0.275</td>
</tr>
<tr>
<td>31a)</td>
<td>Wood crib</td>
<td>0.844</td>
<td>0.60</td>
<td>0.40</td>
<td>0.480</td>
<td>0.275</td>
</tr>
</tbody>
</table>

$W_T$ is the width of the tunnel, $H_T$ is the height of the tunnel, $D_H$ is the hydraulic diameter of the tunnel (defined in Eq. (1)), and $H_{c-f}$ is the distance between the ceiling and the initial top of the fuel.

a) In Test 31 and Test 33 the centre line cold velocity was 0.5 m/s instead of 0.67 m/s.

**RESULTS**

The combustion zone, position of the flame, and the temperature distribution is affected by the dimensions of the tunnel. This means that the effect of a change of one length parameter can be different at different distances from the seat of fire. In Figure 4 to Figure 8 the maximum temperatures near the ceiling at different distances from the seat of the fire are presented. Each figure contain graphs for two different fuels (heptane and wood cribs), presented as variations in tunnel width, tunnel height, and hydraulic diameter, respectively. Note that in each graph, the point representing the largest cross section ($W = 0.60$ m and $H = 0.40$ m) corresponds to an air velocity of 0.5 m/s instead of 0.67 m/s.
The maximum temperature above the centre of the fire increases with the width of the tunnel for both heptane and wood crib fires (see Figure 4). There is a significant difference in the maximum temperature between the different tunnel widths. Even if the absolute temperatures are lower in the heptane case, the increase with the tunnel width is almost as distinct as in the wood crib case. One significant difference between the two fuels is that in the heptane case the temperatures are higher for the largest tunnel height, at least for the smallest tunnel width, while in the wood crib case the lowest tunnel has the highest maximum temperatures above the centre of the fire. This is probably related to the geometry of the fuel and how the flame zone is affected by the ventilation. In the case with the liquid fuel heptane, an increased ceiling height probably moves the flame volume towards the seat of the fire due to increased mixing. In the case with the wood crib as a fuel, the combustion zone is already near the seat of the fire due to the three-dimensional burning inside the wood crib. This can be seen in the higher temperatures above the seat of the fire in the wood crib case. An increased ceiling height does not seem to improve the combustion efficiency. Instead the distance to the hot surface is increased and the increased space for air flow probably cools the gases above the fire. This difference in influence of the tunnel height can also be seen in the middle graphs where the maximum temperatures are plotted against the tunnel height. From these graphs it is apparent that the temperature increases with increasing height for the heptane case while it is the other way around for the wood crib tests.

The use of hydraulic diameter can be seen as an efficient way of combining the effects of both height and width. In the case with heptane where the effect of variation in height and width are similar, there
is a clear relationship between the change in maximum temperature and variation of the hydraulic diameter. The outlier with the relatively high temperature in the graph for heptane can most probably be explained by two different processes that in this case influence the temperature in the same direction. The point corresponds to the case with $W = 0.60$ m and $H = 0.3$ m. The first effect is due to the large width is an increase in the mixing thereby moving the combustion zone closer to the seat of the fire and increasing the maximum temperature in this region. The other effect is due to the low tunnel height giving a radiation effect increasing the burning rate. This effect can also be enhanced by the wider tunnel moving the flame volume closer to the seat of the fire. Even if the walls (and possible radiation from them) are further away from the fuel.

![Graphs showing temperature variation with width and height for heptane and wood crib fuels.](image)

Figure 5  Maximum temperatures near the ceiling 25 cm downstream the seat of the fire.

The measurement at 25 cm downstream of the seat of the fire (see Figure 5) is situated downstream of the heptane pool and above the downstream edge of the wood crib. These temperature measurements represent an intermediate region. There is no clear relationship between the temperature and the width of the tunnel. Only between the width 0.3 m and 0.45 m for the height $H = 0.40$ m is there a significant change. For heptane, the trend is an increasing temperature for increasing tunnel width.

The variation in maximum temperature with tunnel height is not extremely large, but still clear and the temperature decreases with increasing height. The trends are the same for the two types of fuels. There is no clear function of the hydraulic diameter for any of the two fuels.
In Figure 6, the maximum temperatures near the ceiling 50 cm downstream of the seat of the fire are shown. The maximum temperature decreases with tunnel width for both heptane and the wood crib, especially between $W = 0.45$ and $W = 0.60$ m for the case with $H = 0.40$ m. The same trend with decreasing temperatures can be seen as a function of the tunnel height, especially for $W = 0.60$ m. Even if the not all graphs in the upper four figures show significant trends, there is a clear function between the maximum temperature and variation in hydraulic diameter. For both fuels, heptane and wood cribs, the case with $W = 0.45$ m and $H = 0.40$ m seems to obtain combustion conditions leading to relatively high temperatures in the position 50 cm downstream of the fire. The points corresponding to this case do not fall on the regression line for the function of $D_H$, especially for wood cribs.

In Figure 7, the maximum temperatures near the ceiling 75 cm downstream of the seat of the fire are presented. The effect of a change in the tunnel width is much more pronounced in the case with wood crib as a fire source than for the case with heptane, where the change was negligible. Almost the same situation can be seen for a change in the tunnel height, although the effect in the wood crib case is not as clear for a change in tunnel height as for a change in tunnel width. In total there is a negligible effect of a change in the hydraulic diameter for the case with heptane, while there, on the other hand, is a clear decrease in maximum temperature with increasing hydraulic diameter for the wood crib case.
In Figure 8, the maximum temperatures near the ceiling 100 cm downstream of the seat of the fire are presented. The temperature decreases with increasing tunnel width for both heptane and wood crib. The lines for heptane are almost identical for the two heights. This can also be seen in the middle graphs where there is no clear function between the temperature and the tunnel height. For the wood crib case, on the other hand the function between temperature and tunnel height is relatively clear. This difference between heptane and wood crib is also clearly seen in the lower graphs where the functions of the temperatures are decreasing for increasing hydraulic diameter for both heptane and wood cribs, but while the function in the heptane case is only slowly decreasing and is based on somewhat scattered data, the wood crib case shows a clearly decreasing function and an almost perfectly linear correlation.

Thus far temperatures in the same position for different test conditions have been compared. The focus will now be switched to the temperature distribution along the tunnel and how the shape of this distribution is altered when the test conditions are varied. The experimental data is also compared to a theoretical calculation of the average cross-sectional temperature along the tunnel. This model is described by Ingason [10]. It is based on the convective heat release rate from the fire, i.e. a fixed fraction of the total heat release rate is lost through flame radiation. The convective losses are included as a function of the distance from the fire and the average temperature can be calculated as
\[ T_{\text{avg}} = T_0 + \frac{2}{3} \frac{Q}{\rho_0 u_0 A_0} e^{-\frac{h x}{\rho A_0}} \]  

(2)

where \( T \) is the temperature, \( \dot{Q} \) is the HRR, \( \rho \) is the density, \( u \) is the velocity, \( A \) is the cross-sectional area of the tunnel, \( c \) is the heat capacity, \( h \) is the heat transfer coefficient (\( h = 0.02 \text{ kW/(m}^2 \text{ K)} \) has been used in the calculation presented in this paper), and \( x \) is the distance from the seat of the fire. The index 0 corresponds to conditions of the incoming air.

In Figure 9 it can be seen that the tests with heptane have their temperature maximum further downstream (50 cm – 75 cm) than what is the case for the wood crib tests (25 cm downstream of the seat of the fire).

The temperature measured at half the tunnel height and the average temperature of a vertical thermocouple tree are in most cases relatively similar to each other. The largest difference can be seen for the heptane test in the largest tunnel where the average over height at the cross section 75 cm from the seat of the fire is more than 100 °C lower than the half height temperature. The temperatures measured with the lowest two thermocouples are in this case much lower than for the other thermocouples, i.e. there was a clear stratification.
The calculations of average temperature based on Eq. (2) correlate relatively well with the temperature measured at half the tunnel height, at least when excluding the measurements at positions close to maximum temperature. For the tunnel with the smallest cross section, Eq (2) gives a temperature of 1410 °C (not shown in the graph) above the seat of the fire, while the measured temperature is significantly lower.

For heptane, it is apparent that the average temperature and the temperature measured in the ceiling are more similar the smaller the tunnel cross section. For a tunnel with a larger height a clear interface between upper and lower gas layer can be seen. This can be seen also in the case with wood crib, but since the maximum temperatures can be found closer to the seat of the fire, this stratification could be registered also in the middle graph (low but wide tunnel).

**DISCUSSION**
Tests with pools of heptane and wood cribs, respectively, have been performed in a model-scale tunnel where the width and the height have been varied during the test series. In general it is observed that the maximum gas temperatures are affected by the variation of the width and the height, but the

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**Figure 9** Temperatures measured near the ceiling along the tunnel. The position x=0 represents a position above the centre of the fire. Included are also temperatures measured at a height equal to half the tunnel height and averages of the tunnel height, respectively. The line included in the graphs is based on Eq. (2).
result of the variation differ depending on at which position in the tunnel the temperature is measured. In most positions the temperature decreases with increasing dimension, but in several of these positions the change in temperature is relatively small. An exception it should be noted that close to the fire the gas temperature increases with increasing dimension, especially for heptane. In general, the trends are similar for heptane and wood cribs, even if the magnitude of the effect on the temperature varies. Again, one exception is the position near the fire, where the influence of the height on the temperature above the seat of the fire is different for heptane and wood crib fires. One reason for this might be the difference in burning, combustions zone and flame extension for the two types of fuels. Heptane burns with a flame volume arising from the fuel surface. The ventilation flow makes the flame tilt and a change in height or width alters the combustion zone and thereby the position of maximum temperature. The wood cribs burn three-dimensionally, e.g. inside the wood crib. This means that they are affected differently by the ventilation where the flow to some extent passes through the burning wood crib. A change in the tunnel dimensions can alter the air flow and thereby the combustion process.

The geometrical effects of the tunnel on the maximum temperatures is more pronounced further downstream in the tunnel where the temperature is more two dimensional in its character. On the other hand closer to the seat of the fire, the combustion behavior and flame volume are very much affected by the dimensions of the cross-section. For example, when the width is increased the oxygen mixes better with the pyrolysis gases from the fuel, and therefore the combustion zone moves closer to the seat of the fire. The consequence is that the maximum temperature is reached closer to the seat of the fire. The geometry of the fuel clearly plays an important role in this process.

Further, the mass loss rates and heat release rates are affected by the height and width of the tunnel. No compensation for the variation in heat release rate has been performed. The reason for this is that the fire source used in each test series (for the same type of fuel) has been the same and the aim of this study has been to study the effect of the tunnel dimensions on the temperature distribution for a selected fire source in the same way as the tunnel dimensions could affect the expected temperatures during a vehicle fire in a tunnel.

The maximum ceiling temperatures does not always need to be at the centerline of the tunnel. It was observed in some tests that the maximum occurred in between the centerline and the wall. For example in Test 23 the temperature was 640 °C at the centre line, but 680 °C on both the left side and the right side (all measured 30 mm below the ceiling).

Furthermore, the temperatures can be affected by the ventilation as well. A change in ventilation can affect the temperatures in several different ways, or for several different reasons. It has been shown that an increase in the air velocity can increase the heat release rate. The magnitude of the change depends on the starting conditions [6]. An increase of the air velocity will also increase the total air flow and this can lead to a cooling of the gases inside the tunnel. Another effect an increase of the air velocity can have is that it can change the flame angle and combustion zone and thereby locally significantly alter the temperature and resulting in a large effect on individual temperature measurements. These issues are important to take into account when applying the results for different cases. Note that in each graph showing the effect of the width and the height, the point representing the largest cross section \((W = 0.60 \text{ m} \text{ and } H = 0.40 \text{ m})\) corresponds to an air velocity of 0.5 m/s instead of 0.67 m/s. This might have had some effect even if it has not been quantified. In most cases, however, this point seems to follow the general trends. It is only at the position 50 cm where there is a significant difference between the large cross section and the other tests. The different velocity might have some effect, but some of the difference might also be due to the larger cross-section itself.

Note that the theory on the temperature distribution along the length of the tunnel was based on a constant heat release rate. In the comparisons in this paper, the maximum HRR and the temperatures recorded at the time for maximum HRR have been used. In some cases the increase in HRR has been fast and the peak had been sharp leading to only a short time period of high heat release rate. That will
affect the correlation between the theoretical and experimental results.

CONCLUSIONS
Some conclusions can be drawn from the presented results:

- The gas temperature is affected by the dimension of the tunnel. In general there is a decrease in temperature with increasing dimension, but not near the fire where an increase in gas temperature can be seen.
- The effects on tests with the two different fuels are similar, but not identical.
- Near the seat of the fire the burning characteristics for the two fuels are different. In this region the three-dimensional effects in the wood crib case and the effect of the flame position for the heptane case becomes significant.
- For the tunnels with a small cross-section, the temperature is relatively uniform, while an increased stratification and difference between average temperature and ceiling temperature can be observed when the width or height of the tunnel is increased.
- The model of the average temperature correlates relatively well with the measured temperature at half the tunnel height and the average value calculated from temperatures measured in a vertical thermocouple tree, at least a distance away from the fire. Close to the fire the difference can be large.

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REFERENCES
Approximate Trajectories of Droplets from Water Mist Suppression Systems in Tunnels

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ABSTRACT

This paper presents results from a simple analysis of water mist droplet trajectories subject to tunnel airflows up to 10 m $\cdot$ s$^{-1}$. It is shown that individual droplets may be carried hundreds of metres downstream of the nozzle location before hitting the road deck under ventilation conditions that are commonplace in tunnels. Thus, if the current ventilation strategies are to be employed in the event of a fire, the zone length should be considerably longer than 50 m. An alternative strategy, in order to reduce the lengths of nozzle zone, would be to reduce the ventilation flow during emergency response. This appears to be contrary to the recommendations of PIARC. The results suggest that more experimental research into the interaction of water mist, tunnel ventilation and fire plumes is required.

KEYWORDS: water mist systems, ventilation, travelling distance

INTRODUCTION

At present, there is a significant interest in water based suppression systems for tunnel infrastructures. The emphasis, particularly in Europe, seems to be on water mist systems rather than traditional sprinkler systems. Water mist systems are being installed in a number of tunnels in Austria, the Madrid M30 ring road and the Paris A86 ring road. Other road tunnel operators are considering the use of such systems in their existing facilities.

What distinguishes a water mist system from other sprinkler systems is the much smaller size of the droplets. A water mist is a spray for which approximately 90% of the total volume corresponds to droplets of less than 500 $\mu$m in diameter $[^1]$, by comparison, a conventional sprinkler has droplets of the order of 5000 $\mu$m. For tunnel applications, the droplets are usually smaller than 200 $\mu$m. These fine droplets have a high surface to volume ratio and a very low terminal velocity. Using smaller droplets has several advantages, not least the fact that such systems can use much lower water flows, and hence require smaller pipes and smaller reservoirs to feed them. The high surface to volume ratio enhances the heat transfer from the fire to the mist. The low terminal velocity allows the droplets to circulate around obstructions and attack fires in the manner of a total flooding gas (reaching covered locations, for example inside vehicles). However, one major disadvantage of such systems is that droplets are easily blown away from the fire location by the fire-induced flows and the tunnel ventilation.

In the forthcoming PIARC document on “Road Tunnels: An Assessment of Fixed Fire Fighting Systems” $[^2]$ it is suggested that one of the requirements of a fixed fire fighting system is that it should be designed to handle air velocities in the range of 10 m $\cdot$ s$^{-1}$. The implication of this statement is that a suppression system should be designed to operate with the ventilation system running at maximum capacity. However, given the small droplet diameters water mist remains airborne and it is highly unlikely that a large ventilation flow will be near the optimum operating conditions for a water mist suppression system.
The problems associated with the use of water mist systems in tunnels are not trivial. The mechanisms leading to the control of a fire by water mists are complex and poorly understood. There are very few fundamental studies in this area and most of the work focuses on the assessment of performance via large scale tests. To the best knowledge of the authors, no experiments have addressed the travelling distance of droplets in tunnels.

This paper studies the transport of droplets in tunnels using a simple model of droplet aerodynamics and focusing on the travelling distances for different longitudinal ventilations.

THE NEED FOR DROPLET TRAJECTORY CALCULATIONS

Detailed computational fluid dynamics (CFD) modelling of a water mist system can provide some information on the delivery of water to the fire [3], but none of the existing CFD models can adequately calculate the interactions between the water droplets and the fire. Moreover, combinations of existing tests and complementary CFD studies can be conducted to extrapolate performance of a system, but the results would have to be analysed very carefully. There is no precedent in the technical or scientific literature of this being done for a realistic tunnel situation. The complex mechanisms of plume buoyancy, turbulent eddies, flame radiation and flame-chemistry effects would make the state-of-the-art CFD solutions intractable and thus difficult to apply to real engineering designs. CFD simulations alone are not the best first approximation to a problem like the one being studied here when more fundamental analyses have not been used. A first attempt to address the problem must be simple, transparent and easy to validate. Later on, further mechanisms and complexity can be built upon it.

Water mist systems commonly use a zonal strategy; the system is subdivided into a number of zones of a given length, and only those zones closest to the fire are activated in the event of a fire. In a tunnel with longitudinal flow, a commonly adopted strategy would be to activate two zones; the zone containing the fire itself and the zone upstream of the fire location. In order for this strategy to be useful, the zone must be of sufficient length that the prevailing ventilation does not carry the droplets beyond the fire location. See Figures 1 and 2.

Figure 1  A water mist system that reaches the fire location for a given longitudinal ventilation

Figure 2  A water mist system that misses the fire location at higher longitudinal ventilation

Figure 1 shows a scenario where the ventilation is sufficiently low and the zones are sufficiently long that the mist generated in both Zone 1, upstream of the fire, and Zone 2, at the fire location is able to reach the fire location. In the scenario shown in Figure 2, the ventilation is such that all the droplets
from Zone 1, upstream of the fire, (and Zone 2) are carried beyond the fire location before they reach road level. If ventilation rates of this magnitude are to be considered, Zone 1 must be much longer than pictured (i.e. extend much further upstream) in order for any droplets from Zone 1 to be able to attack the fire itself.

The travelling distances of droplets may also be significantly influenced by the slope of the tunnel section, particularly in an upward inclined section where the buoyancy due to the fire itself adds to the push from the ventilation against gravity, as shown in Figure 3. In a downward inclined section the travelling distance may be shorter.

Figure 3 Trajectories of water mist droplets in a horizontal tunnel section and the travelling distance: left) Horizontal tunnel section; right) upward inclined section.

DROPLET TRAJECTORY MODEL

An analytical model which predicts transport distances for water mist droplets has been developed. This is a simple model, merely intended to provide a rough estimate of the average travel distances and provide an assessment of performance under specific conditions.

The model considers droplet trajectories on the vertical centre plane of the tunnel under a horizontal one-dimensional flow. The model calculate the movement of a droplets of diameter $d$ that move at velocity $V_r$. The longitudinal flow in the tunnel $U_r$ is modelled as a parabolic velocity profile (zero velocity at the walls and peak value at the centre) with an average flow velocity $U_0$.

The conservation of momentum in vector notation considering inertia, gravity and drag leads to Eq. (1) for the expression of the droplet acceleration.

$$\frac{d\vec{V}}{dt} = \vec{g} + \frac{1}{2} C_D \cdot \frac{\rho A_d}{m_d} |\vec{W}| \cdot \vec{W}$$

Where $\vec{g}$ is the gravity pull; $C_D$ the drag coefficient given by Eq (2) for a sphere; $\rho$ the air density; $A_d$ the projected area of the droplet; $m_d$ the droplet mass; and $\vec{W}$ the droplet velocity relative to the ventilation flow and given by Eq. (3).

$$C_D = 0.4 + \frac{24}{Re_w} + \frac{6}{1 + \sqrt{Re_w}}$$
The Reynolds number $\text{Re}_w$ in Eq. (2) is calculated using the relative droplet velocity and given by Eq. (4), where $\nu$ is the air kinematic viscosity.

$$\text{Re}_w = \frac{d |\dot{W}|}{2 \cdot \nu}$$

Integration in time of Eq. (1) provides the trajectory of the droplet after being injected into the tunnel at a ceiling height $D$ with a spray velocity and spray angle. Very close to the nozzle, the mist is very dense and the spray momentum dominates the droplets movement. While a droplet is inside the nozzle cone, its trajectory will be a straight line with the initial spray velocity and angle. Typical nozzle cones for water mist applications stretch about $r_n = 2 \text{ m}$ from the nozzle. Outside the nozzle cone, the fine droplets experience a large drag force relative to both the gravitational pull and the inertia, and reach falling terminal velocity (in the range from 0.1 to 0.4 $\text{ m/s}$ for the range of droplet sizes considered here). The droplets are then carried along by the airflow as they fall and ultimately impact on the road deck at some downstream distance $L$ from the nozzle.

Three limitations exist for this model that stem from the assumptions of a horizontal one-dimensional flow, isolated droplets and no fire conditions. In the event of a fire, turbulent eddies in the fire plume will produce complex flow patterns, deflecting streamlines in the vertical direction. Also, a semi-transverse ventilation system will add a vertical component. However, a horizontal average velocity will prevail in the duct. This horizontal average is the velocity component considered in the model. Not including the complex eddies still provides a good estimate of the average flow conditions thus resulting in the average travelling distances (i.e. average path of many droplets falling under perturbed flow conditions). The falling trajectory is calculated here assuming an isolated droplet once it is away from the nozzle (out of the momentum-dominated nozzle cone). This assumes that there is no interaction with other droplets, which is especially valid for low water flow rates (sparse water mists). A dense water mist will tend to slow the longitudinal flow and this results in shorter travelling distances. However, as shown in the results in [3], the isolated droplet assumption could be valid to calculate the trajectory for droplets from the first nozzle upstream of the fire, which happens to be the nozzle setting the optimum separation between water mist nozzle zones. The addition of the fire into the problem will produce even finer droplets (that evaporate as they heat up) and produce an upward lift due to the buoyant plume. These two effects will results in larger travelling distances.

These effects have yet to be investigated in real tunnel situations via testing or CFD simulations. The complexity of the CFD simulations hinders the applicability of the results in the short term. Only in conjunction with large scale experiments, CFD allows a proper understanding of the problem in the long term.

RESULTING TRAVEL DISTANCES

As part of this study we consulted a number of water mist companies and obtained the approximate droplet size distributions in their systems. The following droplet sizes are found to be characteristic of current commercial systems:

- 35 $\mu$m – The diameter is significantly smaller than average size and may be considered to represent the lower bound diameter (hence resulting in the upper bound in travel distances).
- 90 and 120 $\mu$m – These diameters may be taken to represent ‘typical’ droplet diameters of current commercial water mist systems.
- 170 $\mu$m – This diameter is significantly larger than the average size and may therefore be
considered to represent the upper bound in diameter (hence the lower bound of travel distances).

- 300 μm – This diameter is well above the upper bound of droplet sizes, but is also included as an indication of travel distances of larger droplets (i.e. coalesced droplets).

The trajectories have been calculated for a range of ventilation velocities $U_0$, up to $10 \text{ m s}^{-1}$. For the purposes of this paper, the other parameters have been fixed. The tunnel ceiling height $D$ is 6 m, the spray velocity is $10 \text{ m s}^{-1}$, spray angle $\theta_0$ is $125^\circ$, and the nozzle cone size $r_n$ is 2 m.

Figure 4 shows the resulting travelling distance for different droplet diameters and ventilation flows. This shows the trends of the solution to the Eqs. (1-4) which can be explained via a simplified analysis. The mist will reach the floor at a distance downstream from the nozzle $L$ equal to the average air flow velocity $U_0$ multiplied by the residence time of the droplet. The residence time can be approximated by the tunnel height minus the nozzle cone vertical distance divided by the terminal velocity (which is proportional to the square of the droplet diameter $d$). Thus, the travelling distance is proportional to these quantities (Eq. 5). This approximate solution explains the trends shown in Figures 4 and 5, and its accuracy increases for smaller droplets, higher velocities and taller tunnels.

$$L \propto \frac{U_0}{d^2} \left( D - r_n \sin \left( \frac{\pi - \theta_0}{2} \right) \right)$$

**Figure 4** Travelling distances vs. droplet diameter for droplets ejected from the ceiling in a 6 m high tunnel for different airflow ventilation velocities.
Various comparisons of the travelling distances resulting from variations of droplet diameter and ventilation velocity are shown in Figure 6. The effect of the nozzle cone can be observed in the first 2 m of trajectory.

The results from the calculations show that water mist droplets are carried between 60 and 100 m downstream before they reach the road deck in a tunnel with only 3 m $s^{-1}$ airflow. Almost all of the droplets (i.e. those less than $170 \mu m$) will be carried more than 30 m downstream under these conditions. A significant proportion of the water mist may be carried very large distances downstream under these conditions.
Figure 6  Travelling distances for 35, 90, 120, 170 and 300 μm droplets in a horizontal tunnel section, subject to average longitudinal airflows of 1, 2, 3, 5 and 10 m·s⁻¹.

RESULTS & DISCUSSION

The results from these calculations need to be validated before the values area accepted as representative of a tunnel water mist scenario. The only results found in the literature on travelling distances are from one of the simulations provided as part of the larger CFD study of water mist systems in tunnels for fire [3]. The CFD simulation of the turbulent aerodynamics of a 1 kg·s⁻¹ mist from a realistic spray nozzle and the full interactions between droplets and a ventilation of 2.4 m·s⁻¹, in a tunnel 3 m high, provided a travelling distance of 12 m for the 120 μm diameter droplets. This result can be compared to our simple methodology; solution to Eqs. (1-4) for an isolated droplet of 120 μm diameter under the same spray and ventilation conditions provides a travelling distance of 14 m, only 16% larger. This is remarkable given the simplicity of this model and the large computational resource required for CFD.
While the results still need to be validated against experiments, the study seems to provide good estimates and does raise a few questions which must be addressed before water mist systems become common for tunnel fire safety applications.

It has been shown that individual droplets (or sparse mists of droplets which do not interact significantly with each other) may be carried hundreds of metres downstream of the nozzle location before hitting the road deck under ventilation conditions that are commonplace in tunnels. Thus, if the current ventilation strategies are to be employed in the event of a fire, the zone length should be considerably longer than 50 m, especially if droplets smaller than 170 μm are being used (as is generally the case). An alternative strategy, in order to reduce the lengths of nozzle zone, would be to reduce the ventilation flow during emergency response. This appears to be contrary to the recommendations of PIARC, quoted above, and is a non-trivial procedure that will require a thorough analysis of the flows within any tunnel, before implementation. The upper limit of ventilation rate under which a water mist system may be useable needs to be assessed for each commercially available water mist system, bearing in mind that buoyant flow in sloping tunnels can significantly increase longitudinal airflow.

The results of this study can be applied towards the design of lengths for the system zones. Figure 7 shows the trajectories for the range of droplet sizes considered here at three ventilation velocities.

![Droplet Trajectories](image)

**Figure 7** Droplet trajectories under 1, 3 and 10 m s⁻¹ airflows in the first 50 m from the nozzle.

The x axis has been fixed at 50 m in each graph to visualise the length of a typical zone. From this it is quite clear that all droplets of typical sizes will be blown completely out of a 50 m zone by a 10 m s⁻¹ airflow. Even at 3 m s⁻¹, the majority of typical droplet sizes are blown out of a 50 m long zone. Indeed, it is only when the airflow is reduced to about 1 m s⁻¹ that the majority of droplets produced by a water mist spray nozzle will reach the road deck within 50 m of the nozzle.
CONCLUDING COMMENTS

Combining the results of this study with the implications of the wording of the PIARC document quoted above [2] would suggest that water mist systems are not fully appropriate for tunnel fire safety applications. Yet water mists are increasingly being installed in tunnels.

Perhaps the issue needs to be addressed in a systemic manner. Rather than trying to design a water mist system to operate in conjunction with a fully active ventilation system, the designers should rather design a unified system consisting of water mist and ventilation. What are the optimum operating conditions for the unified water mist and ventilation system? It seems unlikely that this will be at maximum ventilation.

The further issue of fire growth vs. traditional design fire should also be considered. Assuming the detection and alarm system is able to initiate the water mist system in the early stages of the fire (see [4]), the fire size will be considerably smaller than the ‘design fire’ (based on peak smoke production) which it was designed to deal with. Thus the actual required ventilation flow will be considerably less than any of the ventilation ‘design fire’ scenarios. Thus the ventilation may be reduced in a safe manner. Also, research needs to be carried out to address the issue of smoke control in tunnels with water mist systems, at present this is an unknown.

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REFERENCE LIST

Full Scale Fire Tests In Yingzuiyan Road Tunnel

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ABSTRACT
Full scale fire tests were conducted in YingZuiYan Road Tunnel, an 1852 m long double tube road tunnel located in Yunnan province of western China. Under three different longitudinal ventilation velocities of 0.5 m/s, 1.5 m/s, 2 m/s and 3 m/s, the response characteristics of optical fiber temperature detector, traditional linear heat detector and two infrared wavelength flame detector were tested. Smoke layer temperature, CO concentration distribution were measured. The similarity of longitudinal and vertical distribution of CO concentration and temperature rise was analyzed. Results showed that the optical fiber detection system seemed to be more reliable than the traditional linear heat detection system. The flame detection system gives the fastest response to the fire with regardless of the wind speed and fire size. The higher the longitudinal ventilation velocity, the lower the temperature below the ceiling and its increasing rate, and the later the response of the temperature-based fire detection system. When the longitudinal ventilation velocity is up to 3 m/s, it will be hard for a current temperature-based tunnel fire detection system to respond to the fire at the early stage. The fire alert criteria should be setup more rationally based on the local normal longitudinal ventilation velocity, cross-sectional size and ambient temperature of the road tunnel. The local vertical distribution of CO concentration and the smoke temperature correlate reasonably well. However, the smoke temperature decayed longitudinally much faster than the CO concentration.

KEYWORDS: road tunnel, full scale test, fire, fire detection, CO, temperature

INTRODUCTION
Big fire disasters occur in road or railway tunnels in recent year, such as in Mont-Blanc, France/Italy (Vuilleumier et al., 2002) and Tauern, Austria (Leitner, 2001) in 1999; Kitzsteinhorn, Austria in 2000; Gotthard, Switzerland in 2001; Dague, Korea (Hong, 2004) in 2003; and Frejus, France/Italy (SCMP, 2005) in 2005. Tunnel fire safety is a hot concern around the world.

Fire detection system plays an essential and important role in tunnel fire protection. Firstly, the fire detection system should efficiently detect the fire at the early initial stage. Other fire protection systems, such as smoke control system, fire suppression system can then be activated. The detection of a fire in an early time also means that more time can be left sufficiently for aid of human evacuation.
Current fire detection systems used in tunnels include traditional linear cable fire detection system, optical fiber temperature detection system, optical grating temperature detection system, flame detection system and image detection system. Due to their different detection methodology, these fire detection systems have their own superiority and shortages. Before taken into use, there fire detection systems should be tested and certificated in laboratories under standard environment. However, it should be noted that the real environment, including the longitudinal air flow temperature and speed, in a road tunnel is changefully with the local weather. It is quite different with that in the standard laboratory tests. What is the performance of these fire detection systems in a real road tunnel should be examined locally in the road tunnel, even they are already passed the standard tests in the laboratory and certificated. This point had also been noticed by Liu et al. Technical requirements for road tunnel detection systems are also very limited in current standards and guidelines.

A long-term cooperative research program on tunnel fire safety had been setup between State Key Laboratory of Fire Science (SKLFS) and Yunnan General Fire Brigade in China. Two series of full scale tests had formerly been finished in YangZong Road Tunnel (2004), YuanJiang 1# Road Tunnel and DaFengYaKou Road Tunnel (2005), concerning the smoke spread which included the smoke travelling velocity and smoke layer interface height distribution, the critical ventilation velocity and temperature distribution in tunnel fires. This paper presents the results of another series of full scale tests conducted in 2007 in YingZuiYan Road Tunnel, which mainly focused on the similarity of the CO and temperature distribution, the reliability of fire detection systems and the discussion of setting up the fire alert criteria for the temperature detection systems.

EXPERIMENTAL

Full scale fire tests were conducted in YingZuiYan Road Tunnel, an 1852 m long double tube road tunnel located in Yunnan province of western China. The cross section of the YingZuiYan Road Tunnel is horseshoe shaped with width of 11.2 m and height of 7.2 m, as shown in Figure 1. There are two vehicle cross passages and three human cross passages between the tunnel tubes. The slope of the tunnel is 2.49%. Gasoline pool fires of 0.5 m$^2$, 1 m$^2$, 2 m$^2$ and 2.5 m$^2$ and a wood crib fire were burned. The Heat Release Rate (HRR) of these pool fires was estimated to be about 1 MW, 1.8 MW, 3.2 MW and 5 MW, respectively. However, the burning behavior of the wood crib in tunnel with longitudinal ventilation seemed to differ largely with that in a quiescent open air. Its HRR was hard to be estimated actually and we can just coarsely assume it to be about 1.0 – 1.2 MW based on the former experimental burning data under the hood of ISO 9705 Room Calorimeter. Total 9 tests were conducted as summarized in Table 1, with longitudinal ventilation velocities of about 0.5 m/s, 1.5 m/s and 3 m/s.
Figure 1. Plan and cross sectional view of the YingZuiYan Road Tunnel

Table 1. Summary of the tests

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Fire source</th>
<th>Wind speed</th>
<th>Detection time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Size (m²)</td>
<td>Height (m)</td>
<td>HRR (MW)</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.3</td>
<td>1.8</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>0.3</td>
<td>3.2</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>0.3</td>
<td>1.8</td>
</tr>
<tr>
<td>7</td>
<td>0.5</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>8</td>
<td>0.5</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>9</td>
<td>Wood crib</td>
<td>1.2</td>
<td>2</td>
</tr>
</tbody>
</table>

Smoke layer temperature, CO concentration and longitudinal ventilation velocity were measured in the tests, as shown in Figure 2. Temperature below the tunnel ceiling and directly above the fire was measured by armoured thermocouples from -6 m to + 9 m with interval of 1 m, taking the horizontal coordinate of the fire source to be 0. The smoke ceiling jet temperature was measured by thermal resistors upstream (from -20 m to -180 m) and downstream (from +20 m to + 450 m). The intervals of the thermal resistors were 20 m. Six thermocouple trees were positioned at -180 m, -20 m, +20 m, +250 m and +450 m. For the thermocouple tree in -20 m and +20 m, which was relative near to the fire, total 27 thermocouples were assigned in each tree from 7 m to 0.5 m high from the floor with same intervals of 0.25 m. For other thermocouple trees, 11 thermocouples were arranged in each tree with height of 7 m, 6 m, 5 m, 4.5 m, 4 m, 3.5 m, 3 m, 2.5 m, 2.0 m, 1.5 m and 0.5 m. CO
concentrations were measured at 6 positions, as also shown in Figure 2. The responses of three different kinds of detection systems to fire occurrence were recorded. They are optical fiber temperature detection, traditional linear heat detection and two infrared wavelength flame detection. The fiber was installed in three different heights, 6.5 cm, 21.5 cm and 36.5 cm below the tunnel ceiling to see their response effectiveness at these different heights. In this paper, discussion will mainly focus on the similarity of the CO and temperature distribution, the response of these detection systems and the setting up the fire alert criteria for the temperature detection systems.

**RESULTS AND DISCUSSION**

The similarity of vertical distribution of CO concentration and temperature rise is given in Figure 3. It can be seen that the local CO concentration and the local gas temperature correlate reasonably well. Figure 4 presents their longitudinal distribution. It was shown that the gas temperature decayed longitudinally much faster than the CO concentration. This should due to the heat loss happened to the smoke layer when travelling along the tunnel.

The response time of the fire detection systems are summarized in Table 1. It seemed that the flame detection system give the fastest response to the fire with regardless of the wind speed and fire size. With the increase of the fire size and the low down of the wind speed, the temperature based detection systems respond earlier. Their detection time also seemed to be much shorter for gasoline
pool fire than for the wood crib fire. However, the optical fiber detection system seemed to be more reliable than the traditional linear temperature detection system. The traditional linear temperature detection cable even damaged after the Test 4 with big fire. However, the optical fiber can work repeatedly.

The fire alert criteria for temperature detection system are based on maximum temperature or maximum temperature increase rate. Their variations with the fire size (HRR) and the longitudinal wind speed are given in Figures 5-8. In China, their criteria are currently fixed to be 68 °C or 5 °C/min. From these figures, it was shown that the temperature and its increase rate increase with the fire size and decrease with the increase of the wind speed. The maximum temperature can not reach the detection criteria for the small fire of 0.7 MW even when the wind speed is 0.5 m/s, which is very low in a tunnel. The maximum temperature increase rate index just got to the criteria for 0.7 MW pool fire with wind speed of 3 m/s and for the 1.2 MW wood crib fire with wind speed of 2 m/s. This should be an uncertainty situation for fire alert.

So, the temperature-based fire alert criteria should be determined rationally from the tunnel height, the longitudinal ventilation velocity and the initial local ambient temperature in the road tunnel. When the longitudinal ventilation velocity is higher, the fire alert criteria should be set to be lower appropriately. So is the tunnel height. Different criteria should be set even for a same road tunnel in different seasons, as the longitudinal air flow in the tunnel should have different velocity and
temperature in different seasons. It is not appropriate to set the criteria to be fixed for a temperature-detection system with regardless of the local condition of the road tunnel.

CONCLUSIONS

A series of full scale tests had been conducted in YingZuiYan Road Tunnel in 2007, for studying the similarity of the CO and temperature distribution and the reliability of fire detection systems. The setting up of the fire alert criteria for the temperature detection systems was also discussed. Results showed that the vertical distribution of CO concentration and temperature rise correlated reasonably well, while the smoke layer temperature decayed longitudinally much faster than the CO concentration. For the reliability of the temperature-based fire detection system, it will be hard for the current system to detect an early stage fire of 0.7 MW with a longitudinal wind speed of up to 3m/s, with fixed alert criteria of 68 or 5 °C/min. It is not reasonable to set the fire alert criteria to be fixed regardless of the ambient condition in the road tunnel. The fire alert criteria should be set according to the local environment in the road tunnel separately. Firstly, the normal longitudinal ventilation velocity should be calculated according to the length and the traffic load of the road tunnel. The fire alert criteria can then be set based on the local ambient temperature (should be different under different seasons), tunnel height and the longitudinal ventilation velocity. When the longitudinal ventilation velocity is higher, the fire alert criteria should be set to be lower appropriately. So is the tunnel height. Their quantitatively relationship should be further investigated and reported later.

ACKNOWLEDGEMENT

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ABSTRACT
Most real fires in tunnels involve Heavy Goods Vehicles (HGV) and most of the fires start at an HGV. One freely burning HGV carrying ordinary combustibles easily reaches heat release rates (HRR) of the order of 100 – 200 MW, which then spreads the fire to catastrophic levels. Tunnel safety authorities often try to quantify performance requirements for fixed fire protection systems by asking whether the system "can suppress a 100 MW fire, or a 200 MW fire". This, as such, is a meaningless question as there is no generic 100 MW or 200 MW fire but all fires are different and depend at least on the actual fuel, the way the fuel is loaded, the tunnel dimensions, and the ventilation conditions. Also, the intent of any water-based fire suppression system in any application is to start the discharge before the fire is very large and prevent it from ever reaching the potential value. Therefore, the question should rather be whether the system “can suppress or control a potentially 100 MW fire, or a 200 MW fire”.

Four different full-scale fire test programs with HI-FOG water mist systems will be analyzed primarily with respect to the relevance of the fuel packages for the intended tunnel application. The results will be evaluated and recommendations for acceptable performance requirements will be provided.

KEYWORDS: water mist systems, road tunnel fires, full-scale testing, performance requirements

INTRODUCTION
There has been quite a dramatic change in attitude during the last couple of years among tunnel fire safety authorities towards water-based fixed fire protection systems in tunnels. Transition from practically banning such systems to the present situation of even requiring systems to be installed is a complete reversal of opinion within a very short time. The next challenge is to achieve a common understanding on the acceptable performance level of the systems. Economic boundary conditions of real installations cannot be separated from the performance considerations: well-intentioned but unrealistic performance requirements may, in fact, lead to the exact opposite as no system will be installed at all due to the unaffordable price.

Performance-based approach has been adopted in different applications for evaluating water mist systems as an alternative to more traditional fire protection systems. The same approach is being taken by tunnel fire safety authorities for all water-based systems and, therefore, they typically require full-scale fire testing to verify the performance of proposed suppression systems. The various fire test programs define the fire scenarios to be addressed and the minimum level of performance deemed “acceptable”. Even though the principal approach is widely in use in other applications, there is a crucial practical difference: fuel loads in tunnel fire test programs have the potential of creating fires in excess of 100 MW, which is far beyond the sizes considered to be controllable by any industrial fire suppression system. And yet, similar simplistic expectations on the fire behavior and the suppression system performance may govern the requirements for “acceptable performance”.

It is assumed that the HRR follows a smooth growth curve and, instantaneously after activating the suppression system, starts a smooth decrease with consequent instantaneous decrease in all temperatures and other measurable parameters like toxic gas concentrations and radiant heat. It is also
erroneously assumed that temperatures within the flame region and its immediate vicinity quickly drop down to tolerable levels so that practically all structural damage could be avoided. This is not at all the case with any large fire even in an open space let alone in tunnel fires involving physically high combustibles with flames impinging the ceiling and highly turbulent conditions in the vicinity.

The overly simplified comprehension has led to overly simplified, randomly selected acceptance criteria determined at a fixed time at fixed, single-point locations. Focusing on irrelevant single-point values obscures the vast global benefits that properly designed water-based suppression systems bring about. These include extensive cooling that aids the evacuation of people from the tunnel and entrance of fire fighters into the tunnel, limiting the tunnel length exposed to damaging temperatures, reduction in back layering, and preventing propagation of fire to adjacent vehicles.

REAL TUNNEL FIRES

Fires in transportation tunnels have a high probability to develop into catastrophic events – both with respect to loss of lives and to financial consequences. In the last 10 years, there have been a number of serious tunnel fires that have completely collapsed the illusion of potentially 30 MW fires that are handled by the smoke extraction systems, that are structurally tolerated by the fire-proof tunnel linings, that create a stratification of hot smoke close to the ceiling allowing people to escape, and that are approachable by fire brigades to extinguish the fire.

The fire in the Mont Blanc highway tunnel on the 24th of March 1999 was a real, tragic eye opener with its 36 victims and huge financial losses. In that incident fire and smoke overwhelmed the ventilation systems and damaged the concrete lining of the tunnel. Fire spread along nearly 500 m of tunnel, created intense heat and toxic smoke that filled kilometers of tunnel from ceiling to floor and prevented fire brigades from getting to the fire area for days. Later full-scale fire tests in the Runehamar tunnel [1] revealed that a truck loaded with ordinary combustibles could easily reach HRR of 100 – 200 MW, i.e. far beyond the 30 MW that had been considered a value representing a truck fire and that had been the design value widely used, for example, for dimensioning ventilation systems.

While the Mont Blanc tunnel was closed for several years, the nearby Frejús tunnel was used as a replacement route. Fire safety was of special concern: the fire alarm systems were renovated, there was a fire safety zone at every 275 m, a state-of-the-art tunnel fire training centre was in active use and the tunnel was part of a European SAFETUNNEL project with the objective of dramatically reducing fire accidents in tunnels. On the 6th of June 2005 a fire broke out in the tunnel and – in spite of all the fire safety measures – it was so hot that fire brigades could not enter for hours. Two people were killed and the tunnel infrastructure was damaged so that the tunnel remained closed for two months.

A very recent fire in California, i.e. the Santa Clarita fire close to Los Angeles on the 12th of October 2007 proved wrong yet another misconception of short tunnels not needing any active fire protection systems as they are easy to evacuate and easy to access by fire brigades. Three people were killed in this 150 m long tunnel that was seriously damaged in the fire involving 31 vehicles. The flames bursting out from both ends of the tunnel prevented the fire brigades from entering the scene.

If and when a fire breaks out in a tunnel the only way to prevent catastrophic consequences is to fight the fire at its very origin as quickly as possible.

HI-FOG FIRE TEST PROGRAMS

Marioff Corporation Oy has conducted several full-scale fire test programs aiming at developing active water mist fire protection systems against conceivable fires in tunnels with the economic boundary conditions in mind. As has been typical with the increased understanding over the years, the fuel loads have increased from test program to test program during the period starting from 2002 with
less than 10 MW fires to 2006 with fires approaching the potential of 100 MW. The key parameters of the four HI-FOG fire test programs are summarized in Table 1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Test site</th>
<th>Tunnel dimensions (m)</th>
<th>Fuel package</th>
<th>Max ventilation (m/s)</th>
<th>Max unsuppressed HRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>IF fire and safety test centre, Norway</td>
<td>8</td>
<td>Stable, concealed spray</td>
<td>1.1</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>Horse shoe shape</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>IF fire and safety test centre, Norway</td>
<td>Horse shoe shape</td>
<td>Pools, wood pallets (UPTUN –type)</td>
<td>3</td>
<td>&lt; 27</td>
</tr>
<tr>
<td></td>
<td>Horse shoe shape</td>
<td>2.55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>VSH Hagerbach, Switzerland</td>
<td>Box shape</td>
<td>Passenger vehicles</td>
<td>3</td>
<td>&gt; 30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>TST (Tunnel Safety Testing), Spain</td>
<td>Box shape</td>
<td>Simulated HGV trucks with wood and</td>
<td>3.5</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>plastic pallets</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The objective of the very first test program in 2002 was to evaluate the thermal management capability of different water mist systems with a stable test fire. A highly concealed spray fire served the purpose of providing a constant HRR even during system operation. In these early tests there was a limitation from the test tunnel owner to prevent temperatures close to the tunnel structures from exceeding 350 °C for any extended periods. This limitation severely limited the size of the test fire as well as the allowed pre-burn times. Consequently, the maximum fire size was 8.1 MW which, at that time, was erroneously believed to represent the size of 5-6 passenger vehicles burning simultaneously.

With the current knowledge of potential fire sizes in tunnels it is sufficient to summarize that the first test program verified the currently well known facts of water mist as an excellent cooling agent and laid the basis for the HI-FOG system designs later on called deluge, hybrid and zoned sprinkler modes of operation.

For the second test program in the same test facility, the tunnel interior had been protected by mineral wool insulation mats allowing for somewhat larger fires. The test configuration was the same as had been used for the UPTUN tests [2], and the test fires were largely similar to those applied in the UPTUN project, i.e. exposed and concealed pool fires and wood pallet fires as shown in Figure 1. The HRR of the four pools burning freely was measured within the 16 – 22 MW range in seemingly identical conditions. These values were consistently larger than the 13 MW estimated from diesel oil burning rate data. The largest fire, i.e. the wood pallet fire had a potential for some 27 MW but a peak of 34 MW was measured, followed by an instantaneous drop down to about 15 MW at water mist activation. Even though it is likely that ventilation enhanced the burning rate, there was some doubt about the reliability of the HRR measurement at a single location in this very short tunnel.

To the very least, the tests could be applied for further thermal management evaluation, based on two thermocouple racks at 1 m distance and 29 m distance downwind from the fuel array. Good thermal management capability of HI-FOG deluge system was again confirmed. The 1 m distance was too short, though, as the lowest thermocouples in the rack could be affected by direct flame impingement, and the 29 m distance was too long for the short tunnel and small fires as the average temperatures even during pre-burn were quite moderate. They ranged from 20 to 75 °C except for the 121 °C measured during the largest fire. This temperature dropped down to 30 °C during water mist discharge.

In the following, the two major test programs with larger and more realistic fires are dealt with in more
All four test programs are described in full detail in relevant third party reports [3], [4], [5], and [6]. The latest test program is dealt with also in publicly available conference proceedings [7] and [8].

PARIS A86 TESTS: REAL PASSENGER VEHICLE FIRE

Fire test scenarios
The first realistic test program was developed to simulate the characteristics of the A86 Eastern Tunnel around Paris, France, and conceivable fire scenarios therein. Particularly the ceiling height of only 2.55 m is a unique characteristic of the tunnel constructed for passenger vehicle traffic only. The transient tunnel ventilation flow during an accident situation is estimated to be initially 6 m/s, which then – with the traffic stopped but with smoke extraction – is decreased to 3 m/s.

The most likely fire scenario in the tunnel involves a collision of two or more cars, which either results in a fire in a single vehicle or leads to a fire involving several vehicles. Figure 2 shows the configurations for the simulated collisions in a 2-lane and 3-lane arrangement respectively. The fire in each case was started in the engine compartment of Car C. Real cars in operating condition were used, and the engines of the cars were run for 15 minutes prior to ignition to warm them. The cars had petrol in their fuel reservoirs and normal rubber tires, upholstery and other plastic contents of modern cars. Figure 3 shows the situation in one test during the pre-burn period.

![Collision scenarios with ventilation from the left.](image)
Three main fire scenarios were applied in the series of 10 tests. In the small fire scenario (about 5 MW) the HI-FOG system was activated before the fire had propagated beyond Car C. In the large fire scenario (> 15 MW up to 30 MW) the fire was allowed to spread freely from Car C to involve also Cars D and E before HI-FOG activation. A special combined fire scenario was also applied, and different fuel leakage scenarios were simulated. In all cases the HI-FOG system was operated for a continuous duration of 30 min.

Acceptance criteria
The objectives for an active fire protection system proposed for the A86 tunnel were defined as follows:

- The temperatures must be reduced in the vicinity of the fire and along the length of the tunnel to levels that are non-threatening to life or to structural elements or other infrastructure.
- The fire must be suppressed and thereby the amount of smoke generated by the fire reduced.
- The fire propagation from one vehicle to another must be prevented, by controlling both maximum temperatures as well as ignition by radiant heat.

These realistic qualitative requirements were converted to the following quantitative requirements:

- The temperature at any point 35 m downwind from the fire shall not exceed 50 °C
- The average temperature 10 m upwind from the fire shall be max 5 °C above ambient.
- The heat flux at a distance of 15 m downwind of the fire shall not exceed 5 kW/m².
- The heat flux at a distance of 10 m upwind from the fire shall not exceed 2 kW/m².
- The fire must not propagate to target vehicles during the water mist discharge.

It is noteworthy that the time factor was left out from the prefixed requirements acknowledging that different sizes of fires, different fire development rates, different activation procedures etc. were to be applied. It is also realistic to allow a certain amount of time for the water mist to bring conditions to the desired level of control. The given distances from the fire were sufficiently long to eliminate the effect of random occurrences and direct flame impingement within the fire zone and its immediate vicinity.

Evaluation of results

Temperatures
Two different deluge system designs were tested. Excellent thermal management was provided in the tunnel in all fire scenarios. Figure 4 shows an example of temperature results at 35 m downwind in one “large” fire test, where the HRR peaked at about 24 MW as shown in Figure 5. With the system activation, a practically instantaneous drop of temperatures is observed. There are slight “bumps” after the initial drop presumably due to rupturing fuel tanks. These abrupt occurrences can be seen more clearly in the temperatures measured just above the fire as shown in Figure 6. Temperatures upwind were not an issue at all but remained close to or even lower than ambient during system operation.
Figure 4 Temperature control 35 m downwind from the fire.

Figure 5 HRR determined during the test.

Heat flux
Heat flux 15 m downstream from the fire is shown in Figure 7. The acceptance limit of 5 kW/m² is reached in about 4 min. Heat flux upwind of the fire was again not an issue at all.

Propagation to adjacent vehicles
In each test the number of cars burning at the time of system activation was recorded. At the end-of-test the number of burned or partially burned cars were counted. These numbers were always the same within each test confirming the fact that the fire did not propagate during system operation. Visually, the following trends were observed:

- in cases where the fire was fully established inside the car prior to system activation, the car was fully consumed
- if fire did start inside an adjacent vehicle after activation of the water mist, it did not consume the car and the damage was limited by the water mist system
- the spillage fires on the floor as well as cars that had been ignited only on the outside were extinguished during operation

Toxic gas concentrations
In addition to the prefixed measurements CO- and CO₂-concentrations were measured 70 m downwind of the fire. The peak readings of all the tests for CO and CO₂ were 790 ppm. and 1.35 %, respectively. Neither of the levels measured are immediately threatening to life.
MADRID M30 TESTS: SIMULATED HGV FIRES

Fire test scenarios
In the Runehamar fire tests [1] the maximum HRR of simulated trucks carrying ordinary combustibles ranged from some 60 MW up to 200 MW and targets at 15 m distance from the primary fuel package were all consumed. These well-defined, simulated HGV fuel packages were applied in the HI-FOG test series in modified forms to represent ordinary trucks driving through any ordinary traffic tunnel, like the tunnels of M30 around Madrid, Spain, that was the primary driving force for the testing.

Figure 8 shows two basic fuel packages applied. The “standard severity” fuel package involved standard EUR wood pallets only, with a potential HRR of >75 MW, whereas the “high severity” fuel package involved 16 w-% plastic materials as well, with potential HRR of >95 MW. The wood pallets were in “dry” condition – moisture contents averaging in the 15 percent range. Yet another, probably the most typical HGV with solid doors on the back of the trailer and vehicle cab in front, was simulated by solid partitions at both ends of the load and they acted as wind shields for the fire.

Figure 8 (left) Standard severity fuel package with wood pallets in stacks, placed on an elevated platform. The fire was ignited by small pans of petrol at the upwind end of the fuel package; (right) High severity fuel package with polyethylene plastic pallets interspersed with wood pallets. The construction of the package was the same as in the most severe Runehamar test except for the shorter total length and for the smaller total number of plastic pallets. The tarpaulin made of non-fire retardant polypropylene is not yet in place.

Most of the tests were conducted without wind shields and tarpaulin, so the 2 or 3 m/s wind from the longitudinal ventilation acted to enhance the fire from the time of ignition. When the tarpaulin was used to cover the fuel package or when the wind shields were applied, they momentarily blocked the wind and slowed the spread of fire into the pallets. On the other hand, the tarpaulin had quite the opposite effects that dominated the fire spread: initially the tarpaulin prevented the fuel package to be pre-wetted at downwind locations and when the tarpaulin started to burn on the vertical surfaces, the fire spread was ultra-fast and quickly involved a large number of dry pallets. In most tests one or more target arrays of stacked dry pallets were placed downwind of the fuel package. The distances varied between 4 m and 8 m.

In the test series of about 40 tests in total, the water mist system was activated before the fires reached their potential magnitudes: the fires were typically allowed to develop to 15 to 20 MW size before activation. In reality, a 15 MW fire is easy to detect and locate with a high degree of precision by any current fire detection technology. The pre-burn times varied between 3 min and 12 min for the different fuel packages. The water was discharged for 30 min after which it was shut off and the fire brigade completed the extinguishment. Two very different types of fires prior to activating the suppression system are shown in Figure 9.
Acceptance criteria

No quantitative acceptance criteria were fixed prior to the tests. The objective was to evaluate the performance of the water mist system on the basis of four measures:

- The relative benefits of the deluge, zoned sprinkler, and hybrid modes of operation.
- The ability to prevent the fire from reaching its potential maximum HRR.
- The ability to provide thermal management in the tunnel.
- The ability to prevent fire spread to adjacent combustibles.

It is informative to analyze the results also against a set of fixed acceptance criteria defined by VdS of Germany for their approval testing with fuel loads representing an HGV. Details of the fuel package are unfortunately too vaguely defined and there are contradictory requirements that make it impossible to determine the potential HRR let alone reproduce the tests. The requirements are the following:

- Temperature on the tunnel centerline 20 m downwind from the end of the fuel array, at a height of 2 m must be \( \leq 50 \, ^\circ\text{C} \) within 2 min after activation.
- The fire must not spread to a target placed 5 m from the end of the fuel arrays, stacked to a height of 2.5 m above floor and covered with tarp.
- The temperature at a distance of 5 m from the end of the fuel array and a height of 3 m must be \( < 350 \, ^\circ\text{C} \) after 2 min and \( < 250 \, ^\circ\text{C} \) after 5 min.
- At the end of the 30 min discharge, at least 10 v-% of the fuel package must remain unburned.

Evaluation of the results

Relative benefits of the deluge, zoned sprinkler, and hybrid modes of operation.

Each of the three HI-FOG modes of operation relies on external detection to pinpoint the fire and open the relevant section valves. A deluge system consists of open spray heads only, divided in sections. When a section valve is opened, all the spray heads in the relevant section start to discharge water. The zoned sprinkler system consists of individually heat-activated sprinklers with a dedicated protective cap structure, divided in sections. When a section valve is opened, all the protective caps in that section are released so that the heat sensitive bulbs are exposed to the hot gases. Bulbs start to break at hot locations and only those sprinklers start to discharge water. The hybrid system is a mixture of the deluge and sprinkler systems: every second nozzle is an open spray head, every intervening nozzle is a closed sprinkler. When a section valve is opened, the open spray heads in the relevant section start to discharge water and the protective caps of the sprinklers are released. If the fire is sufficiently hot, however, sprinklers close to the fire start activating at the locations where they are most effective. The three modes of operation are clarified in Figure 10.
The different amounts of water discharged outside the fire region did not have any consistent effect on the outcome of the test results. For the same result, the zoned sprinkler mode had the lowest total water flow requirement. The hybrid mode with higher total water consumption may be more resistant to higher wind velocities than those tested. This applies naturally also to the deluge mode but the water consumption becomes so much higher that it has a considerable impact on the costs and as such may be a decisive factor in decision making.

Figure 10 HI-FOG deluge (top), zoned sprinkler (middle) and hybrid (bottom) systems with three pressurized sections. The water flux density at the fire location is the same for all three systems, but the amount of water discharged further away from the fire varies.

In the following evaluation it should be noted that the maximum length of tunnel covered with water mist was only 32 m, representing a typical length of a single section. Most tunnel operators require dimensioning for at least two but most often for three sections. Two very different fires will be described: an exposed standard severity fire and the most challenging high severity fire concealed with tarpaulin. A HI-FOG hybrid system was applied in the first case and zoned sprinkler system in the second one, but these very different tests should not be used for comparison of the two systems.

Ability to prevent the fire from reaching its potential maximum HRR. HRR curves for the two tests are shown in Figure 11. The standard severity fire grew to approximately 20 MW within 5 min 40 s after ignition, when the water mist system was activated. There is a clear reduction in the increase rate, and the HRR stabilizes around 20 MW till it starts a gradual decrease. The fire is clearly under control, and, on the average, in all the standard severity tests the HRR was reduced to 27 % of the potential value of 75 MW. The very good performance is primarily due to the simple exposed fuel package that was being pre-wetted from the very beginning of discharge.

The concealed high severity fire was very different. The HRR grew quickly to 20 – 30 MW by which time, at 2 min 10 s the first sprinkler had been activated. 3 min 40 s later 6 sprinklers in total had activated and all the rest (16 in total) soon after that. This full suppression power shows in the HRR curve as the stabilization to 40 MW. However, due to the unpredictable effects of the tarpaulin and plastic pallets in the load, the HRR started a re-growth up to 65 MW, which is less than the potential 95 MW, but the most important result was that this intense fire did not spread to the nearby target.

Ability to provide thermal management in the tunnel
Figure 12 shows temperature profiles along the tunnel ceiling at various times during the tests. Ceiling temperatures in the exposed standard severity test behave as expected: at the time of activation the temperatures are at their highest, peaking at about 900 °C just above the fire. Without suppression the very high temperature would soon spread along extended distances in the tunnel. After activating the water mist system the temperatures drop down quickly in a time-orderly manner.
The curves show the situation at 5, 15 and 20 min after activation. At 20 min temperatures even just above the fire have dropped below damaging levels.

A totally different sequence of events is seen in the high severity scenario. With the tarpaulin, the flames are not initially impinging the ceiling and, therefore, the ceiling temperatures are low at the time of activation. The lowest curve relates to the situation at 1st sprinkler activation and the next one at 6th sprinkler activation 3 min 40 s later. When the partially concealed fire fully develops along the tarpaulin, and consequently involves a major part of the dry wood and plastic pallets, the flames impinge the ceiling and the temperatures increase up to 800 – 900 °C. The three upper curves represent

Figure 11. HRR (left) in standard severity fire test and (right) in high severity fire test.

Figure 12 Temperature profiles along the centerline of the tunnel. The distance between each marked TC location is 5 m. The black rectangle indicates the size and location of the fuel package, the lighter rectangle the water mist coverage length.

the situation at 5, 15 and 20 min after the full suppression power. And yet, in terms of protection of the tunnel lining, the region of potential damage (such as spalling of concrete) is limited to the area immediately above the fire and up to 20 m downwind of the fire.

Figure 13 shows temperatures measured within a cross section at about 25 m distance from the end of the fuel array. In the standard severity fire the behavior is again ideal: at this early stage of fire gases are still stratified but after water mist activation a homogeneous mixture of gases at around 50 °C continues along the tunnel. With the high severity fire the temperatures reflect the delayed HRR increase but at 1.5 m height remain below 60 °C and at the ceiling below damaging levels.
The ability to prevent fire spread to adjacent combustibles.
In the standard severity test the last two stacks of pallets in the fuel array remained untouched by the fire. The total estimated percentage of unburned fuel was 28 v-%. The fact that the end of the fuel package did not burn confirms that fire would not have ignited downstream targets.
In the high severity fire a target array covered with tarpaulin was placed at 8 m from the end of the fuel package. Although all pallets in the fuel package had been consumed, the target array did not suffer any damage, not even melting of the tarpaulin. In another high severity test of at least 45 MW the target at 5 m distance did not suffer any damage.

**VdS evaluation**
Pass/fail judgment in Table 2 is based on instrumentation close to the required locations.

### Table 2  Evaluation strictly based on fixed VdS requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Standard severity fire</th>
<th>High severity fire</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}} = 50 , ^{\circ}\text{C}$ at 2 min after activation at 20 m distance, 2 m height</td>
<td>Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>Situation stabilizes after 3 min of discharge to 45-60 $^{\circ}$C throughout the cross section</td>
<td></td>
<td>Fail at later times as fire increases only after a delay due to tarpaulin effects, $T_{\text{max}} = 70 , ^{\circ}\text{C}$</td>
</tr>
<tr>
<td>No damage on target</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>$T_{\text{max}} = 350 / 250 , ^{\circ}\text{C}$ at 2 / 5 min after activation at 5 m distance, 3 m height</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>T at 2 and 5 min was under 100 $^{\circ}$C and reached its max (&lt; 300 $^{\circ}$C) at 15 min. T at a further location behind the target was higher.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max damage 90 v-%</td>
<td>Pass</td>
<td>Fail</td>
</tr>
</tbody>
</table>

**DISCUSSION**

**Qualitative evaluation**
All results were very convincing of the benefits of the water mist system. In the two large fire test programs the fire propagation was stopped and the fire was suppressed during system operation. After the 30 min discharge period the fire brigade had an easy job to walk next to the fire scene and complete the extinguishment. Damage was limited to the combustibles already in flames at the time of activation, and structural damage was restricted to the close vicinity of the fire.
Fuel package
The use of operable automobiles was a realistic choice for the A86 testing. In spite of some variation in the duration of the initial fire growth the fire development was surprisingly repeatable. The natural variations between tests were compensated by the number of tests allowing for distinguishing them from the performance evaluation. This applies also in general: if the fuel package cannot be defined in exact terms, there must be a sufficient number of tests to be able to quantify natural variations.

The well-defined Runehamar-type fuel packages provide realistic model HGVs for repeatable and reproducible fuel packages. The presence of wind-breaks and/or tarpaulin on the HGV trailers has a large effect on the severity of the fire. Exposed standard severity fire with wind breaks is the least challenging, whereas the high severity fire covered with tarpaulin is the most challenging fire with a high probability of unexpected and abrupt incidents during the test.

Pool fires are not representative fires for tunnels as, in reality, the main result of spillage from vehicle fuel tanks is to spread the fire to adjacent vehicles. The relatively small quantity of fuel contained in fuel tanks burns quickly away. Major spillages or collapses of tanker wagons provide totally different fire scenarios with potentially excessive areas in flames burning for a long time. This is the absolutely worst case scenario and needs to be considered whether the system design should be based on a low-probability worst case situation or a high-probability severe situation.

Acceptance criteria
Fixing quantitative acceptance criteria for scenarios that have not been pre-tested should be avoided altogether. There are no generic numbers applying to any fire scenario that would guarantee an ideal performance in real tunnel fires. Fixed criteria in fire tests always go together with fixed, well-defined fuel packages. When a representative fuel package has been agreed upon, the most important and most generic requirement is to prevent the fire spread to adjacent vehicles. This is easily verified in tests using simulated targets. The requirement for sufficient temperature control is the next most crucial requirement as it allows for a faster completion of extinguishment by fire brigades. These two requirements inherently lead to limited structural damage that realistically cannot be fully avoided.

Requirements that limit heat flux or toxic gas concentrations aim at improving tenability. However, real tunnel fires may involve an unlimited number of different combustibles over a large range of potential fire severity. Heat flux and gas concentration performance limits are not as consistently representative of the benefits of water mist as those related to fire spread and cooling.

Simplistic expectations of instantaneous suppression and smooth decrease in HRR after system activation are never met in the highly turbulent tunnel fires. First, it takes some time for the system to get the fire under control and second, smooth HRR behaviour can be expected only with exposed, simple fuel packages. Tarpaulins, fuel tanks etc. with unforeseen effects on the fire development ruin the smooth behaviour. Good qualitative understanding is needed in analyzing any full-scale fire test results. Comparing just pre-determined numbers obscures completely the true benefits of the system performance: without any insight one could conclude from Table 2 that both systems failed and that the two tests went equally well or bad: both passed three criteria and failed one. And yet, in both cases the systems would have prevented catastrophic consequences in a real tunnel fire.
REFERENCES LIST


Road Tunnel Protection by water mist systems – Implementation of full scale fire test results into a real project

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ABSTRACT

Truck fires in a tunnel can create heat release rates (HRR) significantly higher than 100 MW. Because of a fast spread of smoke and heat the self-rescuing period is shortened significantly. Furthermore it was experienced that fire fighters are not able to approach the fire because of enormous heat and radiation. As consequence, the fire may spread to adjacent vehicles, which is reported for distances of more than 50 m. Tunnels can be damaged severely by fires and the repair works causing in long closing time of tunnels. In addition to direct costs for the refurbishment of the tunnel, further economic losses will occur due to the closure time.

Conventional deluge systems in Japanese and Australian road tunnels are known since the 1960s. During the last years the research work was concentrated in the development of more effective and cost-effective solutions based on water mist technology. Orientating fire tests as well as specifications of minimum requirements were carried out within the European research project UPTUN.

This basic work was extended by the SOLIT research project, funded by the German government. Scope of SOLIT was not only to study the effects of water mist fire suppression systems in tunnels, but also the interactions with other safety systems, such as fire detection, passive fire protection or ventilation. Furthermore, the integration of active fire suppression systems into a holistic tunnel safety system was part of the work program.

Within this research project a large scale fire test program with more than 50 fire tests, including 25 truck fires with a potential HRR of almost 200 MW, was carried out in the test tunnel of San Pedro des Anes (Spain). Furthermore a two weeks testing and training period with the Madrid Fire Brigade was carried out after the SOLIT program.

Two fundamental results were achieved during the fire tests:
Primarily, water mist systems are able to control the HRR of fires in tunnels, so the atmosphere will be improved significantly. Hazardous effects of toxic smoke on people will be reduced and due to the reduction of temperatures and radiation, a fire fighters approach is improved significantly. Furthermore, the fire spread will be hampered and the thermal load on the building structure is also reduced.
Secondarily, due to positive interactions with the ventilation system, the effectiveness of a tunnel ventilation system, longitudinal as well as semi-transversal, is increased significantly.

Based on the results of the SOLIT research project, a water mist system was applied into several parts of the M30 tunnels in Madrid. As a basic principle the technical equipment and the methodology of implementation comply with the UPTUN 251 guidance, recommending minimum standards for water based fire suppression systems in tunnels.

KEYWORDS: water mist systems, tunnel fire, solit research project, M30 Madrid
ACTIVE FIRE SUPPRESSION SYSTEMS IN TUNNELS

The catastrophic effects of fires in tunnel are well known for a long time. It has been shown, that effects of such fires on people inside the tunnel, rescue services and the tunnel structure can be hazardous.

Experience has shown that fires larger than approximately 10 MW, which corresponds to only two cars, possibilities for a fast and safe self-rescuing are reduced dramatically due to the rapid spread of heat and smoke. Due to temperatures above 1000°C in the vicinity of the fire and radiant heat, it is almost impossible for firemen to approach the place for fast and effective fire fighting.

As it also has been shown in the past, smoke and heat can cause enormous damage on the tunnel structure and operational equipment. Beside direct repair cost of these damages, further economic loss occurs due to closure times of major road connections. A study by the International Road Transport Union showed that the direct costs of fire in tunnels are assumed to be approx. 200 Mio. € per year. Further 300 – 450 Mio. € occur because of closure of these tunnels. [1]

Water Mist Systems for Tunnels

Fire suppression systems for tunnels are known since the 1960s. More than 40 tunnels in Japan and Australia are equipped with active fire suppression systems using conventional spray water technology. The main focus of these systems is building protection, although it is under consideration to activate these systems as early as possible for enhancing self-rescuing conditionings.

These systems have shown their effectiveness, also recently, in several smaller fire incidents. However, there is still a lack of knowledge of the effectiveness of such systems with fires containing trucks, e.g. used in the UPTUN fire tests in the Runehamar-Tunnel. A significant disadvantage of these systems is the huge amount of water which is necessary for effective fire suppression. To activate a 90 m section of a common two lane road tunnel, approx. 6 000 – 10 000 l/min are necessary. This also results in large space requirements for Pipes, fittings as well as water storage. Also drainage systems have to be sized for this amount of water. [2]

Already during the European research project UPTUN further work was carried out to improve effectiveness as well as economic aspects of such systems in tunnels by using water mist technology.

Main effects of fire suppression by water mist is the enormous cooling effect and a partly depletion of oxygen in the flame zone by small droplets. The effective cooling of water mist is a result of a very fast heat absorption by the large surface and a vaporization of fine droplets. By using conventional systems the water is just heated up and runs off without further effect on the fire. Because of the volume expansion during the vaporization, the oxygen is partly depleted directly at the flame. As result, water mist can also be used for fighting fires, such as burning liquids, where conventional systems are not effective or additives are necessary. Furthermore, the amount of water needed for effective fire fighting is reduced up to a factor of 10.

Furthermore water mist has a great shielding effect against radiant heat. Especially this effect helps fire fighters to approach close enough to the seat of the fire for faster and easier fire fighting.

The effectiveness of water mist systems was evaluated during two extensive real scale fire test programs in the Norwegian Hobol-tunnel and the Virgolo-tunnel of the Brenner Highway, a major alp crossing. Details regarding these test programs can be found at [3] and [4].

Guidelines and Recommendations

Since the PIARC report “Fire and Smoke Control in Road Tunnels” from 1996 [5], which did not recommend active fire suppression systems in tunnels, extensive research work has been carried out by various parties. Nowadays, the positive effects, possibilities and requirements for active fire
suppression systems in tunnels are known. This also reflects in various up to date Guidelines and Recommendations dealing with the topic fire safety in tunnels. The NFPA 502:2008 now recommends active fire suppression for tunnels under certain circumstances. According to the 2007 issue of “Systems and Equipment for Fire and Smoke Control in Road Tunnels” also PIARC has revised its view. [6]

The most important document is the UPTUN guidance 251 prepared by a group of experts within the UPTUN research project. This document specifies minimum requirements for water based fire suppression systems in sub-surfaces areas, such a technical issues, full scale testing and general layout of systems. [7]

Following statements can be found in these latest documents:

- The decision whether the tunnel shall be protected by an active fire suppression system should be based on a risk analysis.
- Full scale fire tests should be used to evaluate the effectiveness for the specific system and only deluge system types should be uses. Hence, the activation and choice of the zone to be activated is based on an external fire detection system, such as linear heat detection or CCTV systems.
- Special attention should be given to the choice of the components. Reliability and life-cycle-cost aspects should be taken into account, in particular in the design of pipes, valves and pump systems.

THE SOLIT RESEARCH PROJECT

The current change of views in the field of tunnel fire safety experts and in guidelines is also based on knew knowledge of various research work in the field of active fire suppression in tunnels. Probably the largest research project in this area is the SOLIT (Safety of Life in Tunnels) project, which was carried out on behalf of the German government.

Based on the results of the UPTUN project, the effects of water mist fire suppression systems integrated into a holistic safety concept were examined on realistic fire loads, such as truck fires.

The SOLIT consortium was supported by a scientific advisory board with experts from STUVA, TNO, Sintef, German ministries, fire brigades and tunnel operators. Further information about the SOLIT project can be found at www.solit.info.

Fire Test Program

A major part of the SOLIT research project was an extensive test program with more than 50 full scale fire tests. The aim was to study a with mist system regarding:

- Fire control and reduction of fire spread
- Improvement self-rescuing conditions for people inside the tunnels
- Possibilities of fire fighters approach to the fire
- Protection of the building structure.

Furthermore, interactions of water mist systems with other safety systems, in particular ventilation and fire detection were investigated.

In close cooperation with the SOLIT scientific advisory board, following fire scenarios were developed:
Pool fires

Pool fires, with a partly covered surface, creating a heat release rate (HRR) of up to 35 MW were used. This fire scenario is a further development of the one which was already used in the Hobøl- and Virgolo-fire tests. By using this fire scenario the influence of various system parameters of water mist systems as well as interactions with other systems, e.g. ventilation were studied.

Solid truck fire load

The SOLIT class A fire load represents a test mock up of a common truck made by pallets. Figure 1 shows the test mock up shortly after ignition.

Figure 1: SOLIT A fire load shortly after ignition

A similar scenario was already used during the fire test in the Runehamar-tunnel. However, during these tests only free burning fires were investigated, so the data can also be used as reference. By using this data as well as own calculations showed a potential fire load of 180 MW. A potential fire load is known as maximum HRR of a free burning fire using this fire scenario. (Ingason et al, 2003)

Due to temperature restrictions of the test tunnel, no free burning reference tests were carried out. To avoid non-repeatable test results, for conduction of scientific fire tests, standard fire loads are used instead of real trucks and cars. The standard fire loads used in these tests are representing the worst-case approach, which means that the fire potential of this scenario is usually bigger compared to a real truck.

During a period of 3 months more than 50 full scale fire tests were carried out in the Spanish test tunnel of “San Pedro des Anes”. This tunnel has a length of 600 m and represents a common 2 lane tunnel. The existing infrastructure in this tunnel allows carrying out tests with longitudinal as well as semi-transversal ventilation.

For evaluation of test results, approx. 120 different sensors for temperatures, ventilation velocities, gas concentrations and radiation were installed throughout the tunnel. On the one hand this enables the assessment of exposure for people, fire men and the building, on the other hand a calculation of the HRR by using the oxygen consumption methodology.
Results
In the following, major results of the SOLIT test campaign are summarized:

Fire control and fire spread

Based on information of an external fire detection system, the water mist system is activated as early as possible. Thus, the fire development is reduced significantly and the maximum fire size is much smaller in comparison with a free burning fire. Fig. 2 shows the trend of the HRR during activation of a water mist system compared to a similar free burning fire. The effect that the fire is still growing although the system is activated is caused by the tarpaulin which still covers the fire load in the beginning.

For fire tests, fire spread to adjacent objects is assessed by the use of target objects. During the tests with activation of the water mist system, no fire spread to a target, located 5 m downstream of the fire load, was observed. Compared to a real case such as the fire in the St-Gotthard-tunnel and for the Runehamar-fire tests a fire spread over distances of more than 50 m were reported. [8]

As the fire size is limited and reduced significantly compared to a free burning fire also other safety systems can be adjusted accordingly.

![Abbildung 2: Comparison of fire tests with a water mist system and a reference fire](image)

Self-rescuing of people

Great importance is attached to the self-rescuing period, as in most cases rescue services need some time to get inside the tunnel. Great danger for people is caused by toxic gases, which are spreading throughout the tunnel within a very short time.

In addition to the cooling (see Fig. 3) and shielding of the radiant heat, the smoke production is also reduced due to early activation of the water mist system. Furthermore, because of the cooling effect and the limitation of the HRR the effectiveness of the ventilation system is increased. In contradiction to former opinions, a smoke layer is not destroyed completely. Because of temperature differences that still exist in the tunnel cross section a layering of toxic gases can still be observed after activation of the water mist system.
Fire fighters approach

In the past, due to high temperatures and great radiation, fire men had extreme difficulties approaching the place of fire. From the St-Gotthard-tunnel fire it is reported, that at arrival of the fire brigade only few minutes after the start of the fire, a fighting was impossible due to heat and radiation.
Because of the cooling and shielding effect of the water mist, it was possible to approach the fire (see Fig. 4) the SOLIT fire scenarios at maximum fire development and to extinguish them within minutes without problem. An exposure of fire men by hot water vapour was not reported in any case. This was again proven in a special two weeks training and test campaign with the Madrid fire brigade also using other real fire loads like cars, tyres, etc.

**Effects on the building structure**

Upon today, fires in tunnels caused massive damages on the tunnel and on operation facilities inside. In general, by activating a water mist system damages can not be avoided completely. But, with early activation of such system, damages can be reduced significantly and are limited to a few metres. Thus, not only cost for repair works are reduced, but also closing times can be reduced to a minimum.

A more extended report about water mist systems in tunnels and the SOLIT fire tests can be found in the official report of the SOLIT project. [9]

**CASE STUDY: WATER MIST SYSTEM IN THE M30 TUNNELS (MADRID)**

The M30 motor way around Madrid was refurbished and extended during the last years. It is probably one of the largest tunnel building projects at the moment.

In special risk areas with a total length of approx. 5 km a high pressure water mist system was installed already during the construction phase of the tunnel. Based on a risk analysis, the water mist system is foreseen to control a possible fire and to protect the tunnel infrastructure, as well as improve working conditions for the fire brigade. Fig. 5 shows a spray test in one of the M30 tunnels.

As also requested by the UPTUN guidance 251, special additional approval fire test were carried out. These tests and the results of the SOLIT fire tests were the basis for the system layout used for the M30 tunnels.

Also for the technical implementation, the current UPTUN recommendations were taken into account. For example, the positions of nozzles, particularly the height above the road surface, fully comply with the parameters that were tested in the 1:1 scale fire tests.

Only open nozzles are installed, which means that in case of a fire, it will be detected and localized by an external linear heat sensor. This information will be used to open the section valves of the water mist system, so it can be activated in the correct area in the most effective way. In addition to a central control unit in the tunnel control room, the fire suppression system can be controlled by the fire brigade also via local units located in safe areas in the escape ways.

To ensure a long life time and a high reliability of the system, all pipe work installations in the tunnel are made of stainless steel. To avoid damages on the water mist system, which may also lead to a complete failure of the system, all pipes and components are installed at the tunnel ceiling. Regular maintenance and function control of the section valves are carried out automatically by the main control unit.

The pump stations are equipped with special robust high flow rate pump units. By a small number of big pumps, reliability is improved significantly as the total number and the complexity of the components are reduced.
CONCLUSION
By means of fire test with the scale 1:1 and experiences from existing installations it has been shown, that provisions against water mist fire suppression systems, e.g. stated by PIARC, can be refuted by latest research results. In fact, applying a suitable combination of water mist systems with other safety systems, costs for the total tunnel safety system can be reduced and the safety level can be improved. As a general rule, the effectiveness of such system must be proven with real scale fire tests.

Experience for the technical implementation of such systems in real tunnels is gained with systems, e.g. in the Italian Virgolo-tunnel or the M30-tunnels in Madrid. Basic recommendations for planning and installations are given by the UPTUN document 251.

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Assessment of Fixed Fire-Fighting Systems for Road Tunnels by Experiments at Intermediate Scale

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ABSTRACT

Water based fixed fire suppression systems are among the systems that may improve user safety in road tunnels. To properly assess the safety level those systems can lead to, CETU undertook an integrated study to help defining the objectives of fixed fire-fighting systems (FFFS) and to model the effects of those systems on a tunnel fire in a crude way as first approach. To gain better insight into the modelling of FFFS effects on a tunnel fire, an additional study program based on both a theoretical CFD-oriented analysis and intermediate-scale experiments (scaling factor around 30%) has been launched in cooperation with CSTB and CNRS (Poitiers University). Preliminary results of heptane pool fire tests are presented.

KEYWORDS: water mist system, intermediate-scale experiments, 1D modelling, cost analysis.

INTRODUCTION

Fixed fire-fighting systems (FFFS in the following) based on water as the extinguishing agent, are often mentioned as safety improvements for road tunnels. French tunnels are not equipped with such systems except one under construction [1]. In case of a fire, the mechanical ventilation is designed to provide a safe evacuation route to tunnel users to reach emergency exits. In some cases, the ventilation system may be either overwhelmed by the smoke production or unsafe to use because it would endanger some tunnel users (e.g. longitudinal ventilation in a two-way tunnel). For these cases, it could be worth assessing if, whether or not, FFFS can improve the safety level.

Therefore, CETU (French Study Centre on Tunnels) in association with DDSC (French Security and Safety Authority) conducted a joint study on FFFS, also aimed at reconsidering the PIARC position [2] that expressed concerns about the use of FFFS in tunnels. The first stage was focused on identifying fire scenarios for which FFFS may be relevant, and defining the main objectives of a FFFS activation. In a second stage, a case study on two-way tunnels was performed. It was divided into an economic and technological feasibility study and a crude safety levels assessment. Roughly known phenomena were also pointed out. To address those open questions about FFFS use in tunnels, an additional research stage was derived, based on both CFD-oriented analysis and intermediate-scale experiments.

The experimental part of this additional research program is aimed at outlining the major phenomena acting on FFFS efficiency, validating measurement techniques in air/water droplets flow for prospective full-scale experiments, and providing reliable input data for CFD modelling. This experimental program is part of a research cooperation CETU, CSTB and CNRS (Poitiers University).

SCENARIO IDENTIFICATION FOR FFFS USE

To better frame the use of FFFS in road tunnels, a scenario analysis, inspired from the specific hazard
investigations that have to be performed for all French tunnels longer than 300 m, was carried out. This analysis was conducted as a two-step study by: i) identifying tunnel fire scenarios for which FFFS may provide an improvement in safety levels, ii) outlining the objectives of a FFFS activation [3].

**Defining critical scenarios**

To define relevant tunnel configurations and fire scenarios, indexing criteria have been set up. These criteria can be classified into four categories relative to: the tunnel itself (kind, operation mode), the ventilation system (longitudinal/transverse, airflow control), the traffic conditions and the fire Heat Release Rate (HRR). However, combining all these criteria leads to 144 different scenarios that would be studied in details. An other way to define critical configurations is to keep with smoke extraction strategies. Basically there are three main strategies for smoke extraction in tunnel, depending only on the tunnel kind, the ventilation system and the traffic conditions downstream of the fire. Figure 1 shows the distribution of French tunnels in terms of tunnel kind and ventilation.

![Figure 1 Distribution of French tunnel regarding tunnel kind and ventilation](image)

The first strategy is when smoke extraction does not rely on stratification. This is the case for a one-way tunnel with longitudinal ventilation and in a no traffic congestion situation (no users trapped downstream of the fire). Without the activation of a FFFS, the safety level of such configuration is good as far as tunnel users safety is concerned, even if the HRR is greater than the design fire. The expected benefits from a FFFS in this configuration are to ease firemen extinguishing action and to protect the tunnel structure. From a user safety viewpoint, a FFFS has little benefits and even drawbacks because it could lead to poor visibility conditions upstream of the fire (area free of smoke in this case).

The second smoke extraction strategy is based on an expected stratification. This is the case for a two-way tunnel or a one-way tunnel with traffic congestion, both with longitudinal ventilation. The resulting safety level without a FFFS can be considered as fair but depends on smoke stratification that is not guaranteed in general because of the lack of means to control the longitudinal airflow in the vicinity of the fire. Because in this case the FFFS activation leads to a loss of stratification and poor visibility conditions, the benefits of the FFFS in terms of self-rescue conditions and firemen extinguishing action tightly depends on the activation scenario. Moreover, a different ventilation scenario could be used with the FFFS activated, like increasing the airflow regime to dilute toxic gases for instance. Thus this case raises issues that have to be addressed in a dedicated risk analysis.

The third strategy relies on stratification with means to maintain it at least for a self-rescue period. This strategy is used in two-way tunnels with transverse or semi-transverse ventilation. The safety level without a FFFS can be expected to be good unless the fire HRR is greater than design or if the pressure difference at the portals is out of the range of the airflow control system and thus stratification cannot be preserved. In this case too, the loss of stratification due to the FFFS activation may be a major shortcoming.
FFFS objectives and activation issues

As stated previously, an analytical method was derived in [3] in order to outline the main objectives of FFFS activation from a user safety viewpoint. They can be summarized as follow, in chronological order:

• First, to improve the user self-rescue time
• Second, to extend the time during which users who did not escape can be rescued by fire brigade
• Third, to ease firemen extinguishing action
• Forth, to protect the tunnel infrastructure

To achieve these objectives, FFFS activation should avoid disturbing rather favourable evacuation conditions that may exist at the beginning of a fire (e.g. smoke stratification conditions in transverse ventilation).

In terms of activation issues, the critical configurations are the ones based on a two-way tunnel. In this particular case, installing and activating a FFFS raise additional questions that have to be part of a specific safety assessment:

• interaction between a FFFS and the others safety equipments like mechanical ventilation
• effects of a FFFS on self-rescue conditions
• resulting safety level of a tunnel equipped with a FFFS compared to transverse ventilation
• installation and maintenance costs of a FFFS

Part of these issues – especially the last two – were tackle in a specific case study conducted by CETU in cooperation with BG Consulting Engineers.

CASE STUDY ON TWO-WAY TUNNELS

The case study, performed on a particular configuration of two-way tunnel, was divided into three steps. In the first one, a feasibility study, both economic and technical, was performed. The second one aimed at assessing at least in a crude way the safety levels a FFFS can lead to in a two-way tunnel with longitudinal ventilation. The last one was about roughly known phenomena.

In all this case study it was decided to focus the analysis on a 1500m-long old two-way tunnel with no slope in a non-urban environment with typical traffic of 2500 vehicles/day/direction. It was also assumed that HGVs are authorized but dangerous goods. Both ventilation systems were addressed for the sake of completeness. The monitoring level is assumed to be ensured permanently with a CCTV system. For the other safety components, the tunnel is supposed to comply with current French regulations.

Economic and technical feasibility study

To gain a better insight into the available technologies and to design a realistic FFFS installation, CETU and BG Consulting Engineers canvassed FFFS manufacturers for quite detailed proposals given the tunnel configuration and expected fire loads. A detailed analysis of those proposals can be found in [4]. From this analysis it seems that water mist deluge-type systems are the most suitable systems for tunnels especially regarding water consumption (or application rate) and total spraying length. Therefore, a typical water based FFFS for our 1500m-long two-way tunnel, based on a deluge-type water mist system (Class 1 spray) with a total spraying length of 100m and an application rate of 0.7 l/min/m³, was selected for further analysis.

The economic feasibility study was performed through an installation and maintenance costs analysis. The underlying aim of this cost analysis is to compare the cost of transverse ventilation upgrade to FFFS installation in an old two-way tunnel. Relative investment costs were used without accounting for the boring cost. For old two-way tunnels, four configurations were priced with a precision in the range of 20 %: longitudinal ventilation, longitudinal ventilation with FFFS, transverse ventilation and transverse ventilation with FFFS. For the sake of completeness, it was also decided to include in the
study the same configurations but for a new tunnel built with nowadays standards.

The installation cost for a FFFS only in the typical tunnel configuration can be derived from manufacturers proposals and is around 2.7 million Euro. This is to be compared with the cost of an upgrade of the tunnel to transverse ventilation which is 17.7 million Euro for an old tunnel. The upgrade cost is so high because of the over-excavation needed to accommodate the ventilation ducts. Moreover, for a new tunnel the ratio between longitudinal ventilation with FFFS and transverse ventilation is almost double (4.2 M€ for the former and 8.8 M€ for the latter).

The maintenance costs per year were estimated using a fixed percentage of the investment cost, depending on the kind of equipment, following the method suggested by FEDRO (Swiss Federal Road Authority). These costs do not include running costs such as electricity, manning, etc. An averaged maintenance cost for longitudinal ventilation with FFFS is about 95000 Euro per year, whereas for transverse ventilation only it is almost 145000 Euro per year. An overview of typical maintenance efforts can be found in [4].

Safety levels assessment

The main issue raised by FFFS installation, besides the cost that is in favour of installing a FFFS coupled with longitudinal ventilation rather than transverse ventilation, is the safety levels that can be reached with such systems in agreement with the objectives previously outlined. To assess this peculiar point it is necessary to model the effects of FFFS at least in a crude way, and run this model for different fire scenarios.

The analysis is conducted using a specific model for the fire zone coupled with a 1D model for humid air propagation, which results are coherent with measurements collected during recent full-scale fire tests involving FFFS [1]. The choice of a 1D model is justified by the widespread and convenient use of 1D models for simplified assessments. This coupled model allows calculation of the ambient conditions in the tunnel (temperature, heat flux, humidity, opacity, concentration of O₂, CO and CO₂) with and without activation of a FFFS. To express the computed ambient condition in terms of tenability limits, the “Time to Incapacitation” method [5] is applied for each of the above-mentioned factors. This method allows an easy way to compare the extension of dangerous zones in the tunnel, with and without FFFS. Detailed modelling is available in [6].

The results of this analysis are discussed in details in [6, 7]. The effects of a FFFS are clear as far as heat and toxic gases tenability are concerned. The activation leads to a major reduction of the length of dangerous zones, leaving just the vicinity of the fire as untenable. But the main drawback of the activation of a FFFS lies in the visibility distance that is shortened, whereas in transverse ventilation, smoke stratification can manage to preserve zones with higher visibility distance.

Roughly known phenomena and further studies

The model presented previously computes the effects of a FFFS on a tunnel fire in a crude way. Many assumptions have been made to provide a first assessment of FFFS in a two-way tunnel with longitudinal ventilation. The use of a 1D model for the smoke flow is one of the main shortcomings of the present study. Therefore, extra modelling and validation are required. In particular, some knowledge is needed about the influence of the following phenomena on the overall efficiency of the system:

- Interaction with the fire source: HRR reduction due to water discharged in the fire, toxic gases production (combustion regime), fire spreading
- Interaction with the smoke layer: visibility conditions in the spraying zone, influence on smoke stratification
- Definition of design rules: optimum FFFS parameters (droplet size, application rate, nozzles
To gain better insight into those phenomena, an additional study program based on both a theoretical CFD-oriented analysis and intermediate-scale experiments is under realization. The experimental part of this additional study program is aimed at outlining the major phenomena acting on FFFS efficiency, validating measurement techniques in humid air for prospective full-scale experiments, and providing reliable input data for CFD modelling. This experimental program is part of a research cooperation between CETU, CSTB (Research and Evaluation Centre on Buildings) and the Combustion and Detonic Laboratory (LCD) of Poitiers University, with the industrial partnership of Fogtec and Rodio for the FFFS.

EXPERIMENTAL PROGRAM AT INTERMEDIATE-SCALE

Objectives

This research project aims at improving the degree of understanding of the phenomena implied by a FFFS activation in tunnel. To install a FFFS in a given tunnel, the present state of the art implies to perform full-scale fire tests to assess the optimum parameters of the FFFS and the efficiency in case of a fire. However, due to the high costs of full-scale fire tests, it may be interesting to perform intermediate-scale experiments that are very cost-efficient. Actually, with such experiments, three main objectives can be achieved:

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

Test tunnel

The experimental program is being conducted in a test tunnel at scale around 30\% depending on the real tunnel geometry represented. The tunnel is 43 m long, with an hydraulic diameter of 2.17 m and a cross-section of 4 m² (see fig. 2). The tunnel is connected to a fan that can provide a longitudinal velocity up to 5 m/s – corresponding to 9 m/s in a tunnel at scale 1 with a scaling factor of 30\%.

![View of the test tunnel](image1)

(a) View of the test tunnel

![Cross-section view](image2)

(b) Cross-section view

Figure 2 Experimental installation.

Test program

In this research program, a high pressure water mist system is tested as a first step. In the following steps, we plan to test others FFFS as low pressure systems for instance.

During this first stage, 26 fire tests are conducted. Three different fire sources are used: heptane pool, wood cribs and wood pallets. Their sizing is made assuming a full-scale HRR of 30 MW and applying
Froude scaling laws. Tests with covered fire sources (heptane pool and wood pallets) are planned to assess the FFFS efficiency when there is no direct impact of the spray on the fire. For each fire source, tests at different longitudinal air velocity are performed: 1 m/s for stratification issues (under critical velocity) and 2.2 m/s corresponding to 4 m/s in full scale.

Measurement points

Figure 3 Sketch of the measurement sections inside the test gallery

Figure 3 gives an overview of the measurement points inside the tunnel. More than 200 measurement points were installed, including:

- Air velocity: 24 velocity measurement points are installed in two sections: one section at 5 meters upstream from the fire and one section at 18 meters downstream from the fire.
- Temperatures: 52 thermocouples are implanted in six measurement sections. In addition, 8 special thermocouples, protected from water droplets impact, are installed. The values provided by these specific thermocouples are compared with the values obtained from non-protected thermocouples.
- Radiative heat flux: 6 fluxmeters are located in a section 7 m upstream from the fire and 6 others fluxmeters are located in a section 7 m downstream from the fire.
- Opacity measurements: 3 sections of opacity measurement are installed in the tunnel: an innovative laser-beam system developed by CNRS, located 13 m downstream from the fire, usual tunnel sensors based on scattered light principles, located 22 m downstream from the fire and sensors based on light extinction principles, located 23 m downstream from the fire.
- CO/CO₂ concentration point measurements: to assess the tenability conditions, regarding toxic gases, of tunnel users, two point measurements are located at 0.5 and 1.5 m high, 23 m downstream of the fire. The aim is to represent in full-scale, the effects of toxic gases on tunnel users trapped downstream of the fire.

Concerning the HRR which is a very crucial measurement for assessing the efficiency of the water mist system on the fire, two different methods are used. The first one is based on the measurement of the loss of mass of the fire source, whether it is an heptane pool, a wood crib or a wood pallet. A correction accounting for non-complete combustion is applied. The second method is based on the oxygen consumption technique [8]. Downstream of the fire, measurements of the volume flow rate and the concentrations of O₂, CO and CO₂ are performed in this purpose. Comparison of both techniques for a reference test is given in Fig. 4. The difference between the two is quite small and validate the use of the correction on the mass loss signal. The gap between these two curves and the non-corrected mass loss measurement needs further analysis.
Water mist system

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

PRELIMINARY ANALYSIS OF HEPTANE TESTS RESULTS

At this time, 10 fire tests out of 26 have been conducted. They only include fire tests with an heptane pool. Among them, 4 reference tests and 6 tests with FFFS activation have been performed. In this section, only a qualitative overview of the results is given. More data analysis is required to get better insight into the phenomena that are taking place.

Influence on temperature and radiative heat flux

As far as temperature and radiative heat flux are concerned, the influence of a FFFS activation is quite clear (see Figs. 5 to 7). The water droplets absorb the radiative heat flux (Fig. 7) and thus lead to a decrease in temperature upstream and downstream of the fire.

Figures 5 and 6 show the evolution of temperatures on the centreline at different heights, 4 m and 18 m downstream of the fire. Both figures are made with data from a fire test with longitudinal ventilation of 1 m/s. In this case and before activation of the FFFS, there is a clear stratification of the smoke layer (outlined in Figs. 5 and 6) and a backlayering develops upstream. Right after the activation, there is a decrease in temperature levels but also an important mixing in the whole cross-section. Temperatures are in average around 40 °C after discharge. From a user tenability standpoint this mixing has to be accounted for, especially because of its steam saturation level.
Figure 5  Temperatures evolution on the tunnel centreline 4 m downstream of the fire and at different heights (longitudinal ventilation of 1 m/s).

Figure 6  Temperatures evolution on the tunnel centreline 18 m downstream of the fire at different heights (longitudinal ventilation of 1 m/s).
Radiative heat flux evolution on the tunnel centreline 7 m downstream of the fire at different heights (longitudinal ventilation of 1 m/s).

HRR reduction

In the case of an opened heptane pool fire, figure 8 shows that the HRR is reduced by a large amount when activating the FFFS. An other test performed with the same initial conditions in terms of longitudinal ventilation and fire source reproduces the same trend in the HRR evolution (see Fig. 8, curves with symbols). This phenomenon needs to be studied in depth using data from covered heptane pool fire tests and wood pallets ones.

Visibility

From a tunnel user point of view, visibility is a key concern as it can determine the ability of a user to locate the emergency exists and to evacuate. As a result, three different devices measuring visibility (or opacity) were installed in the test tunnel. Figure 9 outlines the influence of a FFFS activation on visibility as recorded by the two transmissiometers located 23 m downstream. On this figure, the
results from two fire tests with similar initial conditions are represented to enforce the quite fair agreement in measurements.

In these fire tests, the longitudinal ventilation was set at 1 m/s and led to smoke stratification downstream. The two transmissiometers clearly show this trend on figure 9 with a higher relative light extinction for the ones located 1.5 m above ground, and almost no light extinction at 0.5 m high.

However, when the FFFS is discharged, there is a large increase of light extinction at 0.5 m, and only a limited one at 1.5 m. The FFFS activation leads to a general mixing of the smoke layer and a loss in stratification. The fact that the visibility is worse close to the ground than at the ceiling is not easy to understand. It may be induced by a larger droplet density close to the ground which increase the scattering. Therefore, for this area, transmissiometers may be less reliable than sensors based on scattered light principles. Further data processing of the scattered light sensors installed in the test tunnel is needed to better understand this phenomenon.

![Figure 9: Initial visibility fraction evolution for two fire tests with similar initial conditions.](image)

**CONCLUSION**

This paper gives an overview of the research program conducted by CETU to assess FFFS for road tunnels. Scenarios for which FFFS may be relevant and objectives of FFFS activation were first established as part of a global approach of tunnel users safety. This first approach was took one step further by cost and safety levels detailed assessments for two-way tunnels where the main goal was to compare both in terms of cost and safety level transverse ventilation to longitudinal ventilation with FFFS. A research methodology is proposed to gain better insight into FFFS effects related unresolved questions.

The intermediate-scale experiments currently under realization, give some interesting preliminary results concerning the impact of a FFFS on temperatures and radiative heat flux. In both cases, for an opened heptane pool fire, there is an important decrease mainly due to radiation absorption by water droplets. However, concerning opacity further data processing is needed to provide a quantitative overview of FFFS influence. Transmissiometers seem to give a quite robust trend on visibility conditions downstream of the fire and point out a loss in stratification after activation of the system.

Experiments with wood cribs and wood pallets, as well as a theoretical CFD-oriented study based on experimental results are currently performed.
ACKNOWLEDGEMENTS

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Fire suppression and structure protection for cargo train tunnels: Macadam and HotFoam®

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b) Svenska Skum AB, Tyco Fire Suppression & Building Products, Kungälv, Sweden

ABSTRACT
The increasing heavy goods transports and potential of transporting goods on rail has put the focus on the fire safety of rail tunnels for cargo trains. In the paper two different aspects of fire behaviour and fire safety in cargo rail tunnels are presented: the effect of the use of macadam on the burning rate of liquid fuels and the possibility of extinguishing simulated cargo trains with foam systems. Two different tests series were performed. One test series with different depth of liquid fuel (heptane and diesel) in a pool with macadam showed that the macadam had a significant influence on the burning rate of the fuel. In a second test series a High Expansion foam system (HotFoam®) was tested in tunnel fire scenarios. Four different principle fire test scenarios were used in the test series in the tunnel section built in the fire hall of SP Fire Technology: hidden fire inside a locomotive mock-up, wood pallets placed on a simulated goods wagon, pool fire placed on a simulated goods wagon, and pool fire placed under a simulated goods wagon. Different types of fuels were used: diesel, heptane, E-85, acetone, and wood pallets. The Svenska Skum HotFoam fire extinguishing system was started with a pre-defined delay after alarm from the installed detection system and was able to extinguish all reported scenarios. Easiest to extinguish (shortest time between foam production and extinguishment) were the heptane fires, both on and below the simulated goods wagon. Most difficult to extinguish (with the same nominal filling rate of foam) was Test 7 with E-85.

KEYWORDS: HotFoam, macadam, tunnel fire, burning rate; extinguishment; foam; rail tunnel, Svenska Skum, Tyco

INTRODUCTION
The importance of the possible involvement of cargo on heavy goods vehicles for the outcome of fires in tunnels has been discussed before [1, 2]. A number of road tunnels fires have occurred throughout Europe with catastrophic outcome. These include the fires in the Mont Blanc tunnel in France/Italy with 39 deaths (1999), in the Tauern tunnel in Austria with 12 deaths (1999) and in the St. Gotthard tunnel in Switzerland with 11 deaths (2001). In all these fires, the cargo in Heavy Goods Vehicle (HGV) trailers played a major role in the outcome. The main reason being that the trailers contain a very high fire load and the fire could easily spread within the cargo and further to adjacent vehicles due to the tunnel ventilation and the wide spreading flames created. The heat release rates (HRR) in many tunnel catastrophes are estimated to be in the order of 300 MW to 400 MW [3], which explains why the rescue services had great difficulty in reaching the fire. Further, the enormous heat, together with the rapid development of both fire and smoke made it difficult for people inside the tunnel to escape. The problem arising when HGV cargoes are involved in a fire was further emphasized during the fire in the I-5 tunnel fire in Santa Clarita, CA, USA on October 12 2007. Despite the short length of the tunnel (168 m, 550 ft), around 30 HGVs were involved in the fire.

It is expected that the heavy good transport on roads and through road tunnels 2010 will have
increased by 40% to 60% (2000 comparison). Interest in transporting goods by rail seems to have increased. The fire in the Fréjus tunnel on June 4, 2005 again put the spotlight on traffic crossing the Alps and that fire prompted the EU to suggest a transfer of at least part of the road freight traffic to railways as one solution [4], creating the potential for a significant increase of the fire risk, to the railways. In recent years numerous fires in freight trains in tunnels have occurred. Examples are the Summit fire in UK 1984, the Eurotunnel UK-France in 1996, the Exilles Tunnel in Italy 1997, the Leinebusch tunnel in Germany 1999 and the Baltimore Howard Street tunnel in USA 2001.

This paper presents and discusses two possible solutions to reduce the effects of a fire in a freight rail tunnel.

**MACADAM**

The aim of the work has been to assess the effect of macadam on the heat release rate of pool fires. Reasons include whether there is an effect of the surface when a flammable liquid is released from a train in a rail tunnel with macadam on the ground. Registering a noticeable effect could lead to important information on the design of fire tests, e.g. for extinguishing systems.

**Experimental set-up**

The fire tests were performed using a pool with an area of 3.1 m² (2 m diameter). The pool was placed beneath the industry calorimeter to measure the heat release rate (see Figure 1.). Macadam was included in the pool up to a height of 0.15 m. Railway macadam of Class I (washed; 32mm–64mm) was used. The total weight of the macadam used in each test was 670 kg. The bulk volume of the macadam was approximately half the free volume of the pool with the same height, i.e. half the amount of liquid could be used to reach the same height in the pool compared to the case without macadam in the pool.

Heptane was used as the main fuel and the volume and depth of fuel were varied. The main parameter varied was the depth of fuel in relation to the depth of macadam, i.e. the level of the upper surface of the fuel in relation to the upper layer of the macadam (see Table 1. for information on these parameter variations during the test series). To limit the time for each test, the fuel floated on a water volume in the pool. To study the influence of the fuel characteristics on the results, two test were performed with diesel oil.

To save time between the tests, the macadam was reused. The macadam was washed between each test even if the heptane is very volatile to ensure that there was no heptane left after the tests. The accumulated heat in the macadam caused the cleaning water to quickly evaporate. In this way the macadam was also cooled before the following test. Some of the tests were ended before the fuel was completely consumed. In the case of heptane, the fuel surface was raised by adding water to the pool. In that way all the heptane was then consumed. In the case with diesel (Test 7) the fire was extinguished, after which the remaining diesel was pumped out of the pool. Any remaining diesel on the macadam was burnt off by using an ignition alcohol. After this test the macadam was not used for any further test.
In Table 1 the test series is summarized. Test 2 is the reference test for Test 3 to Test 6, while Test 8 (with diesel oil) is the reference test for Test 7. Test 1 was a calibration test and is not included in this paper. The amount of fuel was selected to reach a certain depth of fuel, depending on type of fuel and on whether macadam was used or not. Note that the macadam surface was not even or well defined. This means that some pieces of macadam cut the fuel surface even in the tests where the fuel surface was supposed to be either in level with or higher than the macadam surface. An effective macadam level was approximated.

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Fuel</th>
<th>Amount of fuel (L)</th>
<th>Level of fuel surface (cm)</th>
<th>Depth of water (cm)</th>
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</thead>
<tbody>
<tr>
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<td>Free burning without macadam</td>
<td>Heptane</td>
<td>157</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>15 cm macadam</td>
<td>Heptane</td>
<td>78.5</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>15 cm macadam</td>
<td>Heptane</td>
<td>78.5</td>
<td>5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
</tr>
<tr>
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<td>Heptane</td>
<td>157</td>
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</table>

<sup>a</sup> No water was used at the start of the test.

**Results from the macadam tests**

In total seven tests are presented, five with heptane and two with diesel. For each fuel a free-burning test without macadam was performed, these were Test 2 for heptane and Test 8 for diesel.
Four tests were performed with macadam with heptane as fuel. The level of the upper fuel surface was varied (5 cm, 10 cm, 15, and 17.5 cm) while the upper level of the macadam was kept constant on 15 cm. That means that for two of the heptane tests the starting heptane level was below the macadam level, in one test the starting heptane level was the same as the macadam level, while in one test the heptane level started 2.5 cm above the macadam level. In Figure 2, the heat release rates for these four cases are compared to the free-burning case for heptane. Only the first 20 minutes are shown since that is the most interesting part of the tests.

As can be seen from the graphs in Figure 2, there is a significant difference in burning behaviour and heat release rate between the different cases. When the fuel level is lower than the macadam level, the burning rate drastically decreases.

The same trend is confirmed for diesel in Figure 3, where the test with a diesel level of 10 cm is compared to the free-burning case for diesel. Diesel with its lower free-burning rate compared to heptane, exhibits a much slower burning rate in the 10 cm case compared to heptane (see Figure 4).

![Figure 2](image)

**Figure 2** Comparison of heat release rate for test with heptane with the starting fuel surface at different heights. In all tests (except the free-burning test without macadam) the depth of macadam was 15 cm.
Figure 3  Comparison of heat release rate for test with diesel with and without macadam.

Figure 4  Comparison of heat release rate for test with heptane and diesel, respectively. In both tests the starting fuel surface was at the level 10 cm above the bottom of the pool.

The effect of the macadam is quantified in Table 2. The peak heat release rate (HRRmax) is given for each test. Since a fire is a variable process, it is interesting to study average values over certain time
periods. In the table, the maximum values of the arithmetic average over one minute and five minutes, respectively, are also presented. The one minute peak values are compared to the corresponding values for the free-burning tests. For the very slowly burning cases only the first 20 minutes have been included in the analysis. From the analyses it can be seen that the heat release rate for all cases with macadam are affected relative to the free-burning cases. When the upper fuel level is a distance below the upper macadam level there is a significant effect. This effect increases with the distance between the fuel surface and the upper level of macadam. This is shown graphically in Figure 5.

### Table 2 Peak heat release rates for the different cases.

<table>
<thead>
<tr>
<th>Test no</th>
<th>HRRmax (kW)</th>
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</tr>
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<td>282</td>
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</tr>
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<td>8b)</td>
<td>4500</td>
<td>4260</td>
<td>4130</td>
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</tr>
</tbody>
</table>

a) Only the first 20 minutes have been included in the analysis.
b) The final peak in the heat release rate in connection with extinguishment was excluded from the calculations.

**Figure 5** The quotient between the peak one minute average of the HRR for tests with macadam and a free-burning test without macadam, presented as function of the height difference between the level of macadam and the level of the upper surface of the liquid fuel.
TESTS WITH HOTFOAM®

The objective of the tests was to assess the ability of HotFoam as an extinguishment system inside a cargo trains tunnel. The HotFoam System is a high expansion foam configuration where the foam is produced inside the protected area with the produced combustion gases. HotFoam is an extinguishing system developed by Svenska Skum. This is used in industrial installation such as warehouses, production areas as well as in the Marine market for protection of engine and pump rooms.

Experimental set-up

The fire tests were performed inside SP’s main fire test hall. The test set-up consisted of a rectangular enclosure, 6 m × 18 m, with 6 m high walls, partly covered with a ceiling, simulating a tunnel section. The HotFoam system was installed according to Svenska SKUM instructions. Inside the tunnel section different fire scenarios were arranged.

The tunnel section test enclosure was constructed using wood studs and non-combustible, nominally 10 mm thick, wallboards (Promatect®). The ceiling was constructed of the same non-combustible wallboards mounted on a regular T-profile steel frame system. The ceiling area above the fire was insulated with 40 mm (2 × 20 mm) thick mineral wool insulation.

The enclosure measured 6 m × 16 m × 6 m (width × length × height) and was fitted with a 11 m long section of ceiling located centrally, i.e., the end of the tunnel section was blocked and the outer parts of the tunnel section had no ceiling allowing access of fresh air.

For access reasons, two openings were installed in the walls. The openings were fitted with doors that were sealed closed during the tests. In addition, the test enclosure was fitted with several windows for visual observation of the tests.

The main fire test hall is equipped with a ventilation system with air inlets at floor level and air exhaust near the top of the building. During the tests, the ventilation system was run at approximately 100 000 m³/h to 150 000 m³/h to keep the test hall free from the smoke.

The Svenska Skum HotFoam system consists of foam generators and foam concentrate. Depending on the mode of application, the system might also include detection. As the time to activation is critical for the system performance, the system was tested together with a detection system (Distributed Temperature System, DTS) from Agilent Technologies which could be used in tunnel protection applications. The HotFoam system was started a predefined time period (varied during the test series) after the alarm of the detection system (see Table 3).

The HotFoam foam generators (HG-15) used had a nominal liquid flow rate of 30 L/min at 6 bar giving 18 m³/min of foam with an expansion ratio of 600. In the tests presented here 12 foam generators were used.

As the tunnel section does not simulate a full scale tunnel, with additional foam generators away from the fire source, the outer foam generators in the test set-up were mounted in the part of the tunnel that had no ceiling, i.e. with some access to fresh air. It should be noted that the arrangement with the limited ceiling and tunnel length could influence the foam production compared to a test in a longer tunnel.

Four different principle fire test scenarios were used in the test series:

1. Hidden fire inside a locomotive mock-up (see Figure 7a).
2. Wood pallets placed on a simulated goods wagon (see Figure 7b).
3. Pool fire placed on a simulated goods wagon (see Figure 8a).
4. Pool fire placed under a simulated goods wagon (see Figure 8b).

Figure 6  Plan view of set-up and positions of thermocouples.

The locomotive mock-up was constructed from a 9 foot container, outer dimensions of 2.75 m × 2.25 m × 2.2 m, inner dimensions of 2.59 m × 2.15 m × 2 m (length×width×height). The container was fitted with openings simulating windows. The size of the openings was designed in order to obtain a free burning fire of approximately 8 MW. This corresponds to a 5-6 m² diesel pool fire which is the practical maximum size diesel fire inside the mock-up. With a larger fire size inside the mock-
up the heat release rate will be limited by the size of the openings. The nine foot container rested on steel legs 1 m above the ground, which means that the lower rim of the window openings was located 2 m above the ground. A simulated train wagon was located behind the locomotive mock-up, constructed from wood studs and non-combustible wallboards. The dimensions of the simulated train wagon were 4.8 m × 2.4 m × 3 m (length×width×height).

Two different sizes of fuel trays were used in the locomotive mock-up. The large fire tray was a 4.5 m² square steel tray and the small a circular 1.73 m² steel tray. In some tests, a diesel spray fire was used together with the large pool fire.

![Figure 7 Photos of a) the locomotive mock-up and b) wood pallets on the simulated goods wagon.](image)

The simulated goods wagon was constructed from a 4 mm thick steel plate measuring 2 m × 2 m. The steel plate rested on 1 m high steel legs. Standard EUR wood pallets with dimensions 1.2 m × 0.8 m × 0.144 m (length×width×height) were used. The pallets were stacked in piles consisting of 14 pallets each. Depending on test scenario, 2 or 4 piles were positioned on the simulated goods wagon.

In the tests with pool fire placed on or below the simulated goods wagon, the 4.5 m² square steel tray was used.

![Figure 8 Photos of test set-up with the pool fire a) on and b) under the simulated goods wagon.](image)
In Figure 9 a description of all tests is presented. The given approximate potential maximum HRR is estimated from experiences from previous test series. It should be noted that the estimated HRR is based on freely burning fire tests in open space, without any surrounding surfaces. During well ventilated conditions in an enclosure, the total HRR might be higher due to radiation from the hot gas layer and surfaces with high temperature.

### Table 3 Description of the test series.

<table>
<thead>
<tr>
<th>Test</th>
<th>Scenario description</th>
<th>Fuel</th>
<th>Size</th>
<th>Appr. Potential maximum HRR(^a)</th>
<th>Activation</th>
<th>Nominal filling rate (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hidden fire inside a locomotive mock-up.</td>
<td>Diesel</td>
<td>1.73 m(^2) pool</td>
<td>appr. 2.4 MW</td>
<td>Detection + 30 s</td>
<td>2.25</td>
</tr>
<tr>
<td>3</td>
<td>Hidden fire inside a locomotive mock-up.</td>
<td>Diesel</td>
<td>4.5 m(^2) pool and 1.1 MW spray fire</td>
<td>7.4 MW</td>
<td>Detection + 30 s</td>
<td>2.25</td>
</tr>
<tr>
<td>4</td>
<td>Wood pallets placed on a simulated goods wagon.</td>
<td>Wood pallets</td>
<td>2 piles</td>
<td>8.4 MW</td>
<td>Detection + 30 s</td>
<td>2.25</td>
</tr>
<tr>
<td>5</td>
<td>Wood pallets placed on a simulated goods wagon.</td>
<td>Wood pallets</td>
<td>4 piles</td>
<td>16.8 MW</td>
<td>Detection + 90 s</td>
<td>2.25</td>
</tr>
<tr>
<td>6</td>
<td>Pool fire placed on a simulated goods wagon</td>
<td>Heptane</td>
<td>4.5 m(^2)</td>
<td>9 MW</td>
<td>Detection + 30 s</td>
<td>2.25</td>
</tr>
<tr>
<td>7</td>
<td>Pool fire placed on a simulated goods wagon</td>
<td>E85</td>
<td>4.5 m(^2)</td>
<td>4.7 MW</td>
<td>Detection + 45 s</td>
<td>2.25</td>
</tr>
<tr>
<td>8</td>
<td>Pool fire placed below a simulated goods wagon</td>
<td>Heptane</td>
<td>4.5 m(^2)</td>
<td>9 MW</td>
<td>Detection + 30 s</td>
<td>2.25</td>
</tr>
<tr>
<td>9</td>
<td>Hidden fire inside a locomotive mock-up and wood pallets on a simulated goods wagon</td>
<td>Acetone and wood pallets</td>
<td>1.73 m(^2) and 1 pile</td>
<td>6.3 MW</td>
<td>Detection + 30 s</td>
<td>1.875</td>
</tr>
</tbody>
</table>

\(^a\) Based on freely burning fire tests. The values might be higher due to radiation from the hot gas layer and surface with high temperature.

### Results from the HotFoam tests

In total eight fire tests are presented. A summary of the results is provided in Table 4. One way of illustrating the intensity of the fire and the effect of the extinguishment system is to study the temperature in the ceiling. In Table 4 the maximum temperature measured by TC7 during each test is presented. In Figure 9 the time-resolved temperatures registered near the ceiling by TC7 are presented.
### Table 4  Summary of the results.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Alarm Start</th>
<th>Foam production noted</th>
<th>Extinguished</th>
<th>Max. temp. at ceiling$^a$ [°C]</th>
<th>Elapsed time from foam production noted to extinction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1:02</td>
<td>2:18</td>
<td>4:48</td>
<td>359</td>
<td>2:30</td>
</tr>
<tr>
<td>3</td>
<td>0:53</td>
<td>2:06</td>
<td>6:41</td>
<td>706</td>
<td>4:35</td>
</tr>
<tr>
<td>4</td>
<td>2:45</td>
<td>3:53</td>
<td>7:50</td>
<td>741</td>
<td>3:57</td>
</tr>
<tr>
<td>5</td>
<td>2:30</td>
<td>4:44</td>
<td>9:53</td>
<td>890</td>
<td>5:09</td>
</tr>
<tr>
<td>6</td>
<td>0:30</td>
<td>1:40</td>
<td>2:48</td>
<td>1107</td>
<td>1:08</td>
</tr>
<tr>
<td>7</td>
<td>0:31</td>
<td>1:55</td>
<td>8:30</td>
<td>875</td>
<td>6:35</td>
</tr>
<tr>
<td>8</td>
<td>0:35</td>
<td>1:45</td>
<td>2:48</td>
<td>752</td>
<td>1:03</td>
</tr>
<tr>
<td>9</td>
<td>2:15</td>
<td>3:29</td>
<td>10:30</td>
<td>800</td>
<td>7:01</td>
</tr>
</tbody>
</table>

$^a$ In most of the tests, the maximum temperature near the ceiling was registered by TC7 and therefore all given temperature in the table are for TC7.

**Figure 9**  Temperature near the ceiling (TC7) for a) tests with fires inside the locomotive mock-up and b) tests with fires below or on simulated goods wagon. To make the curves easier to compare, the data has been smoothed corresponding to 10 s averages.

**Figure 10**  Photos of the extinguishment by HotFoam of fire in wood pallets on simulated goods wagon.
CONCLUSIONS

The effect of macadam on the heat release rate for a pool with combustible liquid was tested. The following conclusions can be drawn:

- There is a significant effect of the addition of macadam on the burning rate.
- The effect of macadam increases with the distance between the fuel surface and the upper level of the macadam.
- There was a significant effect for both fuels tested (heptane and diesel), but the effect was largest for diesel.

This means that there may be a positive effect on the fire safety in a rail tunnel if the ground surface is covered by a layer of macadam, since the test results indicate that the burning rate of liquid fuels decreases in such cases.

Note that the upper level of macadam is not even or well defined. This needs to be kept in mind when comparing different heights.

Four different principle fire test scenarios were used in the test series in the tunnel section built in the fire hall of SP Fire Technology: hidden fire inside a locomotive mock-up, wood pallets placed on a simulated goods wagon, pool fire placed on a simulated goods wagon, and pool fire placed under a simulated goods wagon. Different types of fuels were used: diesel, heptane, E-85, acetone, and wood pallets. The HotFoam system was started with a pre-defined delay after alarm from the installed detection system and was able to extinguish all reported scenarios.

Easiest to extinguish (shortest time between foam production and extinguishment) were the heptane fires, both on and below the simulated goods wagon. Most difficult to extinguish (with the same nominal filling rate of foam) was Test 7 with E-85. It should be noted that E-85 is a polar substance.

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Reliability and availability of Fire Detection Systems in Road Tunnels

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KEYWORDS: tunnel fire detection, line type heat detectors, reliability, availability

INTRODUCTION

Fire detection systems in road tunnels are used since more than 40 years as an important part of fire safety. Recently they are used to trigger extinguishing systems. A lot of successful detected fires are documented [1]. The system design is almost based on a scenario with a HRR of 5 MW that's typically caused by a fire with 2 small cars or a van [2]. With the very well proofed line type heat detectors detection times below 60 sec are state of the art. This makes it very simple to trigger automatically ventilation systems, traffic signals and to call the fire brigade. And – under some circumstances – to trigger a tunnel extinguishing system.

In the present we may observe a trend to detect smoke in tunnels in addition to the existing line type heat detectors to have a shorter detection time. E.g. in the new Swiss guidelines for tunnel fire detection we have the requirement for smoke detection. We also know from discussions in other countries. In Austria there were tests with aspiration smoke detectors.

I agree that fast detection time is a very good target. But it should not be the only one. After working almost 20 years in the fire detection business for special applications I must say that tunnel applications are together with offshore and military application the most difficult environment for technical equipment. So other criteria's for systems are important too. As reliability and availability.

One way to expressed reliability could be an absence of unwanted alarms. And the availability over the whole life cycle of a tunnel system should be as important. So this paper is focused on the question of reliability and availability of fire detection systems for tunnels.

RELIABILITY OF FIRE DETECTION SYSTEMS IN A TUNNEL SHOWN AS LOW RATE OF UNWANTED ALARMS

What is a unwanted alarm

There are several definitions for unwanted alarms; some people talk about nuisance alarms or false alarms and mean unwanted alarms according to the following definition. Figure 1 shows one existing definition from the Swiss Fire Brigade and the Association of Swiss Safety and security system Installers SES. It's not made for tunnels but it's helpful to understand the systematic.
A comparison with unwanted alarms in building

As a comparison we have exact statistic data from the Swiss Fire Brigade for rates of unwanted alarms [3]. We have a rate of unwanted alarms from about 0.7 by installed systems and years and 0.47 false alarms (year 2006). And there is a rate of real fire alarms of 0.14 alarms per system and year.

Unwanted fire alarms in tunnels

Of course the amount of unwanted alarms in buildings is not fully comparable with tunnels. The environment situation is totally different. Also the consequences of unwanted alarms are more severe:

- Traffic lights stop the traffic; traffic jam could cause a rear-end collision
- A false alarm in a city tunnel during rush hour could cause a traffic chaos
- Ventilation system is speeding up; in big Alp tunnels the power consumption of such a system is comparable with a small city
- Fire brigades and tunnel manager tend to ignore alarms if there are to often false alarms
- If a extinguishing system is triggered we have to anticipate affrighted drivers causing accidents

The reasons for unwanted alarms in tunnels are based on a line type heat detector as detecting systems as follows:

- A typical example for a nuisance alarm in a city tunnel is a truck loaded with hot bitumen (asphalt), standing in a traffic jam. The temperature caused by the bitumen could be the same as that caused by a real car fire.

If there are other detection principles as smoke or flame detector, we have more and other reasons for unwanted alarms:

- Mist/fog in the tunnel entrance area
- Dust e.g. from truck load
- Exhaust gases almost from old trucks
- For video based detection systems there are a lot of more sources for unwanted alarms as reflecting traffic light on wet lanes, reflecting life vests, etc.
EXPERIENCE WITH UNWANTED ALARMS IN ROAD TUNNELS BASED ON EXISTING SYSTEMS

Deal between detection speed and unwanted alarms

A fire detection system acts primarily for the safety of people. Accordingly, the requirement for high system reliability is asked. Detection safety is therefore decisive. Between the requirement of „fastest possible detection“ and the requirement „as few unwanted alarms as possible“ there is the conflict of unwanted alarms which must be dealt with by defining a tolerated rate of unwanted false alarms. Depending on the viewpoint (tunnel operator, fire brigade, and system installer) there are different opinions on the definition of the accurate system setting.

![Graph showing detection speed vs. false alarms](image)

**Figure 2  Detection speed vs. false alarms**

Some experience

Figure 2 shows a function of detection speed (100% means a 5 MW fire in 60 sec) and the rate of unwanted alarms. The rate of unwanted alarms is average 0.5 alarms per system and year based on long time experience. Considering that there are almost 2 lanes with an average length of about 1.5 km we will have about 1 unwanted alarm every 6 year per km.

**HOW TO PREVENT FROM UNWANTED ALARMS?**

There are some important hints to highlight how to prevent from unwanted alarms

Technical:
- Choose the right fire scenario
  - A 5 MW scenario to trigger automatically systems is recommended
  - Smoke detection scenario only for information
- Choose the right detection principle (based on scenario)
  - Line Type Heat Detectors with Class A1 (rate of rise) behaviour strictly recommended
  - Non-resettable (digital)- systems are not applicable because of the maximum trigger temperature that will not be reached by 5 MW scenario
- Choose the accurate system setting
  - To prevent false alarms in city tunnels adjust systems setting partially in sections where traffic jam my occur (after test stage), In some situation detector dependency is recommend
Two detector dependency
  o To trigger extinguishing systems fully automatically it is necessary to have two independent systems

Operational
  • Test stage
    o A three month test stage is recommended to adjust the systems settings and the alarm response characteristics
  • Maintenance
    o A regular maintenance including test of the whole chain from the detector to the tunnel management system should be done at least once a year
    o A easy to applicable on site test facility is helpful

THEORETICAL REFLECTION OF AVAILABILITY IN ROAD TUNNELS

Requirements to availability
Each system operator wishes to have a system availability of 100%; at the same time, everybody knows that this can only be accomplished with the highest of expenditures, which can not be paid for anymore.

Availability could be defined by:
  • definition of the availability (MTTR)
  • definition of a section (length/amount of sensors) that may fail
  • definition of other criteria’s (e.g. short circuit conditions)
  • a combination of the above

Definition of availability
  • MTBF = Mean Time Between Failure = average failure-distance \( \tau \)
  • MTTR = Mean Time To Repair = average repair time
  • \( V = \) availability = \( \frac{MTBF}{MTBF + MTTR} \times 100\% \) \hspace{1em} (1)
  • \( \lambda = \) failure rate = 1 / MTBF

Which availability is achievable
For every engineer it's a fact that 100% availability is not achievable. We know the following graph in Figure 3 well:

\[ \text{Figure 3} \hspace{1em} \text{Failure rate vs. durability} \]
Based on an internal study for a Swiss motorway authority there was found a possible availability of 99.8% for a redundant system. This means a system down time of 17.3h a year!

Reasons for system down are:
- Electrical damage as laser damage (fibre optic systems), fault of electronic components, etc.
- Mechanical damage of the sensing element (accident, unstable truckload (ships, swinging canvas cover, cattle!!!, etc) – less than once in 10 years per system!
- Damage caused by lightning
- Operation/manipulation faults

Compared with other business this is a very good value. Standard IT applications reach 98% per month. For 99.8% there is a need of special measures as redundancy, cluster, etc. Mobile communication reach's about 99%

**Definition of a section (length/amount of sensors) that may fail**

In the fire detection business it's common to define surveillance area that may fail. In many countries it's 1600 m². Based on this you may calculate a maximum length for Line type heat detectors. For a good overview of availability in fire detection systems see [4]

Remark: the Austrian RVS standard describes a maximum length of 1000 m that may fail.

**SOLUTIONS FOR ENHANCED AVAILABILITY OF TUNNEL FIRE DETECTION**

There are different possible solutions to reach the requirements and to enhance the system availability:

a) standard installation:
   - important is to make short section (less than 2 km; better 1000m) to reduce the consequences' of a failure
b) Two independent systems:
   - so called redundant installation brings a very good availability with the possibility to trigger extinguishing systems. Brings also flexibility in case of maintenance. Weakness is the higher price. Take care if 2 optical fibres are installed in the same tube.

![Figure 4 Different solutions for enhanced availability](image)
c) Connecting the sensor cable from both sides:
   most used by temperature sensor cables (multipoint systems) including group separator
   modules to isolate short circuits and breaks. Brings good performance with an acceptable price

d) A sensing element loop:
   mostly used with fibre optic systems. Protect against damage of the sensing element but not
   on damages of the sensor control unit.

![Diagram of sensor and control units](image)

**Figure 5** Different solutions for enhanced availability (2)

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**OVERVIEW OF NATIONAL TUNNEL FIRE DETECTION STANDARD ON RELIABILITY AND AVAILABILITY**

At this time we have the following requirements on reliability and availability in tunnel standards:

**Germany:**
RABT issue 2003/2007; Chapter 2.5.3.2. Fire detection systems
- Localisation distance of 50 m
- Line type heat detector with rate of rise characteristic
- Make several parts (no definition of length)

In tenders there is a demand for systems against EN 54 standards.
Remark: In the scope of the CPD (construction product directive) tunnels are mentioned so they are covered.

**Switzerland (ASTRA)**
Richtlinie "Branddetektion in Strassentunneln" Ausgabe V2.0 2007
- Localisation distance of 10 m
- Combination of Line Type Heat Detector with smoke detector every 100 m
- Redundancy based on additional smoke detector (every 100 m)
- 1 false alarm per year for a 2 km tunnel

**Austria (RVS)**
Projektierungsrichtlinien Tunnelausrüstung RVS 9.282, issue July 2002
- Localisation distance of 10 m
- Line type heat detector with rate of rise characteristic
- Max of 1000 m may fail in case of a fault
CONCLUSION

- Line Type Heat detectors are well proved and fulfil the actual requirements on detection behaviour, reliability and availability
- Smoke detection in tunnels is not appropriate as a fire alarm system because of the rate of unwanted alarms. A smoke alarm is to handle as an information
- To trigger extinguishing systems there must be a two detector dependency to avoid unwanted alarms

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International Road Tunnel Fire Detection Research Project

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ABSTRACT
Fire detection systems are essential fire protection elements for road tunnels to detect fires, activate safety systems and direct evacuation and firefighting. However, the information on the performance of these systems is limited and the guidelines for application of tunnel fire detection systems are not fully developed. The National Research Council of Canada and the Fire Protection Research Foundation, with support of government, industry and private sector organizations, have initiated a project to investigate current fire detection technologies for road tunnel protection. The two year project, which included full scale laboratory in and in-situ examination of detection system performance, was completed in February of 2008. This paper describes the detailed research program and summarizes project findings.

KEYWORDS: detection, design fires, ventilation

INTRODUCTION

Fire detection systems are an essential element of fire protection for road tunnels. Fire detectors should provide early warning of a fire incident, identify its location and monitor fire development in tunnels. Their role is crucial in preventing smoke spread in the tunnel, in controlling and extinguishing fires, and in aiding in directing evacuation and firefighting operations [1-3].

Recent studies, however, indicated that information on the performance of current fire detection technologies and guidelines for use in road tunnel protection are limited [4]. A few test programs that mainly focused on the performance of linear heat detection systems and optical flame detectors were conducted in Europe and Japan [5-9]. Many other types of fire detection technologies, such as spot heat detectors, smoke detection systems and newly developed visual flame and smoke detectors have not been studied systematically. In addition, there are no generally accepted test protocols and performance criteria for use in the evaluation of various fire detection technologies for tunnel protection. The test conditions and fire scenarios were changed from one test program to another. The performances of detectors in these programs were evaluated mostly with pool fires of a constant heat release rate of up to 3 MW. Other types of fire scenarios, such as stationary and moving vehicle fires, were not considered. Another concern on the use of current fire detection systems is that their reliability, including false alarm rates and maintenance requirements in smoky, dirty and humid tunnel environments, have not been systematically investigated.
A two-year international research project, with support of government organizations, industries and private sector organizations, was conducted recently to investigate currently available fire-detection technologies for tunnel applications. The main aim of the study was to determine some of the strengths and weaknesses of the various types of detection systems and what can affect their performance in tunnel environments [10]. The results of the study will provide information for use in the development of performance criteria, guidelines and specifications for tunnel fire detection systems and will be used to update NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways. The results will also help optimize technical specifications and installation requirements for fire detection systems in tunnel applications. Although this research was conducted on road tunnels, the findings should apply to other tunnels, such as those used in subway systems.

Seven tasks were carried out as part of the project. These included full-scale fire tests in a new laboratory tunnel facility and in an operating road tunnel in Montreal, Canada, environmental and fire tests in the Lincoln Tunnel located in New York City, as well as a computer modeling study. Nine fire detection systems that covered five types of currently available technologies were studied in the project. The fire scenarios that were used were representative of the majority of tunnel fire incidents. The scenarios included small open pool fires, pool fires located underneath a simulated vehicle, pool fires located behind a large vehicle, engine and passenger compartment fires in a stationary vehicle, and moving vehicle fires. The fire size and wind speed in the tunnel were also varied.

This paper provides an overview of the project. Research results from a series of full-scale fire tests and environmental tests and from computer modeling are discussed.

SELECTED FIRE DETECTION SYSTEMS

The nine fire detection systems evaluated in the project were: two linear heat detection systems, one optical flame detector, three visual CCTV fire detectors, one smoke detection system and two spot heat detectors. These detectors are representative of current fire detection technologies for use in tunnel fire detection. Information on these systems is listed in Table 1. A detailed description of these technologies is provided in Reference [11].

<table>
<thead>
<tr>
<th>Technology</th>
<th>System no.</th>
<th>System information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear heat</td>
<td>D-1L1</td>
<td>Fiber optic linear heat detection system</td>
</tr>
<tr>
<td></td>
<td>D-2L2</td>
<td>Analogue (co-axial cable) linear heat detection system</td>
</tr>
<tr>
<td>Flame</td>
<td>D-3F1</td>
<td>IR3 optical flame detector</td>
</tr>
<tr>
<td>CCTV</td>
<td>D-4C1</td>
<td>Visual based fire and smoke detection system</td>
</tr>
<tr>
<td></td>
<td>D-5C2</td>
<td>Visual flame detector</td>
</tr>
<tr>
<td></td>
<td>D-6C3</td>
<td>Visual fire detection system</td>
</tr>
<tr>
<td>Spot heat</td>
<td>D-7H1</td>
<td>Heat detector with a fixed temperature</td>
</tr>
<tr>
<td></td>
<td>D-8H2</td>
<td>Rate-anticipation heat detector</td>
</tr>
<tr>
<td>Smoke</td>
<td>D-9S1</td>
<td>Air sampling- system</td>
</tr>
</tbody>
</table>

The configuration and installation of the fire detection systems in the test tunnel was based on the design of a system to protect a road tunnel with dimensions of 10 m wide by 5.5 m high by 2,000 m long. The installation configuration was not changed during the tests. The sensitivity levels or alarm thresholds of the fire detection systems were also not changed during the test series. The alarm levels were required to be the same as those used in operating tunnels and with those used in the environment tests in the Lincoln tunnel.
All the fire detection systems were installed in the tunnel facility by the system suppliers. The performances of the fire detection systems, including response times, and ability to locate and monitor a fire in the tunnel, were evaluated under the same fire conditions.

FIRE TEST PROTOCOLS AND SCENARIOS

Three types of fire scenarios, involving various fire sizes, types, locations and growth rates, were selected for use in evaluating the performance of the tunnel fire detection systems. These fire scenarios were: flammable pool fires, stationary passenger vehicle fires and moving vehicle fires. Flammable pool fires that occur in road tunnels can be caused by fuel leaking from a vehicle or in a collision. The fire develops very quickly and reaches its maximum heat release rate in a short time. The pool fires used in the project included small open pool fires, pool fires located underneath a vehicle, and pool fires located behind a large vehicle. The fuel was gasoline. A propane burner was also used to simulate pool fires in tunnels. The fire sizes in the tests ranged from 125 kW to 3,400 kW. Figure 1 is a photograph of a pool fire located underneath a simulated vehicle in the laboratory tunnel.

Stationary passenger vehicle fires in a road tunnel could be caused by collision incidents, by an electrical failure or by a defective fuel delivery system and exhaust system failures. The fire develops slowly and it could take 8~12 minutes for a vehicle fire to reach its maximum heat release rate [12, 13]. Two stationary vehicle fire scenarios used in the tests were: an engine compartment fire and a passenger compartment fire. A vehicle engine compartment fire was simulated by controlling the growth rate of a pool fire that was placed inside a simulated engine compartment. A passenger compartment fire was simulated using wood cribs and plastic foam inside a vehicle mock-up. Figure 2 is a photograph of a simulated passenger compartment fire in the laboratory tunnel.

Moving vehicle fires in road tunnels could be caused by an electrical failure or by a defective fuel delivery system and exhaust system failures. A moving vehicle fire was simulated by dragging a fire source using a high-speed winch apparatus. Fire tests with different driving speeds and driving directions relative to the detectors were conducted. The fire scenarios adopted in the project were considered representative of the majority of tunnel fire incidents, and presented a challenge to the fire detection systems. A detailed description on the setup of the fire scenarios is provided in Reference [11].

Figure 1  Photograph of a pool fire located underneath the vehicle

Figure 2  Photograph of a simulated passenger compartment fire
FIRE TESTS IN A LABORATORY RESEARCH TUNNEL

Two series of full-scale fire tests were conducted in a laboratory tunnel facility. Tests were conducted under low airflow conditions and under longitudinal wind conditions. The dimension of the tunnel was 10 m wide x 5.5 m high x 37 m long (Figure 3).

Nine fire detection systems were evaluated in the tests. The flame detector and three visual CCTV fire detectors were installed on the North wall of the tunnel. The sensing cables of two linear heat detection systems were installed in a loop on the ceiling of the tunnel. The two spot heat detectors and the sampling pipe of the smoke detection system were installed along the center of the tunnel ceiling. A schematic showing the location of the fire detection systems in the tunnel is shown in Figure 3. Detailed information on the location of fire detection systems in the test tunnel is provided in the project report [14].

The fire scenarios used in the laboratory tunnel tests included pool fires, stationary vehicle fires and moving fires of various sizes (125 kW to 3,500 kW); various growth rates (1 min to 12 min to reach their maximum heat release rates); various locations (open space fire, fires underneath a vehicle and behind a large vehicle) and various fuel types (gasoline, propane, wood crib and foam); and fires with various moving directions and speeds. The fire conditions and smoke spread in the tunnel were monitored using 55 thermocouples on the ceiling, two thermocouple trees, three smoke meters, five heat flux meters, one velocity meter and two video cameras.

For the first series of tests, the airflow velocity in the laboratory tunnel was kept as close as possible to zero. The door at the East end of the tunnel was closed and ventilation air was provided through the louvers in the North and South walls of the tunnel.

For the second series of tests, the door at the East end of the tunnel was open. Longitudinal wind conditions were simulated by running the fan system mounted in the tunnel facility to produce airflow in the East-West direction. The wind speeds in the test series were 0 m/s, 1.5 m/s and 3 m/s.

Figure 3 Schematic of the detection system setup in the laboratory tunnel.
The response of the fire detection systems to the fires used in the tests was dependent on fuel type, fire size, location and growth rate as well as detection method. The fire scenario with a pool fire located underneath a vehicle presented a challenge for the detection systems, as the flame and heat produced by the fire were confined by the vehicle body. A few detection systems were able to detect small pool fires located underneath a vehicle in the initial series of tests with minimal airflow in the tunnel, as shown in Figure 4. With an increase in fire size, more detectors responded to the fire and detection times were also reduced.

The large vehicle body in front of the pool fire did not affect the performance of heat and smoke detection systems, but presented a challenge for the visual-based fire detectors (Figure 5). One CCTV flame detector could not detect the fire located behind the vehicle, as the flames were not visible. For other fire detection systems, the response times decreased with an increase in fire size.

The response of fire detection systems to the stationary vehicle fires in the engine and passenger compartments was slow, because these fires developed very slowly. The flame, heat and smoke produced by the fires were limited during the initial few minutes after ignition.

It was difficult for fire detection systems to detect a small moving fire, since there was no change in the temperature and smoke density in the tunnel. Only the optical flame detector detected the moving fire at the speed of 27 km/h, but not at the speed of 50 km/h in the test series. No other fire detector/detection system responded to the moving fires.

The results for tests under longitudinal wind conditions showed that the response times of fire detection systems could be delayed or shortened, depending on the fire scenario, wind speeds and detection method. The burning rate of large pool fires located underneath a vehicle was increased under longitudinal wind conditions. The temperatures and smoke density near the ceiling were higher and the response times of heat and smoke detection systems were generally shorter than those under low airflow conditions, as shown in Figure 6. For the optical flame and CCTV detectors, there was no systematic change in response time.

The ceiling temperature produced by the pool fires located behind a large vehicle decreased with an increase in wind speed, but the smoke optical density near the ceiling produced by large gasoline pool fires was not reduced. As shown in Figure 7, with an increase in wind speed, the response times of the heat detection systems to the large pool fires located behind the vehicle generally increased, while the response time of the smoke detection system slightly decreased. The response time for the optical
flame detector and CCTV fire detectors generally increased with an increase in wind speeds, as the vehicle shielded the flame.

The duration of the passenger compartment fire was shortened under wind conditions. However, the temperature and smoke density near the ceiling produced by the fire decreased. The response times of fire detection systems generally increased with an increase in wind speed.

![Figure 6](image1.png)  
Figure 6  Response times of detection systems to a 2 m² gasoline pool fire located underneath the vehicle under wind conditions.

![Figure 7](image2.png)  
Figure 7  Response times of detection systems to a 2 m² gasoline pool fire located behind the vehicle under wind conditions.

FIELD FIRE TESTS IN AN OPERATING TUNNEL

A series of full-scale fire tests were conducted in an operating road tunnel in Montreal in collaboration with the Ministry of Transportation of Quebec (Figure 8). The test section of the tunnel was 600 m long, 5 m high and 16.8 m wide (representing 4 lanes). The tunnel was equipped with four jet fans. The performance of fire detection systems in a real tunnel environment and at their maximum detection distance was investigated in the tests. The results were also compared with those from tests conducted in the laboratory tunnel.

Six detection systems were installed in the Montreal tunnel, including one optical flame detector, three visual CCTV fire detectors and two linear heat detection systems. A schematic of the fire detection systems in the tunnel is shown in Figure 9. The detection systems were the same ones used in the laboratory tunnel tests. Three types of fire scenarios were used in the test series: a small open pool fire (125 kW), a pool fire (625 kW) located underneath a simulated vehicle and a pool fire located behind a vehicle. The fire setups were similar to those conducted in the laboratory tunnel. The fires were placed at different locations in the tunnel (FP#1 – FP#4), as shown in Figure 9. Four longitudinal wind speeds were provided in the tests by running the fan system mounted in the tunnel: 0 m/s, 1.3 m/s, 2 m/s and 2.4 m/s.

General observations on the performance of the fire detection systems in the Montreal tunnel tests indicated that fire detection systems worked well in an operating tunnel environment. Their performances were consistent with those determined in the laboratory tunnel tests under the same test conditions.

The linear heat detection systems were able to respond to the small fires used in the tests, based on the rate of the rise of temperature, even if the ceiling temperature produced by the fire was not high. The
detection performance generally was not affected by fire location in the tunnel, but the detection times decreased with an increase in wind speed.

The optical flame detector D-3F1 was able to detect the fires at its detecting range but did not respond when the fire was located beyond its maximum detection distance (~30 m). Its performance was affected by an increase in wind speed.

The three CCTV fire detectors were able to detect the small open fires (125 kW) at the maximum detection range (~60 m). The response times to a fire located underneath a vehicle could be delayed or reduced under wind conditions. Two CCTV detectors, D-4C1 and D-5C2, were able to detect the fire located behind the vehicle when the fire was 32 m from the detectors, and had no response when the fire was 60 m from the detectors. Detector D-6C3 detected the fire at both distances and its detection time increased with an increase in fire distance.

**COMPUTER MODELING**

Due to the rapid development of computer technology and high costs of test programmes, the use of Computational Fluid Dynamics (CFD) models to simulate the dynamics of fire behaviour in tunnels is increasing quickly. The details of fluid flow and heat transfer provided by CFD models can prove vital in analyzing problems involving far-field smoke flow, complex geometries, and impact of fixed ventilation flows.

The current research study employs the Fire Dynamic Simulator (FDS) CFD model [15] to study the fire growth and smoke movement in road tunnels. FDS is based on the Large Eddy Simulation (LES) approach and solves a form of high-speed filtered Navier-Stokes equations valid for low-speed buoyancy driven flow. These equations are discretized in space using second order central differences and in time using an explicit, second order, predictor-corrector scheme.

For the tunnel detection project, the following CFD modeling activities were conducted:

- CFD simulations were carried out to compare numerical predictions against the data from a demonstration test in the laboratory tunnel facility [16]. Further simulations were conducted to assist in the preparation of the full-scale experiments.
- The numerical predictions were compared to the full-scale results to verify the simulations.
Further simulations were conducted to investigate the impact of various fire scenarios, ventilation mode, and tunnel length on fire behaviour and detection system performance. Information from the model will be used in developing appropriate test protocols and for understanding and optimizing the performance of fire detection systems for road tunnel protection.

CFD simulations were carried out to compare numerical predictions against selected experimental data from the laboratory and field experiments. The initial and boundary conditions of each simulation were set to mimic the conditions of the corresponding test. Comparisons were made to temperature and smoke optical densities measurements. Figure 10 shows the comparisons of ceiling temperatures for the simulation of a 1.0 x 2.0 m pool fire under a vehicle for a test in the laboratory tunnel without longitudinal airflow.

In general, good agreement was observed between numerical predictions and experimental data. Some discrepancies were observed in the comparisons of numerical prediction against experimental data for tests with longitudinal airflow especially at the test facility entrance. These discrepancies may be attributed to turbulence conditions and plume fluctuations that were not fully reproduced by the model.

CFD simulations were also conducted to investigate the impact of various parameters, such as fire scenario, ventilation mode, and tunnel length, on fire behaviour and detection systems performance. Four ventilation conditions were studied: no ventilation, longitudinal, fully-, and semi-transverse ventilation. Two tunnels were simulated with lengths of 37.5 m (similar to the length of the laboratory facility) and 500 m and the height of 5.5 m. The two tunnels had three-lane tunnels with 10 m and 12 m widths, respectively. The longitudinal ventilation condition was created by introducing a 3.0 m/s airflow at a tunnel portal. The semi-transverse ventilation condition was
Simulated by injecting airflow at the floor level. Injecting airflow at floor level and exhausting airflow at ceiling was used to simulate the fully-transverse ventilation condition.

Simulations for the two lengths of tunnel produced similar results. Therefore, data produced from the tunnel facility can be extended to longer tunnels. Fully- and semi-transverse ventilation systems produced comparable hot layer temperatures. Longitudinal ventilation systems produced close to ambient environment upstream of the fire.

In general, CFD produces data that can be linked to the performance of linear and spot heat detectors. More effort is required to link CFD data to CCTV and flame detectors in terms of smoke (obscuration, density, or visibility) and the visible envelope of the flame.

ENVIRONMENTAL AND DEMONSTRATED FIRE TESTS IN LINCOLN TUNNEL

With support from the Port Authority of New York and New Jersey, four detection systems representing three fire detection technologies were installed in the south tube of the Lincoln Tunnel. These systems are being monitored over the course of a year to evaluate their performance, particularly relative to maintenance and nuisance alarm immunity. In addition to the long-term monitoring, fire demonstrations were conducted in the tunnel to document the response of the detection systems when exposed to a set of controlled test fires.

The south tube of the Lincoln Tunnel is one of three underwater vehicular tunnels that connect New York City to New Jersey. The south tunnel has been operating since 1957 and has two lanes of traffic. The tunnel is 2,441 m (8,006 ft) long with both lanes being eastbound traffic from NJ to NY. Currently, the south tube accommodates all types of vehicles, except heavy goods vehicles (i.e., tractor trailers). The average daily traffic volume is about 44 thousand vehicles with roughly equal traffic in both lanes. Slow moving and stopped traffic frequently occur. Vehicle speeds range from below 10 to about 60 miles per hour. Typically, the traffic speed is about 20 mph.

The construction of the tunnel consists of a roadway section 6.6 m (21.5 ft) wide and 4.15 m (13 ft 7.5 in) high within a 9.5 m (31 ft) diameter cast iron drum ring with interior concrete lining. Above and below the roadway are air plenums used for full transverse ventilation, supplied low along the roadway curbs and exhausted high at the ceiling. The interior walls and ceiling consist of ceramic tile on concrete. The south tunnel is lit using 100 W metal halide lights, spaced approximately 25 ft apart. Color cameras are located approximately every 69 m (200 to 250 ft). The cameras face west, toward the oncoming, eastbound traffic.

The three types of fire detection technologies evaluated were video image detection (VID) for flame and smoke, optical flame detection (OFD), and air sampling detection (ASD) for smoke. These three technologies were represented by four specific detection systems as summarized in Table 2. All of the detection systems were monitored by the Lincoln Tunnel Supervisory Control and Data Acquisition (SCADA) system.
There were two primary areas of detection coverage in the tunnel: 1) the NJ entrance and 2) the second incline toward NY. The NJ portal was selected to assess effects of weather and varied lighting conditions on detector performance. The second location is west of center in the tunnel and is the location that vehicles must accelerate most; this was deemed to be the location with the most exhaust. The ASD system was only installed in the center location. The ASD system was installed in the exhaust air plenum above the roadway and sampled over a 244 m (800 ft) distance centered on the other detectors.

Based on preliminary results over a seven months period, the OFD system (D-3F1) had three nuisance alarms, the VID flame detectors (D-6C3) had zero, and the ASD system (D-9S1) had one. The VID smoke and flame system (D-4C1) had multiple nuisance alarms per week. With the VID systems, these alarms are immediately shown with video images that can be used to manually assess the situation. However, it is noted that the tunnel camera system is available for review with all reported detection events, regardless of the system. The primary difference is that VID systems can archive the video associated with the alarm condition and highlight the images that are producing the alarm. Many of the D-4C1 alarms were due to flashing lights on service vehicles.

Besides nuisance alarms, trouble signals and maintenance issues are also being monitored. Overall, the VID flame detectors (D-6C3) and the ASD system (D-9S1) had few trouble signals (two each over the initial evaluation period). The OFD detectors (D-3F1) have had repetitive optical faults and the VID smoke and flame system (D-4C1) has had multiple trouble signals. The tunnel environment is very dirty, and the detectors are exposed to varied weather conditions, particularly at the NJ entrance. High build-up of dirt and grime routinely occurs on the devices. The tunnel roadway sections are also routinely cleaned with vehicles that have articulating booms of six rotating brushes. The soap solution and water wash down and scrubbing action can exert 800 ft-lb of pressure and creates a very wet environment. Consequently, any devices mounted in the tunnel must be capable of withstanding a relatively harsh environment. Typical procedures included moving the washing assembly away from mounted cameras. Therefore, the devices that were positioned near the tunnel cameras should have avoided contact with the brushes; however, they did get wet.

To evaluate the fire detection capabilities of the installed systems, the Port Authority conducted a set of fires that were typically used for annual mutual aid drills with local responding fire departments from NJ and NY. The simulated vehicle fire consisted of burning diesel fuel inside a gutted van with all of its windows removed. The fuel was ignited with gasoline and burned in two vertical halves of a 55-gallon drum that were laid horizontally in the back of the van. The estimated fire size was 1 to 2 MW. The fire produced large quantities of black smoke; however, flame was visible at the detector locations through the open windows (the back of the van was facing the detectors). The back window area was 0.44 m². As the fire grew, flames extended out of the open side windows. All fires were extinguished after 5 minutes of initiation.

Five fire tests were conducted: two near the NJ portal at 61 and 30 m (200 and 100 ft) from the detectors and three tests near the center of the tunnel at 61, 30 and 15 m (200, 100 and 50 ft). In general, the detection systems requiring a field of view had trouble detecting the fires in the interior of the van. The primary view of the fires was through the relatively small back window openings. The

<table>
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<tr>
<th>ID</th>
<th>Technology</th>
<th>System Information</th>
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<td>Flame</td>
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<tr>
<td>D-4C1</td>
<td>VID</td>
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<td>VID</td>
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<tr>
<td>D-9S1</td>
<td>ASD</td>
<td>Smoke</td>
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two VID systems did not detect any of the fires. The OFDs detected two of the five fires at the 30 m and 15 m distances. The aspiration smoke detection (ASD) system was only exposed to three of the fires since it was not installed near the NJ portal. The ASD system detected two of the three fires and was quite close to reaching the threshold in the third.

SUMMARY

Nine fire detection systems were evaluated in the present project. These systems were representative of current fire detection technologies for use in tunnel fire detection. A test protocol for evaluating various fire detection technologies for road tunnel protection was also developed. The performance of selected fire detection systems for various tunnel fire scenarios was investigated in a laboratory tunnel and in an operating road tunnel under natural and longitudinal ventilation conditions. Computer modeling was used to investigate the impact of various fire scenarios, ventilation mode, tunnel operating conditions and tunnel geometries on fire behaviour and detection system performance. Selected detection systems were also installed in the Lincoln tunnel and their reliability in real tunnel environments are being monitored over a one-year period. Technical data provided from the project will be used for the development of standards and guidelines, improvement of fire detection technologies and their applications in tunnels.

ACKNOWLEDGEMENT

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References

9. Brugger, S. “Rapid Fire Detection Concept for Road Tunnels,” 5th International Conference on Safety in Road and Rail Tunnels, Marseilles, France, October 2004
Influence of polypropylene fibres on fire spalling and material properties of concrete

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SP Technical Research Institute of Sweden
Borås, Sweden

ABSTRACT

A study of the fire spalling behaviour of concrete has been performed. It has been shown that polypropylene fibres (PP-fibres) reduce fire spalling of the investigated concretes. From the material testing part of this project it was revealed that PP-fibres in concrete modify the drying behaviour and the capillary saturation close to the surface of the concrete, and introduce a plateau in the free thermal strain curve.

KEYWORDS: Concrete, Fire spalling, polypropylene fibres, permeability, drying behaviour, thermal expansion

INTRODUCTION

A deep understanding of the physics involved in the phenomenon of fire spalling of concrete is still lacking. However, many tests have shown that polypropylene fibres (PP-fibres) reduce the damage incurred by fire significantly. The aim of the project presented in this article was to investigate the spalling behaviour of concrete containing CEM I cement in combination with various amounts and sizes of PP-fibres. The fire tests were conducted on two types of test specimens, large slabs, 1800 × 1200 × 300 mm³, tested on a large horizontal furnace with the standard fire curve (EN 1363-1) and the RWS curve; and small slabs, 500 × 600 × 300 mm³, tested on a small furnace. Additional tests, to investigate some aspects of the material behaviour at high temperature, were also performed.

CONCRETE MIXES AND CONDITIONING

The preparation of the concrete was performed at the concrete mixing plant Färdig Betong AB in Borås, Sweden. Färdig Betong AB, included in The Thomas Concrete Group, is the largest ready-mix concrete supplier in Sweden. The concrete mixtures chosen for this study are typical Swedish infrastructure concretes, that have been used in tunnels in western Sweden. Further, the concrete mixes have been modified by the addition of polypropylene fibres (PP-fibres).

The concrete mixes used in the project are shown in Table 1. The main parameters that were varied were: the water cement ratio, maximum aggregate size and type as well as the amount of PP-fibre addition. The names of the different mixes given in Table 1 (letters A, B etc.) will be used throughout this paper. Concrete U is a reference mix for comparison of data during material testing.
Table 1 Concrete Mixes

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<th>Gravel 8-16 mm [kg/m³]</th>
<th>Gravel 16-25 mm [kg/m³]</th>
<th>Water [kg/m³]</th>
<th>Cement CEM I [kg/m³]</th>
<th>Superplasticizer [kg/m³]</th>
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</table>

*CEM II, concrete U is a concrete used as a comparison during material testing*

A petrographic analysis of the aggregate used in all concrete mixes is shown in Table 2. As seen in the table, the dominating part of the aggregate is granite.

Table 2 Petrographic analysis of aggregate

<table>
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<tr>
<th>Size 0.063-2 mm</th>
<th>Size 2-4 mm</th>
<th>Size 4-8 mm</th>
<th>Size 8-16 mm</th>
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<tr>
<td>Mica</td>
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250
All concrete specimens used for fire testing were stored under water approximately half a year and then in air for between 1 – 3 months. More details about the concrete mixes and storage can be seen in reference [1].

FIRE TESTS

Test Methods

One of the aims of this project was to investigate the influence of the severity of the fire on the spalling behaviour. Therefore two different fire exposures were used for the large slabs, the RWS (Rijkswaterstaat) curve and the standard fire curve, EN 1363-1. The RWS curve represents a very severe fire exposure which attempts to emulate a worst case fire scenario in a tunnel, while the standard fire curve represents the temperature development in a room exhibiting a flash over. During the tests on small slabs, the standard fire curve was used. It was not possible to use plate thermometers in the small furnace during the fire tests, but to make the temperature exposure closer to the prescribed in the standard (EN 1363-1) the small furnace was calibrated with plate thermometers prior to the tests.

During the tests on both large and small slabs a compressive load of 10 % of the compressive strength was applied in one direction on the test specimen [1]. The specimens were plain concrete. During the tests temperatures and pressures in the pore system in the cross-section of the slabs was measured and the temperature and change in load were recorded.

Moisture in concrete during fire tests

Concrete filled plastic pipes were used to represent the two sided drying of large slabs. The plastic tubes were 300 mm long, had a diameter of 45 mm and were open at both ends. They were stored under the same conditions as the large specimens that they represented. Close to the day of the fire test, the cylinders inside the plastic tubes were sliced to determine the capillary saturation profiles. The pipes with concrete were sliced into 2 cm thick slices. The size 2 cm was chosen because it was the smallest size possible due to technical constraints associated with the slicing method chosen. The sliced test specimens were then used to determine of the degree of capillary saturation according to the method described by Hedenblad and Nilsson [3]. The results of the degree of capillary saturation measurements, shown in Figure 1, indicate that the specimens containing PP-fibres show a higher degree of capillary saturation close to the surface to be fire tested (0-20 mm). It can also be seen that close to the surface to be fire tested, the sequence from lowest to highest degree of capillary saturation is the same for those concrete types with maximum aggregate size 16 mm as for those with maximum size 25 mm. In both cases the order from lowest to highest is: concrete without PP-fibres, 1 kg 32 μm PP-fibres, 1 kg 18 μm PP-fibres and 1.5 kg 18 μm PP-fibres. Almost the same order from lowest to highest was also seen when determination of the moisture content in cubes was performed, see table 3.
Figure 1 Degree of capillary saturation for different concretes (16 mm and 25 mm are the maximum aggregate sizes)

Table 3 Moisture content in cubes.

<table>
<thead>
<tr>
<th>Max aggregate size 16 mm</th>
<th>Moisture content in cubes [%]</th>
<th>Max aggregate size 25 mm</th>
<th>Moisture content in cubes [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.1</td>
<td>B</td>
<td>5.2</td>
</tr>
<tr>
<td>M (1 kg 32 μm PP-fibres)</td>
<td>5.8</td>
<td>N (1 kg 32 μm PP-fibres)</td>
<td>4.9</td>
</tr>
<tr>
<td>E (1 kg 18 μm PP-fibres)</td>
<td>6.1</td>
<td>F (1 kg 18 μm PP-fibres)</td>
<td>5.4</td>
</tr>
<tr>
<td>I (1.5 kg 18 μm PP-fibres)</td>
<td>5.8</td>
<td>J (1.5 kg 18 μm PP-fibres)</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Results from fire tests

Figure 2 displays a comparison between the spalling depths in large slabs tested using the standard fire exposure curve. One should note that the concrete without addition of PP-fibres, concrete A, exhibits far greater spalling than the other types of concrete. The spalling in concrete A and F can be described as an evenly spread flaking of the specimen surface. The spalling in concrete I, M and N had another pattern, i.e., the spalling was concentrated to one part of the specimen probably through a falling off phenomenon.
The more severe spalling behaviour for concrete without PP-fibres experienced during standard fire exposure was also found for the RWS fire exposure, see Figure 3. However, during RWS exposure all the concrete tested spalled. During the RWS exposure the fire tests were terminated after 30 minutes due to safety reasons.

The test program on small slabs consisted of 40 tests. As see in Figure 4, the trends from the large tests are repeated in the small scale tests, i.e. all concrete without PP-fibres spalled (concrete A-D). There was also some spalling in one of the two specimens of concrete H. This concrete contained one kilogram of 18 μm PP-fibres per cubic metre.
If the results from these tests are compared with the results from the large scale test using standard fire exposure, it can be seen that the spalling is generally less severe on the small furnace. The reason for the difference is believed to be the much greater boundary effects on small specimens during the late stages of fire exposure. These boundary effects are probably negligible during the early stages of the exposure. Proof of this can be seen when comparing the times when spalling starts during the two tests using small slabs of concrete A and the single test using a large slab of concrete A. During the two small scale tests spalling starts after 7.75 minutes and 8.47 minutes which shall be compared with the spalling start 8 minutes during the test on the large slab. When the spalling then continues to a certain depth the boundary effects will be different for the large scale test relative to the small scale test. To summarise, small slabs can be used both to conduct an investigation of the risk for explosive spalling during one dimensional fire exposure, and to provide indication of whether it is necessary to investigate the spalling depth in a larger slab to verify large scale performance. This is an important characteristic of the small scale test which increases the intrinsic predictive quality of the small scale results.

**MATERIAL TESTS**

To investigate the effect of PP-fibres, different types of additional testing were performed. During moulding of the concrete for the fire tests extra slabs were manufactured for material testing. Cores for material testing were drilled from the slabs when the concrete was less than one week old. The material testing specimens were kept in plastic bags until the time of testing.

**Drying tests**

To investigate the drying behaviour of concrete when exposed to heat, a series of tests were performed on cylinders. The main goal was to explore possible differences between concrete with and without the addition of PP-fibres. The most widespread theory concerning the action of PP-fibres is that they promote fast drying by melting and providing channels for the internal moisture to escape [3]. This theory is, however, not the only explanation that has been promulgated. Schneider and Horvath [4] highlight the following theories:

- Improvement of the permeability due to formation of capillary pores when the fibres melt and burn.
- Improvement of the permeability caused by the development of diffusion open transition zones near the fibres.
Improvement of the permeability due to additional micro pores, which develop during the addition and mixing of fibres in the concrete mix.

Improvement of the permeability due to additional micro cracks at the tip of the PP-fibres which develops during heating up and melting.

One should note, however, that all the above theories indicate that in some way the drying process, i.e. moisture transfer, is somehow facilitated by the presence of PP-fibres.

Cylinders, with diameters 34 or 60 mm and length 300 mm, were exposed to three different heating ramps, i.e., 1, 2 or 5 degrees per minute. The heating was performed in a cylindrical furnace with a height of 400 mm and diameter of 200 mm. During the heating, the specimens were hanging on a wire connected to a weight measurement device. The temperature, regulated by the system and shown in the diagrams, was measured a couple of mm from the vertical centre of the specimen.

An example of results from the drying tests on 34 mm cores heated with a 2 degree per minute ramp can be seen in Figure 5 and Figure 6. Concrete A, B and U (reference) are the ones without addition of PP-fibres. When analysing the diagram in Figure 5 it can be seen that U, the reference concrete, exhibits the fastest total weight loss rate up to approximately 400 °C. The weight loss behaviour of concrete A is somewhere in the middle of that shown by all tested concretes while concrete B has the lowest total weight loss after approximately 230 °C. The derivative of the weight ratio curve is shown in Figure 6. With this type of presentation it is easier to discern a systematic difference between the concrete with and without PP-fibres. Concrete A and B have the lowest maximum weight loss rate and the peak in weight loss rate comes at a higher temperature for the concrete with PP-fibres. The reference concrete, U, shows a different type of behaviour, i.e., it exhibits an early peak with a high weight loss rate.

Figure 5  The weight loss of 34 mm cores at the heating rate of 2 °C/minute.
Figure 6 Weight loss rate of 34 mm cores at the heating rate 2 °C/minute. Different colours have been used to indicate different amount of PP-fibres.

Speed of sound

Some clear trends can be discerned when comparing concrete with and without the addition of PP-fibres with respect to the speed of sound, or more precisely the change in speed of sound as a result of heating. Although the heating rates used in these experiments are low, 1, 2 and 5 °C per minute, compared with the rapid heat exposure that leads to fire spalling during a fully developed fire, it is interesting to see how different heating rates influence the change in speed of sound in these specimens. The main trend is that during the most rapid heating used in these tests, 5 °C per minute, specimens without PP-fibres exhibits the greatest damage, see as an example Figure 7. When the heating rate is lower, 1 and 2 °C per minute, this is not as clearly evident.

Figure 7 Speed of sound ratio (after/virgin), cores d =34 mm, heating: 5 °/min up to 600 °C
Permeability after different heating scenarios

The influence of the heating rate on the residual permeability was investigated with the Cembureau method with nitrogen as gas. Two heating scenarios were investigated: 1 °C per minute, or heat shock in a pre-heated furnace, to two target temperatures: 400 °C and 600 °C. The heating at 1 °C per minute was performed in the same furnace that the drying tests were performed in.

The results from this type of permeability experiment after rapid heat exposure shall not be seen as material data, because there will not be a uniform crack pattern through the whole specimen. They are, however, an indication that different heating scenarios can influence the mechanical properties in different ways. The results from the experiments with different heating rates can be seen in Table 4 and Table 5. When heating to 400 °C the investigated heating rates do not influence the residual permeability, i.e. the ratio of the permeability from the specimen heated with thermal shock and by the heating rate of 1 °C per minute do not vary significantly when comparing before heating and after heating. When the same experiment is repeated using the oven pre-heated to 600 °C, however, the specimen exposed to thermal shock is more cracked than the specimen heated slowly. The specimen exposed to a thermal shock has twice the residual permeability as the specimen that has been heated slowly. Cracks close to the edges could be seen on the specimen exposed to thermal shock.

Table 4 Permeability after different heating rates to 400 °C.

<table>
<thead>
<tr>
<th>Permeability before heating</th>
<th>Heating</th>
<th>Permeability after heating to 400 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A4</td>
<td>2E-17</td>
<td>Thermal shock 400 °C</td>
</tr>
<tr>
<td>A5</td>
<td>2E-17</td>
<td>1 deg/min</td>
</tr>
<tr>
<td>ratio:</td>
<td></td>
<td>1,1</td>
</tr>
</tbody>
</table>

Table 5 Permeability after different heating rates to 600 °C.

<table>
<thead>
<tr>
<th>Permeability before heating</th>
<th>Heating</th>
<th>Permeability after heating to 600 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A8</td>
<td>3,2E-17</td>
<td>Thermal shock</td>
</tr>
<tr>
<td>A6</td>
<td>3,2E-17</td>
<td>1 deg/min</td>
</tr>
<tr>
<td>ratio:</td>
<td></td>
<td>1,0</td>
</tr>
</tbody>
</table>

Free thermal strain

Tests of the free thermal expansion of concrete types A, E and I were performed in a test apparatus located [5] at Centre Scientifique et Technique du Bâtiment (CSTB) in France. The thermal expansion up to 600 °C was measured on cores with a diameter of 104 mm and length of 300 mm. The used heating rate was 1 degree per minute.

Test results from the thermal expansion measurements performed on concrete types A, E and I show, as seen in Figure 8, quite similar result for the different concretes. This is expected because the only difference between the concretes is the amount of PP-fibres added and the major driving force for expansion is the aggregate which is the same in all mixes. There is one interesting difference although it is small. As seen in figure 9, at around 200-250 °C the thermal expansion decreases to zero or close to zero for concretes E and I. After this decrease there is an increased expansion rate between 250-300 °C compared to concrete A, so at 300 °C the total strain is almost the same as before the strain plateau. Concrete A is free from PP-fibres while concrete E contains 1 kg/m³ 18 μm PP-fibres and I contains 1.5 kg/m³ 18 μm PP-fibres. Further, the decrease is highest for the highest content of PP-fibres. This behaviour can be seen both in the longitudinal and radial direction of the tested cylinders.
CONCLUSIONS

The addition of polypropylene fibres in concrete prevents or reduces the amount of fire spalling. The mechanism, or mechanisms, leading to this reduction of spalling by PP-fibres is not known in detail. However, the effects of a PP-fibre addition were shown in several different areas in the present research project. PP-fibres:
• reduce or prevent fire spalling
• modify the capillary saturation close to the surface of concrete
• limit the internal destruction at moderate heating, 5 °C per minute.
• modify the drying behaviour at high temperature
• introduce a plateau in the free thermal strain curve.

Other findings, from a limited study of material properties, concluded that concrete without PP-fibres heated with a thermal shock to 600 °C had twice the residual permeability as concrete heated at a heating rate of 1 °C per minute to the same target temperature. The same test performed with a target temperature of 400 °C did not reveal any measurable difference.

ACKNOWLEDGEMENTS

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REFERENCES

Safety Doors in the World’s Longest Tunnel – Test Experience from Selected Prototypes

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ABSTRACT

The Gotthard Base Tunnel will be the world’s longest railway tunnel, with a length of 57 km. The two single-track tubes are linked by 178 cross passages every 300 m approximately, and two stations with an emergency exit for each tube, the location is about one-third and two-thirds along the base tunnel. During the regular operation both high speed passenger trains (up to 250 km/h) and slower freight trains (up to 160 km/h) will run through the tunnel. In a case of emergency, the doors of the cross passages and those of the emergency stations will be essential elements of the safety concept. A high safety level is a very important premise for the operation of a railway tunnel and as well an economic exigency. After the fatalities in some existing long traffic tunnels the public opinion shows special sensitivity to tunnel safety: in general clients and project managers were called upon to undertake every reasonable effort to further increase tunnel safety. In order to assure a long service life (long durability, no revision of the doors in the first 20 years after the installation), the required fire protection (90 minutes with a temperature of 1’000 °C) and the efficiency in case of an evacuation, very high and severe requirements have been set for the delivery of these doors. The client – AlpTransit Gotthard Ltd. – decided to adopt a special procedure for the commissioning and for the evaluation by means of prototypes. A selective bidding procedure with pre-qualification has been started on January 2005. The paper gives a short presentation of the safety concept in case of fire accident (evacuation procedure) and a panoramic of the most important requirements of the different door-types. It gives also the state of progress of the special procedure for the commissioning and the feed-backs from the tests on selected prototypes.

KEYWORDS: emergency door, dynamic load, fire test

INITIAL SITUATION

According to studies by AlpTransit Gotthard AG, the cross passages in the Gotthard Base Tunnel play a decisive part in the safety arrangements. The 175 or so cross passages which link the transport tubes with each other are used as escape routes in case of an incident, sealing off the transport tubes at both ends by means of doors.

The closures must perform the following main tasks:

- in the regular operating phase, they seal the cross passage off from the transport tubes in which the trains travel at up to 250 km/h. They form a protected area for the technical rail equipment.

- during a rescue phase in case of an incident (a fire involving a train in the tunnel), the fire resistance of the doors prevents the fire from spreading into the cross passage and into the neighboring tube which is still intact.
- the doors which are not directly adjacent to the seat of the fire are used as escape doors, and they prevent smoke from passing through into the protected cross passage area during the rescue phase.

AlpTransit Gotthard AG requested testing of the most important requirements for the cross-passage doors in order to ensure the reliable functionality of the installed doors during operation.

All the important requirements for the cross-passage doors are described in detail in a test catalog drawn up by AlpTransit Gotthard AG. A brief summary is given here:

- tightness of the cross-passage doors
- opening and closing procedures, with and without pressure loads
- long-term behavior of the cross-passage doors with respect to suction and pressure loading, due to the passage of trains
- function of the cross passage doors at increased temperatures
- behaviour of the cross passage doors in case of fire.

The specified tests were conducted by VSH Hagerbach Test Gallery Ltd., Sargans/Flums, and the Berner Fachhochschule (Berne University of Applied Sciences, BFH) with the Departments of Technology and IT, Burgdorf, and of Architecture, Wood and Building, Biel, working as a combined team.

TEST

Before commencing the physical tests, the prototypes had to be installed by the manufacturers at VSH Hagerbach Test Gallery Ltd. under the same geometric marginal conditions for tunnels as are to be expected in the Gotthard Base Tunnel. The limited width of the cross passage and the restricted accessibility of the cross passage doors had to be countered with well thought-out logistics.

- **Opening and closing procedures**

For the initial test, the opening and closing forces, together with other functions of the cross passage doors, were determined without a static pressure load in the first instance.

After this, the opening and closing forces were measured with a pressure load on one side. For this purpose, a pressure differential of 500Pa was built up between the front and rear sides of the cross passage doors. In case of an incident, this pressure differential is built up in the cross passage to prevent smoke from penetrating into the cross passage.

Large high-power fans were used to subject a section of the VSH Hagerbach Test Gallery Ltd. to overpressure. The pressure in the tunnel was set to 500Pa by means of overpressure flaps. When the cross-passage doors were opened, the fans had to be readjusted to counteract the pressure loss on the doors.

The following items were measured in connection with this test:

- opening forces in order to open the doors with the pressure differential present
- duration of the automatic closing procedure for the doors
- forces on encountering an obstacle during the door closing procedure
Figure 1: Large fan to build up pressure

Figure 2: Tunnel section in which pressure of 500Pa is built up

Figure 3: Measuring the operating forces with a test robot
Permanent load tests

In order to test the alternating dynamic loads which act on the doors in the tunnel while trains pass through, as a result of the pressure wave in front of the train or the suction ('pull') zone behind it, a dedicated test apparatus was developed which is able to simulate these loads realistically.

This pneumatically operated test apparatus creates a realistic load which allows integral testing of the door structure with all its mechanical elements and seals.

The test object is mounted in a frame in the same way as will happen at the subsequent operational location. A pressure chamber is placed on the side from which the load acts (Figure 4 and 5). In order to reduce the volume, packings are positioned in the pressure chamber. The test chamber is cyclically subjected to overpressure and underpressure via several valves. The load level can be adjusted continuously to the respective requirements. For the test on the cross-passage doors, pressure surges of 20 kPa and underpressures of -10 kPa were implemented. In relation to the area of the cross passage doors, this corresponds to a load of up to 10 tonnes (pressure) and up to 5 tonnes (suction). In this instance, the doors were exposed to 500,000 load changes at a frequency of 0.5 Hertz. Several pressure sensors positioned in the pressure chamber ensure and document the uniform loading of the test object, and are also used to control the test apparatus. If the load pressures can no longer be applied, e.g. due to damage to the seals, an automatic alarm is given and the test apparatus interrupts the testing procedure.

![Diagram of permanent load test apparatus](image1)

**Figure 4: Diagram of permanent load test apparatus**

![The permanent load test apparatus at VSH Hagerbach Test Gallery](image2)

**Figure 5: The permanent load test apparatus at VSH Hagerbach Test Gallery**
In order to investigate the long-term behavior of the cross-passage doors during the permanent load test, the permanent load test is interrupted after about 100,000 cycles in each case; 5 opening and closing procedures are performed; and any damage to the doors is recorded.

In order to assess the results of the permanent load tests, the permanent deformations are then recorded and the operating forces for the opening and closing procedures are measured again under static pressure of 500Pa.

Fire test

In case of an incident (fire), it is assumed that the development of heat in the tunnel allows escape for a certain period, despite the rising temperatures near the seat of the fire. This was simulated by measuring the operating forces on the door during opening and closing, on the rail tunnel side, at a pressure of 500Pa and a simultaneous ambient temperature of 90°C for 90 minutes.

The fire test was carried out on the basis of EN 1363, EN 1634, EN 13501 and according to the client's fire load curve.

The assessment of the fire resistance of the doors was determined using the surface temperatures on the side facing away from the fire. These were continuously measured and recorded on the entire door leaf (Figure 6) and also on the door frame and stops. The measured data from each thermo-element are recorded separately by the data logger, so that any desired average or maximum value can be read after the fire test.

The fire test is carried out as per the Goods Train Fire Curve (ATG). The following requirements must also be met in this case:

- the flames must not come into contact with the cross passage doors
- the temperature should rise to 1000 °C in the first 5 minutes
- the duration of the fire load is 90 minutes
- the fire load should be applied to the entire structure, including at least 30 cm on the concrete frame.

The behavior of the entire system is recorded during the fire test. The behavior of seals and pipe/cable leadthroughs is of special interest.

The concrete frames, which are hardened with PP fibers, withstand the fire loads. Minor detachments
(in the millimeter range, Figure 7) occur on the surface of the concrete, but they do not impair the stability of the frame during any phase of the fire test.

![Figure 7: Instances of detachment on the concrete frame](image)

**CONCLUSION**

The tests with effective loads demonstrated that this is the only method of testing loads in accordance with operational conditions. As well as the cross-passage doors, which were tested as described above, the test apparatus described here can also be used to examine and test other items of equipment for tunnel installations. These items may include equipment that is exposed to alternating air pressure loads as well as fire loads.
Fire fighting access – A probabilistic approach

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ABSTRACT

A large ring road around a major Spanish city has undergone a significant upgrade to improve traffic flows, open up areas for redevelopment and lessen its environmental impact. Parts of the works include lowering sections of ground level motorway into tunnels.

A probabilistic fire fighting access analysis was performed for one part of the tunnels. The main aim of the analysis was to evaluate acceptable distances between fire fighting access points. Two different distances were evaluated; 100m and 200m. The acceptable distance depends heavily on the type of fires foreseen for the tunnel and the different technical systems (detection, ventilation, etc.) incorporated into the tunnel.

This paper discusses the methodology of the analysis. It describes how event tree analysis and CFD modeling were used. The paper gives a description of how a probabilistic approach can be used to evaluate the fire fighting access to a tunnel. The main conclusion for the scenarios evaluated was that it is acceptable with access points at 200m centres instead of 100m centres for this specific section of the tunnels. This was due to the minor consequences associated with increase in distance (from 100m centres to 200m centres) between accesses points produced, which amounted to some extra time in smoke free conditions while approaching the fire.

Another important conclusion from the fire fighting access evaluation was that the probability of a successful fire fighting operation is much higher if the fire brigade is equipped with infrared equipment. The configuration of the ventilation system is very important; fires will behave differently depending on where in the tunnel they start. When configuring the ventilation system the fire size and the fire location are the two most important factors to keep in mind.

KEYWORDS: tunnel safety, fire fighting access, probabilistic analysis

1. INTRODUCTION

This article describes a probabilistic fire fighting access analysis. A probabilistic analysis takes into account frequencies and probabilities for different events. For example it takes into account how often a car fire will occur or the failure probability of the ventilation system. In this way it’s possible to determine how often certain events will occur and to see what kind of events are expected more frequently and what kind of events are considered to be rare.

The opposite of a probabilistic analysis is a deterministic analysis, in this type of analysis the car fire would be assumed to occur (how often is not taken into account) and the different systems would be assumed to work (the probability of failure is not taken into account).

2. PROCESS

This section describes the process of the analysis. The different steps are described in a general way, further on they will be described in more detail.
Event tree analysis

Event trees were used as the basic tool to estimate the frequencies of the scenarios considered. It is important to identify the frequencies for the different events that could occur in the tunnel. This analysis identified the different fire scenarios that were most likely to happen, as well as the fire scenarios that were very rare.

For this analysis it is important to know the traffic volume for the tunnel, the fire frequency for different types of vehicles and the failure probability for different types of technical system used in the tunnel (ventilation, detection, etc.). The event tree analysis forms the base when choosing representative fire scenarios for the main analysis. Return periods were used to determine these scenarios.

Fire scenario modelling / calculation

When the representative scenarios have been determined (the event tree analysis) it is important to see how they affect the conditions within the tunnel. Fires in the tunnel were evaluated with both manual calculations and CFD modelling. The modelling/calculations showed how different zones of the tunnel were affected (temperature, visibility, radiation, etc.) during a fire. The main aim of this analysis is to determine the different conditions (expected from the chosen fire scenarios) that a fire fighting team could be exposed to during an emergency within the tunnel.

Fire fighting access analysis

This analysis established the expected time needed to get close to the fire having in mind the hazardous conditions in the tunnel during the fire. The analysis also established the main criteria that needed to be fulfilled to be able to consider a fire fighting operation successful. There are mainly two factors that have an impact on how a fire in a tunnel can be approached:

- The tunnel environment (visibility, temperature, radiation)
- The distance to the fire (distance between access points)

The main aim of this analysis is to determine the necessary time for different fire fighting approaches and the main criteria for a successful fire fighting operation.

Evaluation

The last step of the analysis is to evaluate the results from the fire fighting access analysis and CFD modelling. The main aim of the evaluation is to determine the differences/consequences between having different distances between access points and in that way evaluate the suitability of the fire fighting access provisions for the tunnel.

3. TUNNEL / SYSTEMS DESCRIPTION - GENERAL

Tunnel description

The tunnel is a bored tunnel; the length is approximately 4 km.

It is divided into two parts; an upper and lower level. The upper level is used for normal traffic, it consists of three lanes. The total width is around 13m and the minimum height around 5 m. The lower level is for emergency vehicles; the effective width for this part is around 6m and the height around 3m. This lower part of the tunnel is separated from the normal traffic upper part of the tunnel, it is
separated by the floor slab supporting the upper level road. The following figures give a good understanding of the layout of the tunnel. The top part of the upper level and a part of the lower level is used for the ventilation system.

Figure 1  Tunnel section

Systems description

The tunnel is equipped with all the safety systems that would be expected of a new modern road tunnel. This article gives a short description of two of the main systems; the ventilation system and the detection system, as these are considered to be the two most important ones for the purposes of this assessment.

The tunnel ventilation system is very important during a fire as the smoke movement within the tunnel during a fire strongly depends on the type of ventilation system used.

The ventilation in this tunnel is fully transverse system. The tunnel is divided into different ventilation sections, each one with an approximate length of 600m. In each section there are extract points every 25m of tunnel length and inlet points at every 10m. In addition to the extracts points there are large capacity main extracts at the beginning and end of each section.

When a fire is detected, the tunnel controller/emergency services will select Mode 2 or Mode 3 as described on the following page.

Mode 1

In service mode the amount of extracted air is the same as the amount of supplied air. The following figure shows the main principles of the ventilation scheme for service mode. The large capacity main extract points are not activated.

Figure 2  Mode 1 – Service mode
Mode 2

Mode 2 is the fire mode used during congested traffic (during an emergency evacuation in conditions of congested traffic). For this mode, the two sections on each side of the fire section will continue to operate in Mode 1 but the fire section ventilation will be modified. The extract rate will increase and inlet air rate will decrease. The following figure shows the main principles of the fire ventilation for mode 2. The large main extract points are not activated.

![Figure 3: Mode 2 – Congested Fire mode](image)

It is expected that the evacuation of vehicle occupants will take place in this mode.

Mode 3

Mode 3 is the fire mode used during non congested traffic or manually by the fire brigade when the evacuation is considered to be over. For this mode, the section behind the fire (where traffic queues behind the incident) will continue in service mode. In the fire section, the extracts points will be closed and the large capacity main extract point at the end of the fire section will start to operate and the inlet air rate will drop. In the section ahead of the fire, one large capacity main extract point will also start to operate, as in the fire section, but the inlet air rate will continue in service mode.

![Figure 4: Mode 3 – Fire Fighting/non congested fire mode](image)

The detection system is vital when it comes to tunnel safety. Many of the safety systems used in the tunnel depend on the detection systems for their operation (ventilation systems, evacuation systems, traffic management systems, etc.). A linear heat detection cable was used in the tunnel; high reliability can be expected for such a system (the coating of the cable protects against aggressive ambient and mechanical influence).

4. EVENT TREE ANALYSIS

This section gives a description of how the event tree analysis was performed. The aim of the analysis was to determine the fire scenarios used as input for the fire modelling.

Event trees

Event trees are used to predict the frequencies/probabilities of infrequent events by the logical connection of a series of much more frequent sub events for which data is available. Event trees work forward from an initiating event to generate branches defining events and paths resulting from secondary (or nodal events) to investigate the range of outcomes. The frequency associated with each branch (outcome) is given by multiplying the initiating frequency with the relevant conditional
probabilities of success/failure.

All the relevant safety systems etc. formed part of the event tree.

The following figure shows a typical section of an event tree, the initial event is a fire in a vehicle. As can be seen from this specific tree there are three different end scenarios (outcomes).

The event trees were based on four basic fire scenarios. These scenarios are:

- Light vehicle fire (uncongested traffic)
- Light vehicle fire (congested traffic)
- Heavy vehicle fire (uncongested traffic)
- Heavy vehicle fire (congested traffic)

These four events formed the basis of the event trees.

Return periods

Return periods are used to choose the fire events used for the FDS simulations.

Return period can be defined in the following way: The average time until the next occurrence of a defined event. The return period is equal to the inverse of probability of the event occurring in the next time period, that is, \( T = \frac{1}{P} \), where \( T \) is the return period, in number of time intervals, and \( P \) is the probability of the next event's occurrence in a given time interval.

The following table shows eight scenarios (and the return periods) from the event trees.
Table 1  Return periods

<table>
<thead>
<tr>
<th>No</th>
<th>Fire Scenario</th>
<th>Return period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Single vehicle (light), Early detection, Ventilation working, Not congested</td>
<td>1.55</td>
</tr>
<tr>
<td>2</td>
<td>Multiple vehicles (light), Early detection, Ventilation working, Congested</td>
<td>4.67</td>
</tr>
<tr>
<td>3</td>
<td>Single vehicle (light), Early detection, Ventilation partial failure, Not congested</td>
<td>14.03</td>
</tr>
<tr>
<td>4</td>
<td>Single vehicle (heavy), Early detection, Ventilation working, Not congested</td>
<td>15.69</td>
</tr>
<tr>
<td>5</td>
<td>Multiple vehicles (light), Early detection, Ventilation partial failure, Congested</td>
<td>42.08</td>
</tr>
<tr>
<td>6</td>
<td>Multiple vehicle (heavy), Early detection, Ventilation working, Congested</td>
<td>47.96</td>
</tr>
<tr>
<td>7</td>
<td>Single vehicle (heavy), Early detection, Ventilation partial failure, Not congested</td>
<td>141.27</td>
</tr>
<tr>
<td>8</td>
<td>Single vehicle (light), late detection, Ventilation working, Not congested</td>
<td>154.32</td>
</tr>
</tbody>
</table>

Choice of fire scenarios

A normal approach for technical design is to use different return periods depending on the event. Design for structural stability for buildings sometimes uses a return period of 50 years for wind events, 475 years for seismic events, etc.

For fire events there are no guidelines about which return periods to use. Normally specific design fires, depending on the types of vehicle that are going to use the tunnel, are used (a deterministic approach). A code approach would have meant a deterministic approach where no consideration is given to the possibility of failure of the detection system, the ventilation system, etc.

In this probabilistic analysis a return period limit of 100 years was used for the fire events (only events with a return period of 100 years or less was considered). To use a fire scenario expected to happen every 100 years as a limit is considered appropriate. When compared with the code approach the fire events used in this analysis are considered to be more conservative than the code approach as this analysis takes the probability of failure of technical systems into account. This means that fire scenarios 1-6 were further analyzed. Some of the scenarios were simulated with CFD. As described earlier the ventilation system has different modes, when “ventilation partial failure” is assumed for the scenarios it means that the “fire fighting mode” is not initiated.

5. FIRE SCENARIO MODELLING / CALCULATION

Scenarios

The results from the event tree analysis are used to determine which scenarios should be modelled. All the chosen scenarios are basically based on the same fire loads, a single vehicle fire and a two vehicle fire. Three of the fire scenarios that were simulated are described in the following table.
Table 2  Fire description

<table>
<thead>
<tr>
<th>Fire Scenario</th>
<th>Vehicle description</th>
<th>Fire Size</th>
<th>Fire description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2 vehicles (light)</td>
<td>14 MW</td>
<td>Fast growing fire (&quot;&quot;&quot;)</td>
</tr>
<tr>
<td>3</td>
<td>1 single vehicle</td>
<td>7 MW</td>
<td>Fast growing fire,</td>
</tr>
<tr>
<td></td>
<td>(light)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1 single vehicle</td>
<td>30 MW</td>
<td>Ultra ultra fast growing fire</td>
</tr>
<tr>
<td></td>
<td>(heavy)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:  (1) The second car starts to burn 2 minutes after the first one.

Fire modelling (CFD)

The chosen scenarios were modelled with a Computational Fluid Dynamics (CFD) software program; the program is called Fire Dynamics Simulator (FDS). FDS is a software package developed by the National Institute of Standards and Technology (NIST) of the USA. The software solves numerically a form of Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport for fires. The program is widely used and the model has undergone a considerable amount of validation work. FDS is used to determine the conditions (visibility, temperature and radiation) in the tunnel during the fire.

6. FIRE FIGHTING ACCESS ANALYSIS

Tactics

Tactics during a rescue operation can basically be described as the ongoing prioritization of resources and measures that the rescue commander will use in to deal with the accident. The tactical approach is heavily affected by the type of accident (large fire, toxic release, etc.), the environment of the accident (tunnel, open road, etc.), the aim if the rescue operation (assist in evacuation, extinguish fire, etc.) and the resources available. The competence of the rescue commander and the personnel also has an influence on the end result. All these components will together influence the overall tactic chosen for the rescue operation and influence the overall result of the operation, “Räddningsinsatser i vägtunnlar” [1].

The following tactics were assumed in the analysis:

- Aim of the rescue operation is to extinguish the fire.
- It is assumed that the evacuation has taken place and asset protection fire fighting is underway.
- There are enough resources to start and continue a fire fighting operation to approach the fire.

As can be concluded from the points above the fire brigade arrive to the accident when the tunnel has been evacuated, the aim of the operation is to be able to reach the fire location and start the extinguishing operation. It is assumed that there are enough personnel to start the operation.

Normally the fire brigade would have to help injured people in the tunnel, this is not taken into account for in this analysis. The aim of the rescue operation is to extinguish the fire (asset protection).

Working environment

The working environment has a strong influence on the success of the fire fighting operation. There
are mainly three factors that need to be taken into account:

- Visibility
- Radiation
- Temperature

The visibility mainly affects the walking speed i.e. how fast a fire fighting team can approach the fire location. The temperature and the radiation from the fire affect how well and for how long it is possible to work efficiently, the radiation from a fire also has strong influence on how close a fire fighting group can get to the fire.

For this exercise the following criteria (working environment) and assumptions have been used:

- Visibility – A visibility distance of more than 15m is considered to allow unhampered fire fighter movement. The document “Fire and Smoke control in Road tunnels” [2] suggests that a minimal visibility distance of 7-15m must be aimed at for fire fighting operations.

- Radiation – A radiation limit of 5 kW/m² is used i.e. if the radiation onto fire fighters is higher than this limit they can’t continue with the fire fighting operation. This limit is also recommended in “Fire and Smoke control in Road tunnels” [2].

- Temperature – It is difficult to establish an appropriate temperature limit. There is a significant lack of research regarding this and it is not that easy to model (the physical fitness of the person, amount of protective clothing, etc. has an influence). For this exercise a limit of 70°C is used, Ondrus [3] suggests a tolerance time of 1 hour for this temperature.

A fire fighter endurance time of 30 minutes is taken (based on available air and a specific rate of air consumption).

**Effectively fight a fire**

An important part of the rescue operation is to be able to get close enough to the fire, it is necessary to get a sufficient amount of extinguishing agent (water) onto the fire.

Swedish research, “Räddningsinsatser i vägtunnlar” [1], has investigated the effectiveness of fire fighting nozzles at different distances from a tunnel fire, and the amount of fire fighting nozzles needed to effectively fight fires from different distances (based on the amount of water needed to extinguish the fire). That research was used to establish criterion for the analysis.

It was considered important that one fire fighting group should be able to start fighting a fire and that the effectiveness of the nozzle must be high. Based on research mentioned above it was considered that a fire fighting group should be able to get within 15m of the fire location to be able to effectively fight the fire. This is used as a criterion when evaluating the FDS results.

**Speed of movement**

The most important factor when assessing the access for the tunnel is the speed that a fire fighting team can move down the tunnel.

The moving speed depends mainly on the visibility within the tunnel but also the time needed to
connect hoses etc. needs to be taken into account. There is not that much research done about this but there is some Swedish research available on the subject, “Räddningsinsatser vid tunnelbränder” [4].

The aim of the Swedish research was to investigate the moving speed of a fire fighting group for different conditions and in that way be able to see how well different accident scenarios could be handled. The average fire fighting moving speeds determined from the research was used in the analysis. It was clear that low visibility and the need to work with hoses slow down the moving speed. The most important factor is considered to be the visibility. This tends to suggests that measures/airs that have an influence on the visibility and the work with hoses is of importance for the moving speed.

**Analysis and results**

For the moving speed analysis two different distances will be analysed:

- 200m between access points (max distance to fire is 200m)
- 100m between access points (max distance to fire is 100m)

The influence of having of having infrared equipment (good visibility) and be able to connect hoses at different distances (every 50m) is also taken into account. The following three scenarios are analysed:

1. Low visibility within the tunnel (smoke filled). The fire fighters start the operation with the hose connected.

2. High visibility within the tunnel (smoke filled but using Infrared equipment or smoke free). The fire fighters start the operation with the hose connected.

3. High visibility within the tunnel (smoke free). The fire fighters do not start the operation with the hose connected; they connect the hose close to the fire (50m).

The following table summarizes the time needed to get close to the fire for the three different scenarios, having in mind the two different access point’s distances.

<table>
<thead>
<tr>
<th>Distance between access points (distance to fire): 200m, 100m</th>
<th>Approach</th>
<th>Time needed to get close to fire (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 – Low visibility</td>
<td>30.76</td>
<td>15.38</td>
</tr>
<tr>
<td>2 – High visibility</td>
<td>11.11</td>
<td>5.55</td>
</tr>
<tr>
<td>3 – High visibility</td>
<td>5.27</td>
<td>3.61</td>
</tr>
</tbody>
</table>

The times shown above do not include the time needed to retreat, this time should conservatively be taken as the same time it took to reach the fire. In reality this time might be less due to the fact that the fire fighters will know the route back.

The following can be concluded from the table:

- For the case with **low visibility** it is unlikely that the fire fighting operation will
be successful. For the 200m distance the 30 minute action time is basically used up before the fire fighting group reaches the fire, for 100m distance they will need to retreat as soon as they reach the fire (no time for fighting the fire).

- For the high visibility cases the fire fighting team will be able to reach the fire, fight the fire and to retreat. For both the 200m distance and the 100m distance it is very likely that the fire fighting operations can be started. When one fire fighting team has to retreat it is assumed that another team will continue to fight the fire.

These conclusions were used in conjunction with the results from the fire modelling to evaluate the fire fighting access.

**Success criteria**

When evaluating the results from FDS analysis it is important to determine the criteria needed to be fulfilled to be able to say that a fire fighting operation is successful.

For this exercise two main criteria have been established (based on former sections, see above):

- Distance (fire fighters must be able to get within 15m of the fire)
- Time (fire fighters must be able to get to the fire location within 12 minutes)

These two criteria are used when evaluating the fire fighting access for the tunnel.

**8. EVALUATION**

The evaluation takes the results from the FDS simulations and the fire fighting access analysis into consideration. In all scenarios the temperature for fire fighting conditions is less than 70°C; high temperatures are only experienced very close to the fire (less than 15m). The same applies for the radiation levels, the 5 kW/m² limit is always within 12m from the fire. As the temperature and radiation criteria are within the limits it’s only the visibility conditions that are evaluated below. It is assumed that the fire fighting team always will approach the fire from the side with the best conditions and that if the start of mode 3 creates worse conditions this mode is not started (or aborted).

The following two sections show a typical evaluation.

**Evaluation 1**

Scenario 2: The fire consists of two light vehicles, the detection system is working, the ventilation system is working and the traffic is congested.

Conditions: The visibility is good (>15m) up to a distance of around 100m-130m on both sides of the fire, assuming ventilation Mode 2 is employed initially. If closer than this distance, the visibility drops to less then 5m. When fire mode 3 starts the conditions on the upstream side stays as before but they get significantly worse on the downstream side and visibility will drop to less than 5m for several hundreds of meters.

Results: If the fire fighting operation is started 100m away from the fire the fire fighters start in smoke filled conditions. If started 200m away from the fire the first 100m are smoke free and the following 100m are in smoke filled conditions. The time difference between the two scenarios is the time needed for the fire fighting group to move 100m in smoke free conditions, an extra time of
approximately 4-6 minutes. If the fire fighters are equipped with infrared equipment (high visibility even in smoke filled conditions) the 200m distance is acceptable. A fire fighting group will be able to get within 15m of the fire location and the time needed to get to the fire is less than 12 minutes. If they are not equipped with infrared equipment both the 100m distance and the 200m distance are considered to be non acceptable. The fire fighting operation is considered to be successful only if the fire fighting group is equipped with infrared equipment.

Evaluation 2

Scenario 4: A fire in a single heavy vehicle, the detection system is working, the ventilation system is working and the traffic is not congested.

Conditions: These scenarios are a bit different from the others. On one side of the fire the visibility is good (>15m) up to a distance of 40m from the fire, this is during fire mode 2, on the other side of the fire there are smoke filled conditions for more than 200m. This has to do with the slope of the tunnel, the smoke from a large fire has a high buoyancy and flows upwards along the positive slope. When fire mode 3 starts the conditions get worse. Both sides, upwind and downwind, of the fire get smoke filled.

Results: If the fire fighting operation is started 100m away from the fire the fire fighters start in smoke free conditions. If started 200m away from the fire the first 160m are smoke free and the following 40m are in smoke filled conditions. The time difference between the two scenarios is the time needed for the fire fighting group to move 100m in smoke free conditions. Even if they are not equipped with infrared equipment the 200m distance is considered to be acceptable. A fire fighting group will be able to get within 15m of the fire location and the time needed to get to the fire is less than 12 minutes. The fire fighting operation is considered to be successful.

9. CONCLUSION

The evaluation part showed that for most scenarios the 100m closest to the fire will be smoke filled, and that the main difference between having access points at 100m centres and 200m centres is the walking time in smoke free conditions. This time is considered to be between 4-6 minutes.

If the fire brigade don’t have access to infrared equipment it is considered that the fire fighting operation for most scenarios (both for access points at 100m centres and 200m centres) won’t be successful. If the fire brigade has access to infrared equipment it is considered that the fire fighting for most scenarios will be successful (both access distances considered).

It is considered that having access points at 200m centres does not significantly change the probability of a successful fire fighting operation. There is a minor difference in time between the two options.

The main conclusion for the scenarios evaluated is that conditions are adequate with access points at 200m centres instead of 100m centres. This is due to the minor consequences associated with the distance increase from 100m centres to 200m centres between accesses points, which amounts to the extra walking time in smoke free conditions. The extra walking time is relatively small and from a cost/benefit or safety perspective the gain in having access points at 100m centres would probably not be justifiable.

Another important conclusion from the fire fighting access evaluation is that the probability of a successful fire fighting operation is much higher if the fire brigade has access to infrared equipment.

10. DISCUSSION

The analysis seems to suggest that the success of fire fighting operation depends more on the
provision of infrared equipment than the reduction of access point distances. The provision of infrared equipment would be a much more cost effective measure.

When evaluating the fire fighting access for a tunnel a probabilistic approach have the following advantages:

1. It can be tailored for the specific tunnel. The traffic volume, the vehicle types, the safety systems, the tunnel layout etc. foreseen for the tunnel can be taken into account.

2. Determine frequent events for the specific tunnel. The analysis gives a range of events that are considered to be more frequent than others, but also shows what events can considered very rare.

With this in mind it should be possible to more effectively plan rescue operations within the tunnel, the different conditions to be expected from certain events are known. The results from the analysis could also be used to prepare training exercises, based on the events with a higher probability of occurrence, for the fire brigade. Another important benefit from the analysis is that it’s possible to see the relative importance of the different safety systems for the tunnel and how they affect conditions in the tunnel in the event of an incident accident (especially the ventilation system configuration is important).

The slope of the tunnel has an important effect on large fires. For the small fires simulated in the analysis, the tunnel slope did not have a pronounced effect. However, this is dependant on the fire location, and for fires located in a section with a very high slope (more than 2.5%) the smoke will most likely behave differently.

The simulations show that for large fires, when placed in a slope of 2.5%, for which the smoke has high buoyancy the ventilation system does not work effectively. Initiating mode 3 for large fires could potentially make conditions worse for this specific tunnel.

The configuration of the ventilation system is very important; fires will behave differently depending on where in the tunnel they start. When configuring the ventilation system the fire size and the fire location (the tunnel gradient in that location) are the two most important factors to have in mind.

11. REFERENCES


2. Fire and Smoke Control in Road Tunnels, ISBN 2-84060-064-1, PIARC, 1999


Incident Management in a Very Long Railway Tunnel

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ABSTRACT

A very long railway tunnel requires additional measures to guarantee a sufficient safety level. These measures as emergency stations and ventilation systems however increase also the complexity of the incident management.

For the 32.8 km long Koralm tunnel the tunnel system and the layout of the emergency station with an 800 m long refuge room and a ventilation system using “bypass channels” are illustrated. Due to the piston effect the running of trains in case of an emergency will have an important influence on the airflows in the tunnel. It is therefore crucial to limit the number and the speed of the trains running to met the ventilation targets.

With the analysis of traffic scenarios characteristic operating situations were analysed to realistically reflect the sequence of events in case of an emergency.

KEYWORDS: tunnel safety, railway safety, ventilation, emergency station

THE KORALM TUNNEL PROJECT

The Koralm tunnel is one of the key elements of the new Koralm railway line, which connects the cities of Graz and Klagenfurt in the south of Austria. The Koralm railway line is part of the Baltic-Adriatic Axis, which represents the easternmost crossing of the Alps and links several Eastern European countries and Vienna with southern Austria and northern Italy (see Figure 1). The Koralm line is a 130-km-long high-performance railway line engineered for a design speed of 200 km/h.

In the centre section of the Koralm line lies the Koralm tunnel, which underpasses the Koralpe mountain range at a depth of up to 1,200 m. Its length of 32.8 km makes the Koralm tunnel the longest railway tunnel located entirely within Austrian territory.

Following the route selection procedure and the environmental impact assessment, the first construction permit in compliance with Austrian railway law was issued in 2006. At the moment, exploratory measures involving pilot tunnels and deep drillings are being implemented in the tunnel area. The construction works are scheduled to start in 2008.
Starting with the design process for the environmental impact assessment, a system analysis was launched to examine the essential elements of the Koralm tunnel. This analysis considered construction and operating phase criteria. For the operating phase, the effects regarding passenger safety, maintenance, power consumption, aerodynamics and operating safety were taken into consideration.

Based upon this analysis, the following system was chosen (see Figure 2):

- Two single-track tubes
- Cross-passages connecting the tubes at a 500 m distance
- One emergency station in the centre of the tunnel with no direct link to the surface
- No crossover inside the tunnel

Figure 2: Tunnel system Koralm tunnel

Emergency exits in new Austrian railway tunnels are – in analogy to the Guideline issued by the Austrian Fire Fighters Association [1] – currently constructed with a standard distance of 500 m, regardless whether they lead to a second tube or to the surface. This standard distance has also been adopted for the Koralm tunnel.

In case a fire occurs in a running train inside a tunnel, the train should leave the tunnel as fast as possible, since the chances of people being rescued are considerably lower inside the tunnel than outside the tunnel.

The TSI (Technical Specification for Interoperability) [2] states that, in case of a fire, the running capability of a train is to be ensured for a period of 15 minutes, permitting the train to proceed at a speed of 80 km/h.

These requirements regarding the running capability of trains indicate that, with tunnels featuring a length in excess of 20 km, the probability of leaving the tunnel decreases. It is in response to these findings that the guidelines call for special measures in tunnels exceeding a length of 20 km [2]. For the Koralm tunnel, the construction of an emergency station in the centre of the tunnel was investigated as an additional safety measure. This emergency station serves the purpose of creating an area which offers exceptionally favourable self-rescue conditions in case of a fire. A train is brought to a halt in the emergency station before its running capability has reached its limits.

A train operation simulation was performed to decide whether a crossover would be needed in the Koralm tunnel. This crossover would primarily be used during maintenance works, since a section of the tube, which is to be worked on, would then be closed. The simulation also covered an increase in train traffic induced by a possible upgrade of the feeder lines. The studies confirmed that, even if no crossover is provided inside the tunnel and if one tube is completely closed due to maintenance works, a sufficient train operation quality can still be ensured.

Safety considerations (accidents caused by switches are reduced, strict separation of tunnel tubes) as well as the need for additional maintenance work (inspection of switches and connecting tunnel tubes with doors and installations) were facts speaking against a crossover.
RESCUE CONCEPT

When developing the rescue concept for the Koralm tunnel, a special effort was made to assure maximum uniformity with the sequences determined for other tunnels of the Koralm railway line and with the Austrian railway network as a whole.

Railway operation
The first operational steps to be taken when a fire occurs inside the tunnel may be summarised as follows:

- All trains shall leave the tunnel; passenger trains which have not passed the emergency station yet shall stop upon arrival at this point.
- All trains, running ahead of the accident train, shall drive out of the tunnel.
- All trains following the accident train shall – by moving backwards – secure the greatest possible distance to the hazard zone, or they shall be evacuated.
- All trains in the second (safe) tube shall either come to a halt or continue their journey at reduced speed.

Self-rescue, evacuation
A self-rescue becomes necessary, when an emergency occurs, that brings a train to a halt inside the tunnel, that keeps a train from driving on and that puts a person’s life at risk. When a train stops at a random location inside the tunnel, the self-rescue is performed via cross-passages leading into the second tube. When a train stops in the emergency station, the self-rescue is accomplished by evacuees proceeding to the rescue room.

People waiting inside the tunnel are predominantly evacuated by passenger trains running on the Koralm line. Problems may occur at night when fewer trains are in operation. In these cases, alternative solutions like “bringing in trains parked at stations along the Koralm line” or “increasing the capacity of the rescue train by adding passenger cars” would be conceivable. An optimized solution will be developed in connection with the operating programme at a later stage, shortly before the tunnel will be opened to traffic.

Assisted rescue, rescue train
An assisted rescue from the Koralm tunnel shall be performed by a rescue team, supported by members of the voluntary fire brigade. For the rescue crew to be transported to the site of the accident, rescue trains shall be positioned at the nearest stations. Rescue operations are planned to be carried out from both sides.

LAYOUT OF THE EMERGENCY STATION

The emergency station in the centre of the tunnel consists of 400-m-long platforms in both tunnel tubes. Inside the emergency station, the walkway, which extends over the entire length of the tunnel, is widened (2,0 m) and raised to the level of the platform (55 cm above rail). The walkway and the emergency exits may thus be kept on the side facing the second tube.

Figure 3: Layout of emergency station
In the emergency station a refuge room is located between the two tunnel tubes. This refuge area is connected to the platforms via escape-passages provided at a distance of 50 m. As Figure 3 shows, a staggered platform arrangement is chosen, which results in an approx. 800-m-long refuge room. A lock divides the refuge room into two equally large parts. At the emergency exits leading from the platform to the escape-passages, 2-m-wide doors are installed. It is envisaged that in case of an incident, all evacuees will proceed to the more distant part of the refuge room (waiting area), where they will be waiting to be evacuated.

This emergency station arrangement offers the following advantages:

- From a fire protection perspective, the waiting area is clearly separated from the affected platform.
- The distance between two escape passages of only 50 m leads to short escape routes.
- People leaving the train cover a distance of approx. 400 m (see Figure 3), in other words they move out of the immediate danger zone. If they were forced to stay in the rescue room directly adjacent to the platform, they would only be shielded by the short escape-passage between the fire scene and the safe area, which would give them the feeling of being very close to the zone of danger. This scenario was considered to be problematic in case of an extended stay in the emergency station – as a period of up to 90 minutes may be required for the evacuation to get underway.
- More space is available for people waiting to be evacuated, a provision which shall help to prevent uncontrolled attempts to leave the waiting room.
- The evacuation and the assisted rescue campaign will be made easier, as unwanted interactions will be prevented (see Figure 4).

![Figure 4: Evacuation train and rescue train in emergency station](image)

**Emergency facilities**

A team of psychologists was asked for an independent opinion about the emergency facilities including the aspects of human behaviour in an emergency situation.

The emergency station shall be equipped with the following facilities:

- Emergency telephone
- Video surveillance and loudspeaker system for announcements
- Lighting system comparable to that of a station
- Seating accommodations
- The provision of separate areas for the treatment of injured persons and for toilets.
EMERGENCY VENTILATION SYSTEM

Tunnel ventilation concept - overpressure in the non-incident tube
The emergency ventilation concept is based on pressurising the safe areas (emergency refuge room and the non-incident tube). In an emergency situation fresh air is brought into non-incident tube by large axial fans located at the shafts at Paierdorf and Leibenfeld creating an over-pressure which prevents smoke passing from the incident to the non-incident tube (see Figure 5). If the escape doors in cross-passages are opened the overpressure will lead to an airflow through the open doors. The air velocity through open doors varies depending on the dog's location and the number of simultaneously open doors.

![Figure 5: Airflows and pressure profile in an emergency situation with a train coming to a halt outside the emergency station](image)

Ventilation of emergency station
The emergency station is located at great depth in the middle of the tunnel. As there is no airshaft in the vicinity of the emergency station a smoke exhaust system could not be realised. The primary objective is thus to prevent smoke penetration into the refuge room. Additionally a backlayering of smoke in the incident tube should be suppressed to allow the fire fighters to access to the train on a smoke free path and to keep following trains (which may have stopped behind the train on fire) in a smoke free environment.

To reach these targets the over-pressure in the non-incident tube can be used. Additionally the following structural and technical measures are taken in the emergency station (see Figure 6):

- Using special air ducts (bypass channels) - located at both ends of the emergency station - and the overpressure produced by the axial fans at the two airshafts, air can be brought to the incident tube. In the case of a train burning in the emergency station this airflow can prevent backlayering.
- The bypass channels are also used to bring air from the non-incident tube in the refuge area and to guarantee a minimal airflow in the escape-passages when the doors are open thus preventing smoke penetration in the refuge room.
- Fresh air supply for the occupants in the waiting area is provided by special fans which are located in the fire fighter access passages (local ventilation system). The air from the non-incident tube is brought in the waiting area through a ventilation duct. When the doors of the lock, which is separating the waiting area from the rest of the refuge room, are open the air is flowing through the open door thus creating an additional safety barrier.
Design criteria
The design of the ventilation system is based on a minimum air velocity of 2 m/s through open doors (in the emergency refuge area as well as in the cross-passages outside the emergency station). The effective air flows however can go below this design target velocity of 2 m/s for a certain time due to the effect of other trains still running in the tunnel system.

Influence of train movement
1-D airflow simulations have shown that the overpressure concept is very robust and stable against the influences of the high barometric pressure differences which occur between the two portals. However due to the piston-effect of trains still running within the tunnel during an incident (e.g. trains leaving the incident or non-incident tubes or rescue trains entering the tunnel) the airflow in the bypass and the escape passages leading to the refuge room can be seriously affected however. To guarantee the functionality of the ventilation system the train traffic during an incident must therefore be controlled and the speed of the trains must be limited.

Figure 7 shows the influence of a running train in the non incident tube on the airflows in open cross passages. In front of a train approaching an open connection air is pressed in the incident tube (Figure 7.a). Depending on the speed and the aerodynamic properties of the train (length, area, roughness, etc.) high airflow velocities can occur in the open cross passage. More critical however is the situation when the train has already passed the cross passage (Figure 7.b). In this case the train speed must be reduced to guarantee that no air is sucked from the incident tunnel towards the non-incident tunnel thus transporting smoke in the safe area.
Figure 8 shows as an example the results of 1D instationary airflow calculations for the passage of a train in the non-incident tube. The airflow in the bypass channel as a function of time is shown. It can be seen, that under the action of the ventilation air is flowing from the non-incident tunnel towards the incident tunnel (negative air flow) after the opening of the flap in the bypass channel (at $t = 73$ min). With the entrance of the train running at 100 km/h (at $t = 82$ min) the air velocity in the bypass channel is steeply increasing until the train passes the Paierdorf air shaft. The air velocity in the bypass then remains constant at approximately 9 m/s.

In the simulation it is assumed that the speed of the train is reduced from 100 km/h to 40 km/h at $t = 91$ min. The train comes to a standstill in the emergency station at $t = 95$ min. This leads to lower airflows in the bypass channel. At $t = 110$ min the train is starting to leave the tunnel. As it passes the bypass channel the airflow through the bypass is reduced to approximately 1.5 m/s. However due to the limitation of the train speed to 80 km/h the airflow is never directed from the incident tube to the non-incident tube.

![Figure 8: Simulation of the train induced airflows through an open bypass channel](image)

**ANALYSIS OF INCIDENT MANAGEMENT BASED ON TRAFFIC SCENARIOS**

Due to the extensive length of the Koralrn tunnel, there is a non negligible probability of several trains running through the tunnel at the time, at which an emergency occurs. In response to this fact, to the necessity of having to evacuate both passengers and crew, and to the requirement of having to grant rescue vehicles access to the tunnel, special operating sequences have to be elaborated. In view of the operating programme currently envisaged for the Koralrn line, 5 different train schedule scenarios have been developed.
As can be seen from Figure 9, Train Schedule Scenario S1 (Day 1) reflects the most common operating scenario. This is the reason why this train schedule scenario has been used as a basis to analyse operating sequences and to define simple emergency response sequences (example see Figure 10).

Subsequent to this initial step, the analysis has further been extended to other train schedule scenarios to determine whether the selected response sequence would also be suited for these cases too (example see Figure 11).

As, for several hours at night, operation will be limited to freight trains, no self-rescue and no evacuation analysis had to be performed for this period.

Boundary conditions and assumptions
It is assumed that, in case a fire is detected in a passenger train, a message is immediately dispatched to the control centre, allowing operational measures to be taken, before the train is brought to a halt. All train drivers inside the tunnel are instantly informed of an emergency by the use of GSM-R technology (voice message or SMS). A reduction of the permissible speed or a stoppage of the train will, depending on the options available, automatically be effected by the train control system, but an emergency stopping of the train shall be avoided.

To determine the operating sequences of rescue train and evacuation train, the assumptions shown in Table 1 were taken into consideration. These assumptions are based on a high number of computer simulations of the airflow induced by running trains as shown in figure 8.

| Travelling speed – evacuation train (passenger train) | 80 km/h |
| Travelling speed – rescue train | 60 km/h |
| Slowdown of evacuation train and rescue train inside the tunnel | 2 km ahead of the incident site, the driving speed is reduced |
| Reversing of freight trains (adequate operating instructions in case of an emergency are still to be elaborated) | 40 km/h |
| Number of trains, travelling at the same time in the safe tube | One train (or travelling speed must be decreased further) |

Table 6: Assumptions made regarding operating sequences

In the endeavour to develop strategies suited to manage emergency incidents, the following topics are to be addressed:

- How will other trains, which are also inside the tunnel together with the incident train, be driven out of the tunnel?
- Which train will be used to evacuate passengers and crew members and from which side shall the tunnel be entered?
- From which side and through which tube will the rescue trains drive into the tunnel (are there several options)?
The decision to analyse possible incident management scenarios with the help of time-distance diagrams allowed sequences to be studied in greater detail and provided answers to such questions as:
Are there ways of moving the train(s) out of the tunnel in case of an emergency?

Is it possible to use other passenger trains as evacuation trains within a reasonable period of time? How long will people have to wait inside the emergency station?

For which sequences will new operating regulations have to be established?

How long will the second tube have to be separated from the incident tube by the use of fire protection measures?

How long will electrical installations, such as ventilation, communication and train control systems in the second tube have to remain functional?

CONCLUSIONS

When designing the emergency station, various aspects have to be considered. By addressing such issues as “prevention of smoke penetration into rescue room”, “fresh air supply in waiting area”, “location of the fire source in relation to the waiting area”, “interaction between evacuation train and rescue train” and “human behaviour in an emergency situation”, a lot of requirements have to be met regarding the structural design and the emergency facilities of the emergency station.

When analysing the train movement in case of an emergency in combination with the incident management strategy and the ventilation concept, the complexity resulting from the excessive length of the tunnel is illustrated. The performance of such a detailed analysis allows rescue concept considerations, operational and organisational measures and structural safety measures to be brought into tune.

The studies undertaken so far show that for the Koralm tunnel even under adverse assumptions for the operating sequences an evacuation of a train is possible within a reasonable period of time. The restrictions of train speeds, which are necessary to keep the second tube smoke free, do not limit the rescue procedures excessively.

The aerodynamic effects of trains on the emergency ventilation system and the resulting maximum speeds for trains in an emergency situation should be verified in special test runs during the start up phase prior to the opening of the tunnel.

REFERENCE LIST


2. TSI-SRT, Safety in Railway Tunnels, Draft 07/2006
Mobile Ventilation as a Tactic Resource at Tunnel Fires

Mia Kumm, Mälardalen University* & Anders Bergqvist, Stockholm Fire Department

ABSTRACT
An emergency operation in case of a tunnel fire can easily become a complex operation. The objectives are to save people in danger, save the tunnel and its installations as well as vehicles trapped inside the tunnel and also, if it’s possible and necessary, reduce the effects on the environment. The strategy and the tactics in an emergency operation are very much depending on the specific tunnel, the fire behaviour and the resources from the fire brigade. One of the key factors is to ventilate the tunnel in order to take the smoke away from the people in danger or to support the fire fighting operation. The possibilities to effectively ventilate the tunnel depend on the knowledge of the fire brigade, the available pre-installed or mobile installations and equipment for ventilation and the tactical approach chosen. In tunnels with only natural ventilation or to improve existing ventilation in tunnels, mobile fans can be used. The possibilities to redirect the flow are dependent of the capacity of the fans, the tunnel geometry and the counteracting forces from outside wind or the thermal buoyancy from the fire. In this paper the tactical approach with ventilation is further analysed and the possibilities and limitations are studied and discussed.

KEYWORDS: Tunnel fires, fire fighting, emergency operation, ventilation, mobile fans

BACKGROUND
The key factors in tunnel safety are the basic design of the tunnel, the traffic management and the emergency response [6]. To control the risk in a tunnel the design and the management of the tunnel is the most important factors. Nevertheless, when an unplanned and unprepared accident occurs, the emergency response is both required and expected by the public. The capabilities of the emergency services are often overestimated. To be able to be effective and have the possibility to provide basic safety measures, the emergency response operation must be well prepared and be integrated in the tunnel management system [7]. The tunnel owner has a major responsibility to prepare for accidents in the tunnel. This includes the duty to ensure that the conditions are such that the emergency operation is possible to carry out in case of an accident [14].

EMERGENCY OPERATIONS AT FIRES IN TUNNELS
Strategy and tactic in an emergency operation
An emergency operation in case of a tunnel fire is a rather complex operation with the objective to save people in danger, save the tunnel and valuable things in the tunnel and also, if it’s necessary, reduce the effects on the environment. The operation consists of a number of different elements [14] that are mixed together depending on the specific situation. The strategy and the tactics in an emergency operation are very much depending on the specific tunnel, the fire behaviour and the resources from the fire brigade. The tactics in an emergency operation can be described as the ongoing decisions by the incident commander (IC) in how to use the available resources, in the most effective manner, depending on objective of the operation. This is, as mentioned earlier, very much depending on the specific situation in the tunnel.

The emergency services are able to work with either an offensive strategy (fight the fire) or a defensive strategy (not fight the fire). Normally you shouldn’t combine an offensive and a defensive strategy at the same time. There are five different tactical approaches, single used or in combinations, to handle the fire situation in tunnels. These different tactical approaches can be combined in different
ways depending on the choice of strategy. The first tactical approach is to fight the fire from the inside of the tunnel, with the purpose to put out the fire and by this save the people in danger. The second is to assist or rescue the people in danger from the inside of the tunnel and take them to a safe environment. The third is to control the airflow in the tunnel in order to take the smoke away from the people in danger or to support the fire fighting operation. The fourth is to fight the fire from a safe position to reduce the consequences of the fire. The last is to treat and take care of the people that without assistance rescued themselves to a safe environment [14]. In the best of worlds, all of these tactical approaches could be used at the same time. This is not the normal in an emergency situation, due to lack of resources. The next problem is to realise that the methods and techniques that are useful in these different situations are both limited and relatively hard to get to work in an effective way. The possibilities and problems with the different methods are further described in a previous report [8].

In this paper the tactical approach with ventilation will be further analysed and the possibilities and limitations will be studied and discussed.

**Ventilation as a tactical approach in an emergency operation**

As a part of a fire fighting operation ventilation can be used as a method to control direction of the flow of smoke in the tunnel. The purpose of the ventilation is to control the quantity and direction of the flow in the tunnel either to support the fire fighting operation or to support the life-saving rescue of people in danger.

The heat release rate from the fire (HRR) and the fire growth rate are two of the most important factors that influence the tunnel safety in general in case of a fire. The velocity of the airflow in the tunnel will have an important impact on both of these factors [14]. The air flow in the tunnel, together with the HRR, will also affect the emergency operation. The HRR will correspond to the production of both the heat and the smoke. The air flow will, for most cases, control the direction and the situation of the smoke in the tunnel. The heat and the smoke are the two most important factors to handle in a fire fighting operation. The flow of the smoke will have an impact in how and where the emergency operation will start and how it will be carried out. The access to the fire will be limited by the radiation heat from the flames as well as the radiation and convection heat from the smoke layer. By controlling the direction and extraction of the smoke the emergency operation can be carried out with less heat exposure on the fire fighters.

The air movements inside a tunnel can be created by pre-installed mechanical ventilation but can also be caused by natural reasons like buoyancy due to height and temperature differences or outside wind. At tunnel fires the smoke distribution inside the tunnel depends of the air flow. Airflows in tunnels can be divided into three different groups depending on their affect on the smoke distribution. The different groups are tunnels with low air velocities (< 1 m/s), moderate air velocities (1-3 m/s) and high air velocities (> 3 m/s). [5] At low velocities the smoke usually is clearly stratified close to the fire. As the tunnel walls cool the smoke, the smoke layer usually falls down and the full cross section can be filled with smoke, figure 1.

![Figure 1: Smoke progression in a tunnel with an airflow that is less than 0.3 m/s](image-url)

This situation will force fire fighting units to penetrate a smoke filled environment to be able to reach the fire site. The offensive fire fighting operation will be hard to manage if it will be necessary to penetrate long distances of smoke filled environment [8]. The practical maximum range of operation with a BA-unit in smoke filled tunnel environment will be approximately between 100 and 200 meters. The shorter the distance is to the fire, the higher will the radiation from the flames and the
smoke be towards the fire fighting units [8]. This will have an impact on the units and will reduce their possibilities to reach the fire site in order to suppress the fire. The higher the heat release rate is from the fire, the greater the impact will be on the fire fighting units from both the flame radiation and the heat flux from the smoke [3].

In very short tunnels, where the fire creates smoke with a high temperature, the stratification can be kept the full length of the tunnel. In tunnels with only natural ventilation and with no or only flat slopes, the air velocity at many times is less than 1 m/s [9, 10]. For such tunnels even small fires can cause long distances of back-layering.

For a fire fighting operation to succeed, the emergency services must be able to control, or at least adjust the operation to the flow of air in the tunnel. To be able to do an effective offensive fire fighting operation, the back-layering effect and the heat radiation from the smoke must be controlled and minimized.

For air velocities between 1 m/s and the critical air velocity the length of the back-layering can vary between zero and 17 times the tunnel height, figure 2 and 3 [5].

![Figure 2: Smoke progression in a tunnel with an airflow that is approximately 1 m/s](image)

![Figure 3: Smoke progression in a tunnel with an airflow that is between 1 and 3 m/s](image)

For air velocities over 3 m/s – the critical velocity, no back-layering effect occurs at normal size fires, figure 4.

![Figure 4: Smoke progression in a tunnel with an airflow that is over 3 m/s](image)

As soon as the air starts to flow inside the tunnel, the turbulence can destroy the stratification of the smoke. If the tunnel is filled with smoke it will reduce the possibilities for both the evacuation of people in danger and the fire and rescue operations downstream the fire. But as the environment, regarding toxicity and heat radiation from the smoke layer, is improved downstream the fire as well as it controls the back-layering and gives the rescue services a possibility to reach the fire, the advantages with ventilation usually outweigh the disadvantages in small and moderate sized fires.

To be able to control the direction and the velocity of the air in the tunnel, the emergency services can either use mobile fans or the pre-installed ventilation systems in the tunnel. Tunnels can be equipped with different types of ventilation systems. This can for example depend on if it is a road, rail or a metrotunnel, how long the tunnel is or the amount of traffic. The tunnel can, normally, have natural ventilation, longitudinal ventilation systems or transverse ventilation system. In tunnels with natural ventilation system the emergency services have to be able to either just follow the natural conditions or use mobile fans to produce the longitudinal air flow through the tunnel. In tunnels with longitudinal or transverse ventilation systems the emergency services have to be able to use these systems to create the best conditions for the operation and can in some cases use mobile fans to support the installed
systems. In this paper the ventilation of tunnels with mobile fans is presented, analyzed and discussed.

**SMOKE AND HEAT VENTILATION WITH MOBILE FANS**

Mobile ventilation is a commonly used method when fighting compartment fires in normal buildings. The purpose with the ventilation is either to create an overpressure in adjacent areas around the fire compartment or to evacuate smoke from the fire compartment itself. For this purpose the emergency services normally uses medium flow (8-9 m³/s) mobile fans (PPV-fans). The experiences and routines that have been developed in the emergency services for ventilation operations in fighting compartment fires are not automatically applicable for use at a tunnel. Because of the differences in geometry between ordinary buildings and tunnels, the normal recommendations concerning the use and position of the fan in relation to the opening is not the same and special tunnel ventilation routines has to be used. The size of the fan (i.e. the capacity – pressure and primary flow), the tunnel geometry, the ambient conditions and the size of the fire are critical parameters and will decide how effectively the ventilation will be. If ventilation with mobile fans is to be used, the choice is either to use high flow (>30 m³/s), usually lorry mounted, fans with high capacity or to use combinations of the smaller, medium flow, PPV-fans the emergency services usually use for compartment fires. There are three main differences between using mobile fans for offensive smoke ventilation in tunnels and in compartment fires in buildings.

1. In a compartment fire the dynamic pressure produced by the airflow is used to create a slight static over pressure inside the compartment. The purpose is to create a pressure difference that will force the hot smoke out from compartment to the surroundings. In a compartment in a building there usually is a big increase of the cross-section area inside the inlet opening. In tunnels the cross-section area usually are similar the full length of the tunnel.
2. In tunnels the fans are used free blowing and the area inside the tunnel can be counted as decompressed. The static overpressure on the outside of the tunnel is used to prevent any flow in opposite direction along the tunnel walls and through the opening, figure 5. But it is mainly the dynamic pressure (the flow) from the fan that creates the air flow in the tunnel and not the static overpressure.
3. Tunnels are also relatively long and they present normally a high counteracting resistance that the dynamic pressure created by the fan has to overcome. [4].

The capacity of the single PPV-fan is too low to be effective for using in tunnel fires, except if it is a very short tunnel with a small cross-section area [4, 20]. In general it is the primary flow (air flow through the fan) and the force created by the fan that are the important parameters when comparing fans. The primary flow will always pull in entrainment air in the air cone, but the entrainment air should not be counted as a single value in itself. It is the force created by the primary air flow that decides the amount of entrainment air into the air cone and by this it is therefore the primary flow that should be compared.

![Figure 5 Schematic airflow when using a high flow fan outside a tunnel opening](image)

The influence of tunnel geometry and outside wind on the ventilation effect

If the counteracting resistances (geometry, ambient wind, the fire, etc.) are too high, the fan, or the set of fans, cannot create a dynamic pressure strong enough to force the direction of the counteracting flow to turn around. The result will be either a short circuit of the air flow over the fan, figure 6 or that the air flow is re-directed only in parts of the tunnel length, figure 7. In those cases when the counteracting flow and the flow created by the fan are of similar magnitude, a special phenomenon
can be seen. The fan creates a flow in the middle of the cross section, but the ambient wind still creates a counteracting flow at the tunnel walls, figure 8. [4, 12]

To understand the effect from the ambient wind, one of the most important questions is the impact from the wind on the tunnel portals. For buildings this is normally presented as static pressure coefficients and pressure profiles. The uncertainties how these apply on tunnels are considerable as not much research can be found in this field. Most pressure profiles are developed for closed buildings. [1] Already for buildings with large openings these pressure profiles can be uncertain. With tunnels the uncertainties are even larger. Existing equations for normal buildings cannot be applied on tunnels unless adjusted for the special conditions tunnels offer. The local geometry is significant for the pressure the wind will apply on the tunnel portals. Therefore the variations between different tunnels can be considerable. Simplified the force that the outside wind applies on the tunnel can be described as the summary of the pressure at the portals times the tunnel cross-section area. The inflows at the tunnel entrances are usually very turbulent in tunnels with natural ventilation. It is not unusual with outgoing air flows close to the tunnel walls and an ingoing air flow in the centre of the cross-section [10].

New research also indicates that the flow through large openings in buildings and wind induced flows in tunnels are being flow driven instead of being pressure driven. [1, 11]. A newly finished wind tunnel study [11] shows that the porosity - the size of the tunnel opening in relation to the blockage area of the surrounding mountain, the length, i.e. the resistance in the tunnel and the direction and velocity of the outside wind, are of significant importance for the wind induced flow in the tunnel [11].

As the flow inside the tunnel influence the fire growth and the maximum HRR [3, 16, 17, 18] as well as the tactics of the emergency operation, the IC need to follow the actual conditions in the tunnel. The IC should also be aware that the metrological conditions can alter during the time of the operation and that both the ambient wind and the fire in the tunnel are dynamic processes that have to be monitored. In tunnels with considerable slopes, the buoyancy effect created by the heat from the fire can counteract with the natural airflow in the tunnel. When the buoyancy overcomes the wind induced flow, the airflow in the tunnel can suddenly reverse and put the emergency personnel at risk. The IC therefore needs to monitor not just the fire, but also the ambient conditions in respect to the emergency personnel’s safety inside the tunnel.

**High flow fans**

Previous tests performed [19] at the not yet opened 1100 meter long Kalldal railway tunnel in the north of Sweden, showed that high flow mobile fans effectively can create the desired airflow and thereby ventilate the tunnel. The chosen HRR was made considerable lower, only 2,6 MW instead of the commonly used 15MW in similar tunnels, to prevent damage on the already installed technical equipment in the tunnel. The main aim of the tests where to verify a mathematical model for deciding the required capacity of ventilation given the HRR and the size of the tunnel. The achieved test results corresponded well with the calculated air velocity in the tunnel, but also showed the efficiency of high flow mobile fans. [19] With these fans, a similar method as in compartment fires was shown effective. The fan where placed outside the tunnel entrance and tilted so the air cone fully covered the tunnel opening. If the capacity of the fan is big enough the over pressure at the opening prevents back flow close to the tunnel walls and the primary flow through the fan with the additional entrainment air will ventilate the tunnel, figure 5.
Combinations of more than one medium flow fan (PPV)
The access to high flow fans is unfortunately low among both emergency services and tunnel operators around the world. Tunnel openings can also be located in inaccessible areas where high flow fans are impossible to use. Railway tunnels in rural areas can be unapproachable unless covering the last distance by foot. This in combination with that most fire units already are equipped with PPV fans makes it interesting to compare for which tunnels and under what conditions combinations of PPV fans can be used with a desired effect.

Previous ventilation test in the Masthamn tunnel in Stockholm showed that it is effective in shorter tunnels to use combinations of ordinary PPV fans in order to create an airflow and by this ventilate the smoke from the tunnel. [20] The test also showed that it is more effective to place the smaller combinations of fans in a parallel combination instead of a serial combination. At the tests the optimal location for the fans where tested – one tunnel height outside the tunnel opening, at the tunnel opening or one tunnel height inside the tunnel. The highest velocity where achieved when the combination of 4 PPV fans where located one tunnel height inside the tunnel. For locations outside the tunnel a back flow occasionally could be seen at the tunnel walls. This implies that the pressure is not enough to create a flow through the full cross-section in the full tunnel length. As the PPV fans create a lower positive static pressure inside the tunnel than the high flow fans, the location inside the tunnel protects the fans from side wind effects and makes the full primary flow enter the tunnel. The location inside the tunnel results in no static pressure at the tunnel opening but instead use the dynamic pressure created by the flow to ventilate the tunnel.

This will only be possible at short tunnels, with small cross-sections and low counteracting ambient winds. If the ambient wind pressure at the opposite tunnel opening and the wind induced flow inside the tunnel will overcome the fan induced flow, the fans will not succeed to reverse the air flow in the full cross-section or in the full tunnel length, figure 7. For strong counteracting winds the air short circuits over the fans, figure 6. If the forces of the wind, or the buoyancy, are of similar size as the fans, the two bi-directional flows will meet in the tunnel. Either one or both flows turn towards their entering tunnel opening or a flow through the full tunnel length is created by the fans in the middle of the cross section while the wind create a flow in the other direction at the tunnel walls, figure 8.

**Figure 6**
Short circuit over the fans

**Figure 7**
Reversed fan flow due to counteracting winds

**Figure 8**
Tunnel seen from above with back flow along tunnel walls

PPV in combination with a tunnel cover
To be able to secure that ventilating with combinations of smaller fans is possible, even when there is a counteracting wind or the buoyancy effects counteract the desired flow direction, a tunnel cover can be mounted at the location of the fans at the tunnel opening. The tunnel cover prevents the short circuit over the fans and supports the effect of the fans. The primary flow through the fans creates a pressure difference on either side of the tunnel cover and if openings are placed in the tunnel cover around the fans, entrainment air can be let into the tunnel and increase the flow, figure 9.
Figure 9 Schematic effects when using a tunnel cover to support the PPV fans

The use of the tunnel cover can be divided into three steps. First the tunnel cover is raised and placed over the fans. The wind induced counteracting flow in the tunnel stops and a static over pressure can be seen at the tunnel cover as it curve in the wind direction. Secondly the fans are started and the tunnel cover prevents the air to short circuit over the fans. As the air flow in the desired direction is stabilized, the static pressure at the tunnel cover is changing. The force from the primary flow instead creates an over pressure on the outside of the tunnel opening and creates an under pressure on the inside of the tunnel cover. The third step is to let entrainment air through the tunnel cover and in to the tunnel. As long as the fans can overcome the static pressure from the wind on the opposite tunnel opening, the air flow from the fans, with the additional entrainment air, will ventilate the tunnel in the desired direction [12].

Previous tests performed [12] in the 637 meter long Stadsgård tunnel, verified that the air flow in the tunnel could be reversed in the full cross section. The test where set up using a tunnel cover in combination with the same set of four PPV fans that were used in the prior Masthamn tunnel tests [20].The fans did not succeed to reverse the wind induced flow in the full tunnel cross section without the support from the tunnel cover. Instead the situation, as shown in figure 8 with a back flow along the tunnel walls, was created. The total volumetric primary flow in the test were approximately 34 m$^3$/s. Regarding the primary flow it were comparatively equal to the flow at the high flow fan that were used in the Kalldal tunnel tests [12, 19]. It should although, again, be noted that the positive pressure created is weaker for the PPV fans than for the high flow fan. Other combinations of fans were tested, but with less effective results than with the four PPV fans.

Tests [12] were performed at two different occasions with two different ambient situations that created different counteracting air flows in the tunnel. Without the tunnel cover, the maximum velocity achieved in the middle of the tunnel, significantly differed between the two test occasions. With the tunnel cover, the maximum velocities of the air flow in the tunnel were similar between the two tests. This indicates that the full primary flow and the entrainment air where flowing in the tunnel, regardless of counteracting wind at both the two different occasions.

All fans, or combination of fans, will though have a maximum counteracting wind velocity that it can overcome. The tunnel cover will not work with all types of fans at all occasions, but regardless of type of fan the tunnel cover support the capacity of the fan and prevent short circuit of air. The tunnel cover could also support high flow fans placed at the tunnel opening in those occasions where the counteracting forces are close to the capacity of the used fan. But when using large high flow fans under relatively normal fire conditions and in moderate length of tunnels, this is not necessary as the fan itself creates enough force and flow [12].

**RECOMMENDATIONS FOR CHOICE OF EQUIPMENT AND METHOD**

The emergency operation could easily grow into a complex situation, where the IC has to make judgments and decisions based upon few facts and uncertain information and it is of great importance that there are thorough contingency planning made on beforehand. All emergency services with tunnels within their action area should make adequate planning and preparation for the object of interest. The contingency plan has to be developed on basis of the objects as well as the available resources from the emergency services. The shown, table 1, should be seen as an example for the usability for the three different methods in case of the need for a ventilation operation in a tunnel.

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Based on the results from earlier mentioned tests [8-13] the three different methods have been compared.

1. A set of four parallel medium flow fans placed one tunnel height inside the tunnel.
2. A set of four parallel medium flow fans placed one tunnel height inside the tunnel in combination with a tunnel cover.
3. One single high flow fan placed one tunnel height outside the tunnel.

These different methods are then compared for three different tunnel lengths, three different cross section areas and at some counteracting airflows inside the tunnel. The values have been calculated by using the equations developed by Ingason and Romanov [13] and later verified and adjusted for counteracting wind in the research project in co-operation between Mälardalen and Gävle Universities. [9, 11, 12]. The surface roughness in the tunnel was set equivalent to blasted rock, approximately 200 mm. The pressure drop over the fire was set to 10 Pa. To fulfil the acceptance criteria the reversed velocity had to reach the level moderate air velocity or higher. The original air flow also had to stop or reverse in the full cross section area. No back flows along tunnel walls were allowed. For counteracting wind induced velocities over 1 m/s, in longer tunnels with larger cross section areas, complementary tests have to be performed as the equations not have been validated for higher counteracting wind induced velocities, especially regarding bi-directional flows. Complementary tests are planned and will be performed in the Kalldal tunnel during spring 2008.

<table>
<thead>
<tr>
<th>Tunnel length ↓</th>
<th>250 m</th>
<th>1000 m</th>
<th>2000 m</th>
<th>Counteracting wind in tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m³</td>
<td>1,2 and 3</td>
<td>1,2 and 3</td>
<td>2 and 3</td>
<td>0 m/s</td>
</tr>
<tr>
<td>30 m³</td>
<td>1,2 and 3</td>
<td>2 and 3</td>
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<td>2 and 3</td>
<td>2 and 3</td>
<td>2 and 3</td>
<td>0 m/s</td>
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</tbody>
</table>

**Complementary test will be performed during spring 2008**

As shown in table 1 the combination of medium flow fans (1), with acceptable safety margins, only can be used for reversing flows in shorter tunnels (≤ 250 m), with small or moderate cross section areas (≤ 30 m²). To support the existing direction the combination could be used without length limits. It should though be noted that in cases where the outside wind direction is not stable and at risk of reversing the used method, for the fire fighters safety, should be carefully considered. In tunnels with longer distances to the location of the fire the fan, or combination of fans, should be able to withhold the reversing flow due to changing outside wind direction, the required time for the fire
fighters to retreat from the tunnel. As the outside wind direction changes relatively slowly over time [9, 10] the required safety can be kept, as long as the IC keeps himself updated of the outside wind conditions.

For longer tunnels (1000 m – 2000 m) with larger cross section areas (30 m² - 50 m²) two different methods can be used; large high flow fans (3) or combinations of medium flow fans with the support of a tunnel cover (2). Both methods have its advantages and difficulties. For tunnels with good connecting infrastructure at the tunnel openings lorry mounted fans can be altered from one tunnel opening to the other in case of the changing of strategy, without the need of de-mounting of a tunnel cover. The combination of medium flow fans and a tunnel cover, on the other hand, can be used at tunnel openings where larger lorry mounted fans can’t reach. The frame of the tunnel cover could also be mounted at the up-stream side of the tunnel, when only supporting the existing direction, to prepare for changing wind directions or decreasing outside winds in case of tunnel slopes counteracting the wind induced flow. The system with a tunnel cover in combination with a high flow fan could theoretically be used in very long tunnels, but have not yet been verified by full scale tests. The choice between the presented methods should be done as a part of the emergency services contingency planning based on the actual objects, available resources and economic presumptions.

**DISCUSSIONS**

The size of the fire is together with the length of the smoke filled distance from the entrance of the tunnel to the fire site, probably are the factors that will affect the fire fighting operation in the most direct way. The air flow in the tunnel will have a large impact on both these factors. The HRR and the fire growth rate will partly be affected by the velocity of the air flow. The movement of the smoke will follow the flow of the air. To create an air flow with a ventilation operation without the knowledge of how the flow will affect the fire and by this the production of heat and smoke can change the situation from a possible, from fire suppression point of view, to a hopeless fire inferno. On the other hand, a ventilation operation can change the fire fighting situation from a situation where nothing can be effectively done, to a situation where it is possible to suppress the fire. Ventilation will probably be a method that has to be used, at least in occasions where the fire is medium sized or larger. Not ventilating the tunnel as an active decision based on the facts at the fire site can be a wise decision, but not ventilating the tunnel because of its complexity is not the right way to handle the emergency operation.

The use of ventilation is a common way for the emergency services to handle compartment fires in building. With this experience routines has been developed and adopted. Almost all ICs know that ventilation operations can change a bad situation to a better, but it can also change a bad situation to a much worse. To use ventilation on a compartment fire in a ventilation controlled stage of the fire will increase the HRR of the fire. In a fire in a tunnel the situation has to be monitored from another perspective – the fire load. In the road tunnel the fire load can be simplified in types of vehicle and type of cargo. Fires in cars, lorries and buses are probably fires that will not exceed a HRR of 30 to 40 MW. In these cases the environment, regarding toxicity and heat radiation from the smoke layer, is improved downstream the fire, considered that the ventilation does not influence the HRR. The air flow will control the back layering, the heat radiation and gives the emergency services a possibility to reach the fire in order to suppress it. The advantages with ventilation usually overweight the disadvantages, especially when the fire starts to decay and there is no risk for further fire spread. If the fire is large, or if there is risk of fire spread to more fire load, the situation can be different. In these cases increased airflow can result in a much worse situation.
CONCLUSIONS
The tactical situation for the IC is not just to monitor the fire and smoke conditions, the handling of people in danger must be prioritised.

The use of ventilation can have other purposes than just support the fire suppression operation. For example the different ventilation methods can be used to;

- Create a longitudinal air flow and by this support the evacuation upstream the fire.
- Create a longitudinal air flow and by this control the smoke so that the fire fighters can approach to the fire site. The velocity of the air flow should only prevent the back-layering against the airflow. Air flow should be maintained at the speed of the critical air velocity. Higher velocities can make the fire spread to fire load down-stream the fire.
- Increase the flow in the tunnel to reduce the concentration of heat and toxicity downstream the fire site. This ventilation should not be used if the fire load is large, because it will increase the HRR.
- If the fire fighting operation can not control and suppress the fire supported by a longitudinal air flow due to for example a large fire load and there are people in danger downstream the fire reversed ventilation can help. The direction of the airflow can be reversed after the unaffected tunnel area is evacuated. People in danger that originally where downstream the fire will now be in a smoke free environment and can be reached by the emergency services.
- Extraction of the smoke from the affected sections or areas of a fire.

Combinations of medium flow fans only can be used for reversing flows in shorter tunnels, with small or moderate cross section areas. For longer tunnels with larger cross section areas two different methods can be used; large high flow fans or combinations of medium flow fans with the support of a tunnel cover.

The emergency operation must be objective orientated. If the objective is to rescue people in danger the choice of strategy and tactical approach has to be based on this. If an offensive fire fighting operation is to be done, it must support the rescue of people in danger. To make this judgement, the time factor has to be a part of the operation. If the ventilation operation is to support the fire suppression operation, a quick suppression can be necessary if the HRR should increase.

The conclusion is that an emergency operation has to be a well judged mix of different methods that supports the objective of the emergency operation. Ventilation operations can and should be a method that is used when fighting fires in tunnel. To make the right decision at the right time, demand a high level of expert knowledge from the IC. It also demands usable methods that can control the smoke and the fire behaviour. As the result from an emergency operation depends on the conditions at the fire site and the effective use of the available resources, it is important that the methods used is a part of a contingency planning and not invented at the scene of the fire. The contingency planning should be used as a decision support for the IC. The decision making will though be a dynamic process that follows the course of events at the scene of the fire.

ACKNOWLEDGEMENTS
The tests in the Masthamn and Stadsgård tunnels were performed with the kind permission from Stockholm Harbour and SL, the Stockholm Metro. At the tests in the tunnels used for rail traffic Stockholm Metro has contributed with valuable help regarding safety planning, safety personnel, equipment and manpower. The wind tunnel tests that were performed to investigate some of the phenomenon that occurred in the real tunnels and to validate the equations regarding counteracting winds were sponsored by the Swedish Saving Banks Foundation. The authors would like to thank the above mentioned organizations, whom without this research would not have been possible to perform.
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Tunnel Incident Management in Frankfurt am Main

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KEYWORDS: Tunnel Fire Operations, Fire Department, Frankfurt

INTRODUCTION

The city of Frankfurt am Main

City data

The city of Frankfurt am Main is located in the heart of Europe. The urban area covers a surface of 248 km² (95 mi²). The city’s original population ranges around 655,000 people. In addition to that, more than 360,000 commuters enter the city every day, so that in day times there are more than 1,000,000 people in town. This is the largest number of commuters a city has in Germany.

Specific risks

If you talk to people which places they know in Germany nearly everybody will answer you “Frankfurt” because they once entered Europe through FRA, the Frankfurt International Airport. FRA is Europe’s most frequented airport at all. Actually about 51,000,000 people use FRA every year to get to or come from 307 destinations in 109 countries all over the world. Also about 1,750,000 tons of cargo are handled through FRA every year. The constant growth of air traffic will cause a considerably extension of FRA in the next years. This extension includes a new runway, a new terminal which will rise the passenger capacity of FRA to over 80,000,000 per year and several new buildings to meet the requirements for the future and everything it brings like the new Airbus A 380. FRA itself runs its own private fire department, so that initially the fire department of the city of Frankfurt is not responsible for the airport. But if there’s any kind of incident exceeding a primarily defined level of dimension, also the city’s fire department will respond to the airport.
Another facility the Frankfurt Fire Department has to care about is the city’s main central station. In here, about 350,000 passengers enter or leave the station in about 1,800 trains every day. Interesting about the building is, that most of the total building area is located under the ground level. That includes an underground shopping centre and two different lines and types of the metro system, which will be mentioned a little bit more detailed later.

The most characteristic thing about Frankfurt am Main is its skyline and the high-rise buildings that are forming it. In the city you will find Europe’s highest buildings and the biggest amount of skyscrapers on the continent. Actually a total of 383 high-rise buildings are completed (including 10 over 150m), 5 are under construction and another 20 are planned. Due to the relatively strict building codes in Germany the skyscrapers themselves are not posing so many problems to the city’s fire department in daily operations, of course if you disregard any kind of possible acts of terrorism and the consequences from it. A more critical look has to be set to old or even historical building structures which were constructed in times when building codes weren’t based on today’s knowledge.
The city has also three big chemical plants which cover a surface of more than 1500 acres. All of them also run their own private fire departments, the cooperation between them and the city’s fire department is comparable to the situation at the airport.

Fire Department of the city of Frankfurt am Main

The municipal fire department consists of about 1650 members of operational staff. These are divided in approximately 800 members of the professional fire department, 800 members of the voluntary fire department and 50 inspectors of the department of fire prevention. In addition to that, about 200 people work for the department as administrative staff and technical employees. The Department is led by the Chief of Department, Prof. Dipl.-Ing. Reinhard Ries. Every day, there are 186 people on active duty, assigned on 13 engines, 7 ladders, 25 ambulances, 1 MIC-Unit, 1 EMS- helicopter and different types of special units and incident command vehicles. These units are assigned to actually 9 fire stations. In the next years the number of stations will increase to 12. The special units include two heavy rescue units, with one of them specialized on accidents on railway-systems, a high-rise unit, a water-rescue unit, a hazmat-unit, a mass casualties unit, an AR unit and an animal-rescue unit. Some of these units are permanently staffed like the heavy rescue units, the hazmat unit, parts of the water rescue and the mass casualties unit, others are operated by a corresponding engine or ladder unit. All engine and ladder units respond to support the special units in operations.

The incident command system is based on four levels from A- D. Starting on the lowest with level D, this is the commanding officer of an engine or special unit. Level C includes 4 battalion chiefs in a 24 hour tour, with 2 additional battalion chiefs weekdays on the day tour. Level B includes 2 division chiefs, one responsible for the eastside and the other one for the westside of the city. An additional division chief is on duty on the day tour of the weekdays. The highest planned officer on duty is the commanding officer on level A, the citywide tour commander. He is responsible for all actions according to the Fire Department and the EMS in the whole city. The voluntary fire department runs 28 stations all over the city and completes the professional fire department at more comprehensive incidents and at calls in their response area at weekday’s nights and on the weekends.

TUNNELS IN FRANKFURT AM MAIN

Overview

The following kinds of tunnels are under the jurisdiction of the Frankfurt am Main Fire Department:

- Two street tunnels
- Two railway tunnels
- Two metro systems, one operated by the city, the other one operated by the country
Street tunnels
The longer of the two street tunnels is the so called “Theater- Tunnel” (Gutleuttunnel), which is located downtown in an inner city area. The tunnel itself is about 500m (0.3 miles) long, and runs on two-way traffic with one lane for each direction. The tunnel has an own radial ventilation system and various emergency exits. From the fire department’s point of view, this tunnel is uncritical, operations caused by accidents or car fires have never caused any serious problems.

Railway tunnels
In 2002 the German federal railway company (DB AG) opened a high speed railroad track between Frankfurt and Cologne on which the trains run on a speed up to 350 km/h (about 220 mph). Therefore the time of travel between the two cities has been reduced to 1hr 15 min. To enable that top speed it was necessary to build a total of 18 tunnels along the track. Two of these tunnels are under the jurisdiction of the Frankfurt am Main Fire Department. The tunnels are located around the airport. One of them was build to cross the biggest highway interchange of the city. The two tunnels are 990m (0.61 mi) and 1883m (1.17 mi) long. Every tunnel is equipped with escape routes, emergency exits, automatic shut-offs with grounding for the catenary and some ventilation devices.

Metro system
Frankfurt’s metro system has an overall length of 113 km (70.2 mi). The system is operated by two railway companies, one owned by the city and the other by the state. Some of the stations are used by both companies. Technically, the two systems are different. The System owned by the city just covers the city and some suburban areas around. The federal system covers a large area around the city and is more like a supra-regional train system for the whole Rhein- Main area that is put underground in the inner city parts of Frankfurt. Technically, the systems are also different. The city’s system operates with a voltage between 700 and 750V DC. The voltage of the federal system reaches from 13.000 to
17.000V AC. Both systems use a catenary system for the electrical power supply. Electrical shut-offs are carried out by the control centres of the two companies, grounding has to be done manually on scene. Only the city’s system has ventilation devices in parts of some stations and the tunnel itself.

From all the possible incidents, the ones in the metro tunnel system are the most complicated. For this reason a closer look is given on this topic. The results and findings are transferable to the other types of tunnels.

METRO FIRES

Problems
A fire department is facing a wide variety of problems in case of a fire in a metro tunnel. First there’s the smoke that extends quickly and nearly uncontrollable because of the weather conditions in the underground system. Other trains, still moving in different parts of the system, are also causing pressure differences that are interfering the air movement and possible attempts of ventilation. Connected with that, smoke and toxic gases have a bad influence on the possibility for the self-rescue of the affected passengers.

The transfer of fire and heat to other parts of the concerned carriage is supported by the narrow tunnel system, which works like an oven in that case. The heat exposure, which might reach up to 1300°C within minutes, also has a negative influence on the tunnel construction itself, it might cause the collapse of parts of the tunnel section.

Causes
The possible causes for metro fires are also different. First there are technical reasons on the coaches, like engine- fires caused for example by overheating or technical defects. One of the biggest problems in that case is the oil used for the insulation of the transformer system. The quantity of this oil varies between 700 and 1500 l (185 – 370 gal), depending on the type of the train. Also electrical short circuits, often followed by a cable fire, are possible. The braking system might also be a cause for the ignition of a fire, with brake hot-boxes occurring from time to time. Inside the coaches electrical devices like for example under seat heaters might catch fire, especially when proper ventilation is impeded by baggage.

Other reasons for fires in coaches are the ones caused by intention like arson or possible terrorist attacks. Operations on that kind of incidents first do not differ from the ones caused by technical defects, because in the first phase the cause of an incident is not always determinable.
Objectives
As a conclusion from the recognized problems and causes it is possible to define the objectives to reach an appropriate level of safety. So the main objectives are:

- Minimize the danger of a fire breaking out,
- Guarantee a rapid activation of the fire alarm and fire fighting operations
- Enable endangered people to save themselves, and guarantee the others to be saved by the fire department
- Limit the fire to the smallest possible area
- Minimise consequential damage to the tunnel construction and possible disruptions of the vehicle service.

In the following, the overall concept of the city of Frankfurt am Main to achieve these objectives should be presented a little bit more detailed.

PREVENTION

Determination of the initial situation
To get an idea of what in case of a metro fire might happen, the boundary conditions have to be defined. In Frankfurt the first step to be initiated was to find out how a metro coach is behaving under fire conditions. The objective was to determine the heat and smoke exposure rate of a standard coach that is in daily use in the city’s metro system. For that purpose, a research institute was charged to conduct a full scale burn test with an original coach.

Actions taken
The results of that test were taken as planning criteria for a comprehensive review of all existing metro stations. In addition to that, the fire protection in the coaches itself have been improved by the use of different materials for seats and interior lining to prevent ignition. With the determined rates for heat and smoke, artificial smoke tests have been realized in nearly every station, especially the large ones with different underground levels, different lines and metro systems.
In the stations different technical installations were made to improve the level of security and to achieve the following objectives:

- Limitation of the maximum distance to a safe area (metro station or emergency exit) to 300m (982 ft.),
- Prevent smoke to reach the area of the escape routes for at least 15 minutes after the start of a fire,
- The low-smoke layer must be more than 2.5m (8.2 ft.) high and the visibility must be more than 15m in the first 15 minutes (phase of self rescue),
- During the next 15 minutes (rescue phase by the fire department) there must be a low-smoke layer more than 1.5m above the escape routes.

The following measures have been taken to achieve these objectives:

**Measures in the building**

**Constructive measures**

1. Smoke barriers and smoke doors have been installed to prevent the smoke from influencing the escape routes for the defined amount of time,
2. Ventilation systems were improved in some stations, others will follow,
3. The indication of the escape routes has been completed and improved,
4. GSM-repeaters have been installed to enable passengers to use their cell phones also for emergency calls,
5. Lifts have been equipped with a so called “dynamic evacuation mode”, that prevents a lift from stopping in a smoke filled area,
6. Escalators have been set to support a possible evacuation,
7. The emergency lightning system has been improved,

**Organisational measures**

1. Emergency phones have been installed in a wide range. With these phones the caller is directly connected to the control centre of the metro operator.
2. Every station is monitored by a camera system. All pictures are transferred to the control centre of the metro operator. The control centre is also able to look at the emergency phones via the camera connection.
3. An operational and danger avoidance plan was created for every metro station. In that all information about the building and its important features like exits, the fire alarm panel and positions of hydrants are displayed,
4. For some stations a computer simulation of the evacuation combined with a simulation of a fire was made to verify the defined objectives.

**Measures for the fire department**

1. A repeater system for the department’s handheld radio system has been installed to cover the whole underground area,
2. Hydrants and standpipe- systems have been installed where not available,
3. Electrants have been installed where not available
4. If a station was equipped with different fire alarm systems these were brought together to one central panel point,
5. Bigger stations were equipped with a PA- system, existing systems were brought together at the fire alarm panel to enable the use by the FD,
6. Additional grounding devices have been stocked in the station for emergency use.
7. The fire department was equipped with plans and manuals from the stations and the used trains, these were custom- made for the FD’s needs,
8. Regular trainings have been established in the metro system and the metro depot to handle the trains.
OPERATIONS

Fire and rescue response unit in Frankfurt am Main
The basic unit for the response on fire and rescue operations in Frankfurt consists of a command vehicle, two engines and a ladder truck. EMS units are added as and when required. Every engine is staffed by an officer, an engineer and four firefighters. The command vehicle includes a chief and his aide, the ladder is operated by two firefighters, acts alone or supports one of the engine companies.

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Equipment of the attack team
Each engine has two attack teams that are both equipped with protective gear, SCBA, tools for forcible entry, hose lines and nozzle, escape hoods for possible victims, a rescue rope, a flash light, a handheld radio and various accessories like webbings or keys for hydrants and standpipes. In addition, the first team on every engine carries a thermal imager.

Breathing apparatus
In tunnel operations the Frankfurt Fire Department uses SCBAs as well as rebreathing apparatus. Both systems are equipped with a radio system that transmits data like the actual pressure and the remaining operating time to the engineer. Also an evacuation and an emergency signal can be transmitted via that connection.

The rebreathing apparatus are allowing an operating time from up to 4 hours. Each ladder carries three of them, additional apparatus will be provided by the hazmat-unit.

Rapid intervention team
Every time an attack team is entering a building using SCBAs an rapid intervention team will be provided. If an engine first arrives on the scene alone, the second SCBA team is used as rapid intervention team for the first minutes. With the arrival of the second engine, the first team of the second engine will be the rapid intervention team because this team is also equipped with a thermal imager. The number of firefighters in the rapid intervention team is always adjusted to the size of the scenario, so it increases at larger scenes. Operations in the metro system differ as described later on.
Heavy rescue unit
For rescue operations in the tunnel system the Frankfurt Fire Department uses two heavy rescue units. These vehicles are two-way vehicles that can operate on roads as well as on railway tracks. An operation on the tunnel track is only intended on scenarios without fire. The main purpose of the vehicle is to bring all the heavy rescue equipment to the scene of the accident and work as a transporter for possible victims. The vehicle is provided with different hydraulic-jacks, grounding devices and other heavy rescue equipment.

In case of a tunnel fire the heavy rescue unit supports the engine units by the grounding and with the special knowledge they have about the metro system.

E-powered railway trolley
For the transport of firefighters, equipment and victims on the tunnel tracks, the Frankfurt Fire Department uses some electrically powered railway trolleys. The trolley is deployed by four firefighters and operated by one FF as a driver. The top speed is between 10 and 15 km/h (6 – 10 mph) depending on the load to carry. The trolley has a breaking system and is used in the metro as well as the railway tunnels.
Mass casualties unit
For incidents with a huge amount of victims the Frankfurt Fire Department uses a mass casualties unit. Part of that unit is a container system which carries tents and medical equipment like heart defibrillators, oxygen and huge amounts of dressing material and pharmaceuticals. The mass casualties unit is able to treat up to 500 victims.

Dispatch policy, tactics and incident command
In case of a reported fire in the metro system the command and communication centre of the Frankfurt Fire Department would dispatch two of the previously mentioned fire and rescue units to the corresponding station. Additionally a division chief is dispatched for the coordination of the two units. Special units like the heavy rescue unit, the hazmat- unit, another fire and rescue unit that operates the mobile ventilators and the mass casualties unit will be alarmed and sent to the scene or a primarily defined staging area.

To each of the neighboured stations the command and communication centre would deploy an additional chief, an additional engine, one ladder and an ambulance. The citywide tour commander would take over incident command after arriving at the scene. He is supported by a mobile command centre. Another chief might be dispatched as traffic liaison officer to the control centre of the metro operator.
Tactics for the first arriving engine

The mission for the first arriving engine at a metro fire is to get as quick as possible to the origin of the fire and extinguish it. The quick extinction of the fire is the only possibility to prevent the scenario from becoming worse or getting out of control. So in this case it’s first the fire, then the rescue of possible victims. For that purpose the two attack teams and the officer enter the concerned metro station together and stretch the first hose line. All following units support them, start the rescue of possible victims and provide the SCBA rescue team.

LIST OF REFERENCES AND FURTHER INFORMATION
A list of references is available at the author. If you have any further questions please do not hesitate to write me an e-mail at jens.stiegel.amt37@stadt-frankfurt.de
Research Needs for Safety and Security in Roadway Tunnels

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ABSTRACT
This paper reviews the results of a research needs workshop conducted by the United States Transportation Research Board on Safety and Security of Research Needs.

KEYWORDS: research, priorities, fire, tunnels

BACKGROUND
The number and length of U.S. roadway tunnels is insignificant in comparison with many European countries. However, increasing traffic congestion in urban areas and growing land values in the United States make underground structures increasingly attractive for highways and transit compared to other options.

The American Association of State Highway and Transportation Officials (AASHTO) is the recognized standards development organization for the construction and maintenance of the U.S. highway infrastructure. In 2004, the AASHTO Subcommittee on Bridges and Structures created the Technical Committee on Tunnels (T-20) to address increased concerns for safety and security in the U.S. tunnel inventory. In support of the activities of the T-20 Technical Committee, the Federal Highway Administration sponsored an international scanning trip in late 2005[1]. The focus of the scan was on equipment, systems, and procedures incorporated into modern underground and underwater tunnels by leading international engineers and designers. Team members identified a number of underground transportation system initiatives and practices that varied from those in the U.S. in some respect. The team recommended that nine of these initiatives or practices be considered for further study in the United States. The recommended areas for increased focus were:

- Way Finding, Signage and Human Behavior, Motorist Education
- Automatic Incident Detection, Warning, and System Response (including mechanical and traffic management)
- Risk Management Approaches to Inspection and Maintenance
- Guidelines

As a next step, the AASHTO Technical Committee on Tunnels requested and received approval through the Transportation Research Board’s National Cooperative Highway Research Program to conduct a workshop on research needs for safety and security in roadway tunnels. Project 20-7 Task 230 was approved in May of 2007. A project panel was formed to oversee the project and plan the workshop.

SCOPE
The goal of the workshop was to review the state of the art and develop recommendations on research needs for improving safety and security in roadway tunnels, to be presented to the AASHTO Technical Committee on Tunnels for their review and consideration for funding through the National Cooperative Highway Research Program.
WORKSHOP
The workshop was held on November 29 and 30, 2007 at the National Academies Beckman Center in Irvine, CA. There were approximately 65 participants in the workshop including members of AASHTO Committees, highway agency representatives and a broad spectrum of members of the highway and fire protection engineering communities. The NCHRP project panel selected five international speakers to address the key research areas identified in the AASHTO scan. Three additional domestic speakers were invited to address the scan, a recent transit related research needs assessment [2], and a review of world wide standards for fire safety in roadway tunnels. Significant opportunity for participant input was provided for in the agenda. The workshop agenda is found in Appendix A.

RESEARCH NEEDS
Each invited speaker was asked to present the state of the art in one particular aspect of tunnel fire safety and identify research needs from their perspective. In addition, workshop participants were invited to submit research needs ideas prior to the workshop. Two panel sessions during the workshop generated a great deal of discussion amongst workshop participants and further generation of suggested research needs.

The project panel reviewed and synthesized the information from the workshop and identified ten key research needs statements for consideration by the AASHTO T-20 Technical Committee on Tunnels. These statements are shown below in the order of interest expressed by participants in the workshop.

I Effective Fire Suppression: Suppression is an effective strategy to minimize the impact of fires on roadway tunnels. There is worldwide controversy regarding the appropriate design approach to fire suppression and its impact on and integration with fire fighting operations. The objective of this research program is to explore the effectiveness of deluge and water mist suppression systems on selected design fires. The influence of activation time and ventilation should be explored as should impacts on tunnel tenability. A comprehensive literature review on recent worldwide research as well as full scale testing should be undertaken.

II Design Fires for Roadway Tunnels: Understanding and characterizing the range of fire scenarios that can occur in roadway tunnels is an important first step in developing design guidance for this application. The objective of this research program is to develop an appropriate basis for the design of fire protection strategies for tunnels. The project should include the following components:

- Research on the effects of different ignition sources on incipient times for fires in modern vehicles
- A risk based approach that provides a design basis for both large and small incidents and considers the potential for alternatively fueled vehicles
- Development of appropriate design parameters that can serve as the basis for the design of suppression, detection, emergency egress and other systems.

III Requirements for Egress and Emergency Signage: Recent worldwide research and applications have developed a significant body of information on effective egress and emergency signage. The objective of this research program is to collect information and develop standards for emergency egress and traffic control signage for tunnels to include the concept of LED lighting for vehicle spacing, egress signage location, etc.
IV Tunnel Operations and First Responders: First responders are a critical element in the overall response to fire incidents in tunnels. Tunnel operators need guidance to integrate emergency response into their emergency planning procedures. The objective of this research program is to develop operating protocols for tunnel operators for emergency conditions to include the roles for and communications between fire responders. Aspects such as ventilation control, power loss, and response time, and driver behavior scenarios, should be explored.

V Training and Education: The behavior of truck and passenger vehicle drivers can have a major impact on the consequence of a fire event in a tunnel. The objective of this research program is to develop targeted training materials for safe behaviors for car and truck drivers. This should include a formal assessment of the impact of leaflet type education; research on new education and training methods; and formal training programs for truck drivers, enforced as a condition of license renewal.

VI Benchmarking Tunnel Incidents: A comprehensive understanding of tunnel fire problem is necessary to determine the allocation of resources and target appropriate research and design guidance. The objective of this research program is to develop and implement a process to benchmark fire incidents in U.S. tunnels. This should include an upgrade of the domestic tunnel scan; a study of near miss accidents in tunnels; a continuation of the international technical exchange, in particular to Asian countries; and development of a database of lessons learned.

VII Design Basis for Egress Systems: Human behavior in emergency situations is critical to the design of egress systems. European studies may not be directly relevant to the performance of the U.S. population. The objective of this research program is to investigate aspects of egress behavior of the U.S. population to provide an informed basis for egress design. Issues such as panic response, walking speeds, and attachment to vehicles should be explored.

VIII Effective Incident Detection: Effective early stage fire detection can reduce the costs of fire incidents and increase available egress and emergency response times. However, tunnels represent a harsh environment for conventional fire detection systems. The objective of this research program is to build on current research to identify effective fire detection systems for tunnel applications and develop performance and installation criteria (eg spacing). A particular focus for the research is quick response smoke detection and dual purpose CCTV systems.

IX Fire and Smoke Ventilation System Design Methods: Ventilation system design for roadway tunnels may be governed by the fire condition; current design bases are prescriptive in nature. The objective of this research program is to develop a design method for ventilation systems which is based on critical velocity and accounts for the impact of sensor type and location.

X Performance of Structural Materials in Tunnels in Fire Incidents: Tunnels represent a unique and extreme environment for construction materials which compromises their performance in fire conditions. The objective of this research program is to study the impact of tunnel environments (moisture, design loads, configuration) on the response of concrete and fire proofing materials in fire incidents. Spalling and stability should be explored.

XI Guidelines for Tunnel Geometric Design for Fire Safety: Tunnel geometry has an impact on the impact of fire incidents in tunnels and should trigger when fire safety systems are required. The objective of this research program is to develop guidelines for accident prevention (sight distance, curve radius, shoulder/curb design) to minimize fire incidence. Criteria based on tunnel length, traffic volume and type to trigger fire safety provisions should be developed.
XII Application of Intelligent Transportation Systems (ITS) to Emergency Operations in Tunnels: ITS provides the technology to integrate driver behavior with emergency operations. The objective of this research program is to develop guidelines for the use of ITS to guide tunnel drivers toward safe vehicle spacing, emergency closure procedures, and other safe behaviors in road tunnel fire incidents.

SUMMARY AND NEXT STEPS
These research needs, together with overall input received at the workshop, are under consideration for research implementation through the National Cooperative Highway Research Program. Thus this workshop is the first step toward what participants hope will be an investment in the improvement of roadway tunnel safety and security by the U.S highway community.

ACKNOWLEDGEMENT
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REFERENCES
APPENDIX A

Workshop on Safety and Security in Roadway Tunnels

November 28-29, 2007
The Arnold and Mabel Beckman Center
of the National Academies of Sciences and Engineering
Irvine, California

FINAL AGENDA

Wednesday, November 28, 2007

9:00 Welcome/Introductions/Workshop Charge
Harry Capers, Chair, NCHRP Panel 20-7 Task 230

AASHTO/FHWA International Scan on Underground Transportation Systems Safety and Security – Summary and Critical Issues
Steve Ernst, Federal Highway Administration

Chris Hawkins, PB Americas, Inc.

10:30 Way Finding, Signage and Human Behavior
Gunnar Jenssen, SINTEF, Norwegian Fire Research Laboratory

Fire Growth and Heat Release in Tunnel Incidents
Haukur Ingason, SP, Swedish National Testing and Research Institute

13:30 Incident Detection and Tunnel Ventilation
Peter - Johann Sturm, Graz University of Technology, Austria

15:30 Risk Management and Safety Concepts for the Oresund Link Immersed Tunnel
Mikael Braestrup, Ramboll, Denmark

16:30 Panel Discussion – Research Needs

Thursday, November 29, 2007

8:30 Guidelines and Standards for Roadway Tunnel Safety
William Connell, PB Americas, Inc.

9:30 Panel Discussion – Needed Guidelines

11:00 Summary of Research Needs
Kathleen Almand, Fire Protection Research Foundation

11:30 Concluding Comments, Next Steps for AASHTO Technical Committees
Harry Capers, Chair, NCHRP Panel 20-7 Task 230
INTRODUCTION

In the City Line rail tunnel project there are a lot of risks present. This paper refers to how risks in the operational phase, when trains are running, could be addressed when the perspective is widened. The technical data of risks, dimensioning data etc are intentionally not presented.

A wider perspective is achieved by going a step further than just applying regulations and standards, and copying earlier projects. Probably the most important aspect is to find out the purpose and background of rules and legislation etc, and how they should be applied to the specific project. Other important factors are being updated on new hazards and threats, taking in new experience collected from accidents and collecting results from new research. A wider perspective could also be used inside the project by interacting more to achieve safety systems that are reliable and will function when the tunnel is in operation.

Some examples will be presented from the City Line project, and there are also examples from other tunnels to make the picture more complete.

PRESENTATION OF THE PROJECT

The City Line is a double-track railway with two new stations that is to be built in an approximately six kilometre long tunnel under the city centre of Stockholm.

Figure 1   City Line, Stockholm
The City Line will be used by the commuter train services. Other services will continue to run on the existing two tracks via Stockholm Central Station. The two new City Line stations, City and Odenplan, will be important junctions with direct access by escalators to the Stockholm metro. The total cost of the City Line is approximately SEK 16 billion. The line is planned to become operational in 2017.

The City Line

The City Line projects safety approach to manage risks in the operational phase has the structure shown in figure 1 below. Starting with a Target-document describing the projects safety goals including a defined safety level, and the different regulations, standards etc relevant to the project the base was set to write a preliminary Safety concept.

![City Line. Structure of safety documents](image)

The Safety concept describes
• Safety policy and Safety targets
• conditions for design (traffic, trains etc),
• functional requirements for safety including evacuation strategy and rescue intervention aspects.
• strategies for risk assessment

The Safety concept is used for information and communication within the project as well as with authorities, operators etc. However, the main function of the Safety concept was to form a base for forthcoming work with safety within the project. In that work different necessary investigations were identified and then carried out such as evacuation studies, fire simulations, explosion calculations etc. Adjustments were made and a Safety evaluation (Quantative risk assessment, QRA) was carried out and compared to the Safety targets. After required adjustments to the Safety concept it was completed and handed out for use in the early design phase. The SITS (Safety in Technical Systems and Functions) was then developed for system design phase to ensure each systems performance in terms
of reliability, availability, maintainability and safety. This was outlined in six design criterion for each system and formed a base for the design and construction.

1. Required function incl. redundancy requirements
2. Time limited derating
3. Function at power or communication failure
4. System availability and maximum acceptable faults
5. Faults leading to impact on traffic
6. Function during fire or accident

Changes in regulations or project design need for further investigations etc are continuously implemented and followed by revision of the QRA and if necessary changes in the Safety concept and the SITS-document.

RISK PERSPECTIVE

Identifying all possible risks and defining the limits of different risk assessments within the project is a difficult challenge. Today, every tunnel project of any importance carry out risk assessments and for the operational phase many aspects have to be addressed. A few aspects which widen the perspective are given below.

Risk levels

Setting a well defined level of acceptable risk for the operational phase is important, and defines the scope of work. In Sweden this may be more easily achieved than in most countries since the National Rail Administration has defined acceptable risk levels for Rail tunnels. The acceptable level of risk is based on a combination of statistical data of accidents and an ambition to lower the level of risk. The project may use it as it is, or add/subtract other project specific risks. For the City Line project the risk levels were redefined because of the two underground stations.

![Swedish National Rail Administration FN-curves for tunnels.](image)

Safety or risk should also be looked upon from a community perspective and the project may increase/decrease the overall safety level in different ways. Transports will probably have a different pattern including new routes and ways of transport. Transports will probably also increase, something which certainly affects the risks. Since the City line is a commuter train tunnel it will change the
transport pattern of people and also affect safety in the connecting metro stations. The train capacity revealed on existing tracks can be used either by regional trains, goods transports or transport of hazardous goods. If used for transport of hazardous materials it would increase the risk on the existing rail line, but increase safety from the city’s perspective if transports by road decreased with the same amount. A special risk assessment was carried out showing that most likely the regional trains would replace most of the revealed capacity, and the change in transports of all goods on rail through Stockholm would more or less the same.

Adjacent safety and risk objects

The City Line is a tunnel beneath the city centre of Stockholm and will pass close to other more or less sensitive tunnels and buildings. These will impose a threat to the City Line and vice versa. The correct safety measures to limit the risk must be taken after careful analysis of each individual object. The regulations and standards are weak in this field and the adjacent objects sometimes have a restricted access that will make the task more difficult.

Examples from the project are; an adjacent building will have their second escape route, through windows with help of fire brigade ladders, blocked by the location of a construction site.

Part of an escape route from the tunnel goes through an existing tunnel which was found to include distribution pipes for gas.

Existing old tunnels that have to be passed within a minimum distance had no fire protection of their load bearing structure.

In another project connections to adjacent tunnels created a risk for flooding. The weak parts were found quite a distance away in the adjacent tunnels.

Combined risks

Each risk is often handled separately in the risk analyses, and combined risk scenarios are limited. This is often not a problem when it comes to more common accidents since everyone is more or less aware of the combined risks and they are included in the risk assessment. Other combined accidents are often neglected and not included for the reason that they do not “significantly contribute” to the overall risk. As for rare accidents and sabotage this ought to be considered with more care. Proven deadly combinations are; airplane collision and fire; explosion and fire; fire and flooding. Neither in this field regulations and standards alone will assure the project with adequate safety and security. Risk assessment is necessary, and since cost effectiveness often is poor due to very low probability for combined risks there are often only limited measures taken. However, sometimes these measures will make the difference between severe and catastrophic consequences.

In the Baku metro accident the fire beneath the train caused by an electric arc destroyed the pneumatic door system. The train was crush loaded and the sliding doors could not be opened manually because of the pressure against the doors. This led to reconstruction of most metro trains in Stockholm.

In another tunnel project flooding was considered a risk but evacuation evaluated to be safe before water reached to a dangerous level. Later in design it was found that all light in the tunnels would be gone before evacuation was completed and thus preventing safe evacuation. Small changes in design corrected this.
SYSTEM DESIGN PERSPECTIVE

Striving for perfect safety needs a red line from A to Z that may not be broken. From Safety concept to everyday operations all safety systems have to form a well fitted jig saw puzzle that covers the risk picture. This requires understanding of the red line of all designers and staff involved and each part must be designed to fit the puzzle in respect of safety.

In the City Line project we have put a lot of effort into background studies to be able to better define the design criteria for each part and better cope with changes in overall project design. We have had a series of scenario studies together with many involved parts to get a better understanding and design. Two important things that we have identified in system design are discussed in the following.

Dimensioning scenario/data

There is a large risk in using a single figure or scenario as design criteria for safety, and especially if the analyst/designer is not familiar with the background and its uncertainties. If the design criteria is based on a worst case scenario there is no risk, but normally that is not the case. Instead the design criterion is a figure, or scenario, processed by considering many aspects such as probability, cost-effectiveness etc applied to a fictive standard tunnel. For a wider perspective in a specific tunnel project it is wise to question whether the criterions are valid or if they ought to be revised. Reasons for that could be new experience from research or accidents, a new type of traffic or tunnel design etc.

Examples are: The Safety refuge in the Mont Blanc fire where you supposedly would be in safety during the fire until rescued. The fire became more severe than expected and the safety refuge turned into a trap instead.

The design of fire protection of train tunnels in Sweden where the temperature curve and requirements first were copied from the National Road Administration who in turn got them from international road studies and research. In the City Line project it was discussed whether the requirements ought to be changed since only commuter trains and no goods trains will be running in the tunnel.

An explosion design criteria defined as a certain amount of explosives, and all protection measures are optimised to fulfil this criterion. If the criterion is exceeded it might lead to severe consequences. A safety factor, study of uncertainties or a set of scenarios are ways to minimise this risk.

Fire protection of load bearing constructions are well defined in most requirements for tunnels, but there is often nothing regarding bare rock tunnels without lining. In recent fire tests it has been shown that there could be considerable spalling of rock which might lead to a collapse of the tunnel.

Reliability and availability for installations

A chain is never stronger than its weakest link. Installing a safety system only provides the desired risk reduction if the safety system is in operation. Some installations will have high and well defined requirements on reliability and availability. Normally these systems are the one critical to production and used on daily basis. Security systems such as locks and money handling systems and safety systems such as platform screen doors are normally amongst them. Systems purely for safety or security and systems seldom used and without any effect on normal operation are often forgotten. Many safety and some security systems don’t have criteria’s for reliability and availability, and that are only acceptable if other safety and security measures are taken to compensate when the system is out of operation. In the City Line project a lot of effort has been put into reliability and availability as well in possible solutions to compensate for systems out of order. This will be used for further discussions of functionality and need for back-up systems with the operator.
Examples are: Automatic fire detection systems are often vital for initiating other safety systems and giving alert signals. In the Mont Blanc tunnel fire, as in many other fires, it was out of order and no compensating actions were taken. (If this contributed to the disaster, and how much, is a matter for discussion.)

Emergency valves/doors for protection against flooding have many design parameters, but reliability and availability are often forgotten.

Smoke management systems of today are often complex with reversible fans, a lot of dampers and different plans for different scenarios. In nearly all full-scale tests we have carried out the system did not fulfil the expectations. Neither did it in the Mont Blanc tunnel fire.

In risk assessments with event tree analysis there are normally probabilities shown for safety systems operation. In reviews with comparisons to system design there are no analyses or requirements set on how to meet the assumed probability of operation.

**Integrating safety in all design**

Safety and security consultants are often handled separately from other disciplines and their only objective is to assure safety and security. This gives them the possibility to optimise the solution within their responsibilities. If they are introduced at an early stage and given the mission to interact with other disciplines it will benefit the project. Very often the solutions can be quite different and more cost-effective.

Examples are: Distance and location of emergency escape routes between tunnels were chosen by optimising distribution equipment for power and signalling. This resulted in more cross passages but less cost overall due to easier access to equipment, less niches required in bored tunnels and less requirements on other safety measures.

Parallel safety tunnel used as fresh air inlet channel to stations, and access for service vehicles to installations minimise downtime. (Alternative was through dense city centre traffic.)

Platform screen doors introduced during the project for ventilation reasons gave new possibilities to limit the risk and redesign safety to a different more cost-effective solution.

Systems used in normal operations may be used in emergency situations, but only if all requirements for reliability, availability, maintainability and safety are met. A criterion used in the City Line is that the operation during an emergency may not be the opposite of normal operating conditions. Change flow of air and movement of people etc takes time and present new risks.
Upgrading in the future

The society’s demand for safety and security is constantly increasing since we are moving up the Maslow steps with all our basic needs fulfilled. If not interrupted by disease, war or some thing else terrible, it will continue. To meet new and higher requirements in the future after the project is finished we should try to find solutions that are possible to upgrade. This is best practised on the safety and security as a whole, meaning that we ought to preferably build with a high standard on the measures impossible or hard to upgrade, and a lower one on those that are easy to upgrade if wanted. The cost effectiveness might sometimes be a bit lower and decisions have to be made about the value of the possibility to upgrade safety and security.

MANAGEMENT

The capability of managing safety in the operational phase differs between organisations and should be considered in safety design. Design of a closed/local system such as a metro system gives the opportunity to, within the system; decide whether to increase safety on rolling stock, the tunnel, personnel etc. Open systems as road and rail line tunnels do not have the possibility to affect the vehicles, instead they are a condition.

Managing safety in an emergency situation will require the staff to be well trained and have adequate safety instructions. Operational organisations managing many tunnels need the tunnels to be similar, from a safety point of view, to maximise the probability to manage them correctly in case of emergency. This will narrow the safety approaches possible and safety measures preferred in designing the tunnel.

If the safety system tend to be difficult and complex to run automatically it is easy to adopt the solution to run it manually from a control centre. To many disasters has that in common that staff in the control centre were put up to situation that they could not manage. In the City Line project we have required that all safety systems that are to be operated manually should be confirmed by the organisation responsible for manual operation.

Cooperation with authorities

Cooperation with authorities in respect of a wider perspective divides into understanding and supporting intervention for rescue organisations and revealing what’s behind the requirements and standards. This will support a design that takes care of the differences between urban and countryside tunnels in terms of rescue resources.

Involving the rescue services and the police in design is easier if they also will benefit from the cooperation. In the City Line project we’ve searched information about strategies in other projects, research, experiences from around the world etc to share with them. An important part of the cooperation has also been the different scenarios we have run through together to find suitable solutions. This far only the fire brigade has been involved, but as in other projects lately the intention is to involve the police.

In terms of what is behind the requirements in the regulation most work in recent time in the City Line has been focused on the new European Technical Specifications for Interoperability Safety in Railway Tunnels, TSI SRT. As an example the access ways for rescue services should be 1,4 m wide and 2,25 m in height. It seems the reason is that the firemen have to carry equipment and always have their helmets on, but it is not defined where to locate them or how many that is needed! In a scenario/discussion we take this as a condition and then look at the whole situation such as the necessity of transporting people on stretchers, the possibility of having more narrow parts of the access ways, doors, stairs etc.
SABOTAGE PERSPECTIVE

Arson, terrorism and other human sabotage acts are threats that have to be taken into consideration when planning safety and security.

Arson is one of the most common causes of fire in buildings open to the public, something which also applies to underground stations. Fires started by arson have potential to be more serious and cause greater damage. This is because the perpetrator might bring fuel; select where to ignite and with the intention of causing a rapid fire growth. A more sophisticated arsonist might also interfere with the fire detection system so that the alarm will be delayed.

Fire records of arson in Sweden so far show only minor fires in underground station and tunnels. Nevertheless, there have been serious arson fires in metro trains outside the tunnel system. Minimising the amount of combustible material in the stations and tunnels and use of fire rated material are the safety measures normally taken. Today supervision by CCTV and other security arrangement also have a high priority. Preventing people from gaining access to the tunnels is essential for many reasons and arson is one of them. Since arson is often conducted by youths trying to prove themselves tough it is essential to catch them to avoid further attempts. Risk assessments should include the risk of an arson attack.

Sweden has been spared from terrorist attacks over the last decades and is proud to be an open society. An open society, however, also means that documents and drawings normally are not classified in governmental and community run projects and should be handed out to anyone who asks for them. To prevent terrorists from using information from risk assessments and identify weaknesses, it should be stated early in the project what information that should be classified. The probability of a terrorist attack changes over time and, as mentioned earlier, the design should preferably give the possibility to easy upgrade the security for this kind of threat.

Adjacent objects of interest to terrorist might lead to the necessity of improved safety and security within the tunnel itself as a part of the protection of the adjacent object.

Combined risks are identified by organised terrorist groups as a possible weakness. It should be addressed by not having these kinds of risks that can be used in terrorism, and by classifying the analysis of combined risks. It is more difficult to have safety design parameters classified and instead it is important that exceeding the design parameters do not lead to severe consequences.

REFERENCES


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The City Line project, Stockholm
Tunnel Explosion Characteristics

Rickard Forsén
FOI Swedish Defence Research Agency
Defence and Security Systems and Technology, Tumba, Sweden

ABSTRACT

Certain objects/structures may need to be designed in order to withstand the high pressure loads from explosions. Examples of such objects/structures are military buildings made for force protection both above and below ground, civil defence shelters, certain industrial buildings for instance where dust or gas explosions may occur, structures/buildings close to dangerous goods routes and also vital infrastructure objects/buildings that may be exposed to antagonistic threats. Explosions in tunnels and the pressure generated are significantly different from pressure generated from an unconfined explosion in the open. FOI has a long experience of work with explosions in tunnels. Some examples of such work will be presented as well as the characteristics of blast pressure in tunnels and possible countermeasures will be discussed.

KEYWORDS: tunnels, explosions, blast, pressure.

INTRODUCTION

An explosion is a sudden increase in volume of a mass and release of energy in an extreme manner, usually with generation of high temperatures and release and expansion of gases. An explosion creates a shock wave, which is a compression wave in the surrounding air that propagates outwards faster than the speed of sound. An explosion may also result in the generation of high velocity fragments from objects close to the explosion. The energy causing the explosion may originally have been stored in the system in a variety of forms; these include chemical or pressure [1]. Examples of chemical explosions are initiation of high explosives (such as TNT) or a mix of hydrocarbons and air. Examples of pressure explosions are bursting pressurized gas-filled vessels.

Certain objects/structures may need to be designed in order to withstand the high pressure loads from explosions. Examples of such objects/structures are military buildings made for force protection both above and below ground, civil defence shelters, certain industrial buildings, for instance where dust or gas explosions may occur, structures/buildings close to dangerous goods routes and also vital infrastructure objects/buildings that may be exposed to antagonistic threats.

Swedish building design codes for tunnels, both road tunnels [2] and railway tunnels [3], state that for certain structures in tunnels a dynamic explosion load should be considered according to Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Overpressure (MPa)</th>
<th>Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evenly distributed inside tunnel</td>
<td>0.1</td>
<td>50</td>
</tr>
<tr>
<td>Locally over an area of 4m·4m inside tunnel</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Evenly distributed inside escape routes</td>
<td>0.05</td>
<td>50</td>
</tr>
</tbody>
</table>
In these codes it is also stated that a risk analysis is required to determine actual dynamic explosion loads (other than according to Table 1) if:

- Dangerous goods class 1 (explosives) or class 2 (gases) [4, 5] will be transported in the tunnel
- If human hazards are particularly high (if a tunnel is attached to a structure where people are staying more or less continuously)
- If consequences of a local damage is particularly large, for example for a tunnel below water when the tunnel is the only connection.

In a risk analysis the effects and consequences of different accidental scenarios are calculated and frequencies of the scenarios are estimated to determine risks that are compared to tolerable risks as a basis for suggested risk reduction measures.

Besides road and railway tunnels also other underground structures may be necessary to design for a certain explosion loading. Examples are underground parking garages located below vital objects such as head offices, governmental buildings or police headquarters.

**EXAMPLES OF TUNNEL EXPLOSION APPLICATIONS**

There are at least three different possible methods to determine the load from an explosion in tunnel geometry or the damage to structures from such an explosion. These are:

- Experiments either in full or small scale
- Calculation models, simple empirical or advanced CFD-codes
- Systematic studies and compilation of data from accidents (or intentional acts).

FOI experiences concerning explosion blast loading and resistance/vulnerability to structures from such loads originate mainly from military but also from civilian structures/problems. Below is a list of examples of projects/activities that have been undertaken during recent years.

**Shock tubes for generation of blast pressure**

A shock tube is a tunnel or other tube-shaped structure where a blast pressure can be generated either by release of pressurized gas or a detonation, for example of high explosives. The primary purpose with a shock tube is not to make realistic predictions of blast in for instance road tunnels but to generate well defined loads in a simple and reproducible manner for studies of different objects’ reactions to dynamic/explosive loads. One big advantage with a shock tube is that a comparatively large explosion in the open can be simulated with a small charge inside the shock tube. FOI has access to a large, explosive-driven, shock tube at Botele Udd north of Stockholm (Figure 1). Examples of objects studied by FOI in this and other shock tubes are blast valves, hatches and doors to military or civil defence building structures, wall elements [6] and windows etc.
Fortifications in rock
Underground tunnels and chambers in rock have traditionally been used by military forces for extremely strong protection of people and materials. Traditionally also strong barriers were mounted inside the tunnels. The idea to omit the barriers to only use the tunnel geometry as blast reduction, possibly with a number of turns and tunnel area changes etc., were examined in a multi year project [7]. Detonations outside the tunnel adit (Figure 2) were accomplished to simulate conventional weapons detonation. The pressure inside the tunnel system was recorded and the impact to people and material was evaluated.

Figure 1. A partly cut away drawing of the shock tube at Botele Udd.

Figure 2. Plan of tunnel system geometry for tests with blast propagation into tunnel system.
Underground storage of ammunition in rock chambers

Large amounts of high explosives or military ammunition may be stored in underground rock chambers in order to reduce the effects to the surroundings if an accidental explosion should occur. A series of tests with different charges such as bare high explosives, propellants, ammunition and mixes were carried out in a several hundred metres long rock tunnel system (Figure 3) in Älvdalen [8]. Up to 10 000 kg of high explosives were detonated in this scale model of a real storage. Video recordings of the entrance of the tunnel were made and pressure gauges were mounted at different locations both inside and outside of the tunnel.

Even if the overpressure from an explosion inside an underground rock chamber does not cause breakage of the rock overburden, the effects from the tunnel adit may be considerable. Anders Bryntse [9] has examined the pressure outside an ammunition storage chamber in rock. When the pressure wave inside the tunnel reaches the adit a rather complicated progress occurs illustrating the nature of a air blast pressure wave as both a shock wave and a jet according to Figure 4 below and [10].

A long duration jet is formed outside, and simultaneously a short-duration shock wave is spread in all directions. A building or other object in front of the exit is exhibited to the shock wave but also to the jet, if it reaches this location. In a calculation with AUTODYN the explosion of 10 000 kg inside a chamber of 1000m³ connected to a straight tunnel with 100m length and with 10m² cross section area was simulated. The pressure load against a 5x5m target located 100m in front of the adit was
determined (Figure 5). The target is first stroke by the short duration shock followed by the long duration pressure from the jet.

![Figure 5. Pressure time history against a target 100 m in front of the adit of a 100 m long tunnel where 10 000 kg detonates.](image)

**Accidents with dangerous goods transport inside tunnels**

As a basis for design of tunnels where dangerous goods are to be transported different accidents has to be considered. Explosions may be caused from transport of dangerous goods class 1 (explosives) if for instance the vehicle is colliding with another vehicle or object. A fire in the vehicle may also eventually result in an explosion. A discharge of dangerous goods class 5 (oxidizing agents) caused by a collision could be mixed with leaking liquid hydrocarbons such as diesel fuel from the vehicle and this mix could be initiated and cause explosions in the same manner as dangerous goods class 1. Also discharges of dangerous inflammable gases from dangerous goods class 3 could be initiated and explosions can not be excluded. A risk analysis was carried out for two proposed road tunnels, approximately 300 m each, at E18 along Tensta and Rinkeby [11] where consequences to buildings on top of the tunnel from detonations of 200 kg up to 16 000 kg were calculated as a basis for risk analysis concerning dangerous goods accidents.

**Acts of terrorism**

Even though energetic materials are not normally transported in railway passenger cars the risk of acts of explosion sabotage in subways can not be excluded. A calculation has been made of pressure from different charge weights detonating inside railway passenger cars and on underground railway platforms [12] (Figure 6). The results form the basis of design of doors and walls of escape routes for passengers on the platforms.

![Figure 6. Plan sketch of assumed geometry for a platform in a subway.](image)
CHARACTERISTICS OF EXPLOSIONS IN TUNNELS.

Explosions in tunnels and the pressure generated are significantly different from pressure generated from an unconfined explosion in the open.

**High explosives**
The pressure generated by a detonation of high explosives inside a tunnel is considerably higher and with considerably longer duration than when generated by a corresponding charge outdoors.

Examples of important parameters of the tunnel affecting the pressure attenuation are:

- Length of tunnel and standoff from explosion to target
- Cross section area of the tunnel
- Roughness/friction of the walls
- Turns of tunnel direction and area changes etc.

Close to the explosion a very complicated pressure time history occurs but further out a more well defined shock wave progress takes place that can be estimated by rather simple empirical formulas and diagrams.

In order to demonstrate the difference between detonations of high explosives inside a tunnel and outdoors in free air a calculation was made using LS2000 [13]. A charge of 400 kg (estimated maximum charge weight of a private car) and a charge of 16 000 kg (maximum allowed weight of high explosives class 1.1 on roads) were considered to detonate inside a tunnel with 50 m² cross section area (Figure 7).

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Figure 7. Calculated overpressure (incident) versus standoff for 400 kg and 16 000 kg high explosive in a tunnel.

As can be seen the overpressure from a 16 000 kg charge in the open is about equal to the pressure
from a 400 kg charge in the tunnel at 50 m standoff. The overpressure inside the tunnel exceeds the pressure from a corresponding charge outdoors with at least an order of magnitude.

Gases
High explosives are not the only possible cause of explosions in road and railway tunnels. If a discharge of inflammable gases is initiated outdoors in free air the generated pressure is probably not the most dominant effect. However, in a tunnel geometry, confinement may cause an increase of burning velocity which also may create considerable pressure levels besides the heat radiation. Even detonations in a mix of gases and air can not be excluded. The potential of extensive damage is very large since hydrocarbons contain about 10 times more energy (if stochiometricly mixed with air) than high explosives.

POSSIBLE COUNTERMEASURES TO PREVENT OR REDUCE EFFECTS OF EXPLOSIONS IN TUNNELS

Examples of possible countermeasures to reduce potential damage from explosions in tunnels comprise:

1. Exclude high explosives and other potentially exploding substances from tunnels
   a. Certain dangerous goods transports forbidden entirely or allowed only on limited occasions
   b. Detection of, for example, high explosives (antagonistic threats)
2. Automated systems with blast energy absorbers initiated with sensors to detect an explosion
3. Design of structures inside the tunnels and at the adits to resist the load from explosions.

1. Even though removing dangerous goods transports from tunnels is an advantage for the tunnel and its surroundings it may be outweighed by the disadvantages in that the risks for the alternate routes may be higher to the society as a whole. A lot of efforts are made to develop fast and accurate detection systems to reveal antagonistically carried high explosives. However, fast detection and at significant standoff distances remains one of the most difficult challenges.

2. Automated systems for blast energy localisation in underground openings have been applied in coal mines (with risks of methane explosions) for decades [14]. To reduce the effects of an explosion, a blast energy absorber that contains a blast suppressing agent (for example water mist) dispenser, is utilized. However, there are major drawbacks for the existing systems such as:

- Lack of reliability of blast identification
- Low speed of blast energy absorber activation
- Inadequate discharge of blast absorbing agent.

3. The most robust method of preventing unacceptable damage from tunnel explosions is still to design vital structures to resist the effects of blast pressure along the tunnel or at the adits where also proper standoff (to inhabited buildings etc.) is vital.
REFERENCE LIST


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Overview of Tunnel Security Protection Strategies

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ABSTRACT

Tunnel protection strategies are complicated by two factors. First, the public and/or motor vehicles and train cars must be allowed into the facility. Second, there is no reliable method of fast screening for dangerous materials and/or weapons that would not cause long delays in transit through the tunnel. However, standard practices regarding facility protection can be applied in order to provide and increased level of security leading to “acceptable” risk. These strategies include protection of both cyber and physical facilities themselves and involve the application of methodologies which dissuade potential attacks. Deterrence of attacks (prevention) via applied security protocols is the best method of facility and personnel protection. Although planning for response to security breaches and critical events is critical to facility safety, it is clearly better to never have an incident occur at all. This discussion will review security issues that impact the overall tunnel security environment

KEYWORDS: tunnel security, security strategies, security policies, physical security, cyber security

In the planning and implementation of any security strategy, a “philosophical” choice is made. Organizations and individuals choose between a policy which prevents common, but low impact events and those which are less likely to occur, but have a great effect on the facility and public. For example, the operator of a mass transit facility may have to choose between the installation of sensors for detecting biohazard material, or the use of “low tech” methods to deter explosive attacks on the facility. Biohazard material may be great cause for alarm and would cause great fear on the part of the public, but the chance of its actually use are small in comparison to the use of explosives against transit facilities. This dilemma is illustrated in the following slides which show that (in general) events with the most impact are the rarest. Due to the present state of fear regarding terror incidents many (most?) security strategies are developed to preclude the rarest, but most terrible types of events. However, security planning that is developed to begin to reduce more common crimes and events actually reduce the chances that a large event may occur. For example, increasing uniformed police presence to deter pick pockets and prevent petty crimes also deters those with greater malicious intent.
Protection of tunnel facilities is also complicated by several other factors:

- Many tunnel facilities are actually “iconic” structures
- Tunnel (transit) facilities have a history of terror attacks
- Tunnel facilities are important to the economy of both local and regional areas
- Due to the above, tunnels are an “attractive” target for terrorists for both the generation of fear in a populace and actual negative impact on an economy.
Facility security planning can be divided into the following areas:

Cyber Security
Signage
Identification
Locks & Locking Devices
Access Control (Doors +)
Cameras
Alarms
Communication
Biometrics
Exterior & Fencing
Response Plans
Proactive Planning

Cyber Security:

While not directly a point of this discussion involving physical security procedures, cyber security policies and procedures are a vital part of any security plan. Computer control of life safety systems, physical security systems, plant facility operations, and fire response procedures are a fact of life. Thus, the tunnels cyber systems must be protected. Tunnel operators need to employ persons who are “experts” in this field and are generally known as a Computer Security Officer (CSO). These individuals have specific training and certification in the cyber security arena and should be knowledgeable in both prevention AND recovery. They should develop plans to prevent attacks from both external (hacking) sources and internal computer employee sabotage. Employee cyber issues are most often caused by personnel issues, but can be devastating never the less.

Signage

A very unglamorous and often overlooked area of facility security is the use and installation of proper signage. Signs which designate secure areas are a basic yet key part of any security plan. Not only do they actually work in keeping out the clueless or curious, the signs are important as they establish they demonstrate to the public and employees that the facility is “serious” about its security plan. The signs are often useful in the interview, arrest and detention of individuals found in locales closed to un-authorized persons. Signs eliminate the problem of “I didn’t know I couldn’t go there, etc” and give authorities the right to interrogate those individuals to determine the actual reason(s) for trespass. In addition local laws may require that signs be posted in order to prosecute for trespassing.

Identification

The prevention of unauthorized entry into secure areas is a basic and key element in security planning. In fact, it is the goal to which security planners strive for. Plans which allow only authorized and “vetted” individuals into secure areas are the basic building blocks of any security scheme. In fact, if a facility can’t actually physically secure non-public areas then all other security procedures are worthless. The identification of authorized employees can be accomplished in a variety of ways including the display of photo ID cards, physical review and comparison to stored photos/digital images, guard personal knowledge of employee appearance, etc. However, all these plans have one goal: the denial of entry of unknown and unauthorized persons. Numerous systems for the identification of employees/authorized visitors exist and can easily be implemented. The complexity and cost of these systems should be determined by the threat level (intelligence) against the facility and impact on the general operation of the site.
Locking devices (hardware) have been employed literally for centuries to keep out those who do not belong in a specific area. Locks are, in general, useful tools which are relatively cheap to install and use. However, the lock system by many facilities is often compromised by the fact that control of keys has not been maintained, keys are not recovered from those who employees who leave their jobs, keys are not numbered or issuance recorded, or the locks used not “high security” and can easily be copied in any lock shop. Key control systems should be based on a standard master/sub master system where only a few “grand master” keys are issued. These keys will open any lock in the facility. Most employees need only be issued masters, or sub-master keys which are designed to only open doors in their specific area. Thus, the computer room operators can open doors in their area, but cannot, for example get into the HVAC room, etc. Keys should be stamped with a serial number which is recorded on issuance of the keys. Keys should be recovered from employees who leave the facility and their “final” paycheck should not be issued until the key is returned.

Locking devices can also be upgraded to key card systems which allow entry either via physical swipe of a card with a magnetic stripe, or only “waved” in front of a card reader if equipped with a proximity chip (RFID). These key cards should also have a photo ID and can be coded via color, or specific job code to immediately identify authorized areas. Pin number entry and biometric parameters can also be used for increased security.

Key cards provide a number of advantages over physical keys. These include the ability to nullify a card immediately on loss or the card or employee dismissal, the ability to change authorized area entry easily, the tracking of who is in a particular area at any given time, and identification of what time employees enter an area.

Access Control (Doors +)

Access Control is part of the processes noted above. It simply means that only authorized persons are allowed in secure areas. This can be accomplished via guard review of persons needing entry, the use of locks/key cards, etc and the establishment of physical barriers (doors/walls/etc) to delineate secure environments. Often, simply putting a lock on a door with a sign “only authorized persons” is enough security to control areas which are not critical to facility operation.

Cameras and Alarms

Cameras and alarms should be a normal contingent of security protocols. The alarming of secure areas and the knowledge that alarm systems are present are of great deterrent value. Persons with mal-intent will often bypass areas with alarm systems and seek other easier venues. There are literally hundreds of alarm systems commercially available for installation and it is just a matter of cost to determine which system to employ. However, at a minimum, the alarms need to sound both at the alarm location itself and at a remote monitoring site. In addition, standards need to be established which identify the maximum time allowed for alarm response. In short, if it becomes known that either no one responds to an alarm, or that the time for response lengthy the alarm is worthless.

Camera systems as well are commercially available and easily installed. At a minimum, the camera systems should be installed in a manner that can actually record and identify the faces of persons passing the camera view. The camera system should also record the image seen for a minimum of 30-60 days. Camera systems can also be tied into the alarm system so that they immediately focus on areas where an alarm is activated.

Visible cameras have great deterrent value, but are often considered too intrusive for use. “Hidden”
cameras can record the same image, but have little deterrent use. In general though, cameras should be thought of as a reactive rather than a preventative, or proactive system. Even when the images are monitored it is rare that a security operator will identify a problem until after it has occurred.

**Communication**

Internal and external communication systems are vital parts of security planning. The ability to both warn employees/visitors of a hazardous event and the use of two-way communication equipment with security personnel is crucial. Warning systems which tell personnel to evacuate or “shelter in place” are commercially available and again, are just a matter of cost. However, the use of these systems without either an emergency plan, or the practice of such plan has very little value.

Two way communication protocols for emergency systems should NOT include reliance on cell phones. Experience has shown that in emergency situations cell phones are not a reliable method of exchanging information as the local system will become overloaded and collapse or the volume of calls will be so high that connection is impossible. “FM” type systems with hand held radios or the use of plug in “fireman” type phones are the only reliable communication systems that should be employed. Open radio communication systems (known in the US as “citizens band”) can be compromised and monitored by the press. The use of dedicated FM systems is more expensive, but is more secure and reliable.

Also vital in a security plan is the identification of a person who is responsible as the public information officer (PIO). This person becomes the “one voice” for your facility in an emergency and acts as the point of contact for the media and public. The use of the PIO has several advantages including the important fact that only “true” information is released and rumors, or unfounded “facts” are not released to the general public. In emergency situations, this can prevent panic and assists those looking to find missing persons as they can be directed to public evacuation sites and/or hospital & morgue facilities.

**Biometrics**

Biometric security devices (hand geometry, retinal scans, fingerprints, ear lobe topography, computer face recognition, etc) provide an increased method for prevention of unauthorized access. The use of these biological factors is believed to produce positive identification of the person desiring access. In general, a person first identifies himself/herself via the use of a key card and then is queried by the biometric device. This involves looking into a scanning device, placing a hand under a scanner, a finger on a platen, or waiting for the computer to compare face/ear lobe with stored images. However, there is resistance to the use of these devices due to both health and personal liberty fears. Eye scans cause the most health trepidation and fingerprint comparison often cause personal liberty issues. In general, most people show little reluctance to hand geometry systems, but this methodology is considered, in general, “less” secure. The deployment of these systems in any given facility is made as a balance between access, security, and employee/public acceptance.

**Exterior & Fencing**

Fencing of the facility (where possible and appropriate) can be a physical barrier and/or a psychological bar to unauthorized entry. Tall fencing (2 meters or greater) acts as a physical barrier and immediately establishes areas as restricted. The tall fencing systems can often not be employed for a variety of reasons including aesthetics and facility setting (urban vs. rural). Short fencing (1 meter or less) does act as a minor physical barrier, but also sets the secure perimeter. In locations where the establishment of a closed area for “curtilage” purposes is needed, a short fence will suffice. Also, a short fence prevents accidental incursions and can save time/money in false alarm response.
The fencing can (should) also be combined with signs to further identify the facility as secure. Fencing also physically funnels persons and vehicles to authorized entry points for inspection and thus reduces the number of security personnel needed for this purpose.

Response Plans

Response plans can be divided into two specific areas. First, an emergency action plan (traditional plan) needs to be developed. These plans include the facility response to “all” hazard types and involve either evacuation or sheltering in place of employees and public. These plans determine what the duties of each employee are in the various types of emergencies and should be known to all employees. For example, all workers need to know not only what route to take in an evacuation, but also what to do in response to a fire, or medical emergency, etc. Employees should also be aware of where they should go after evacuation (rally point), what their responsibility is to make sure others have left the facility, what route they should take, and how they should help the public and visitors to relocate. The certification that employees/public has been evacuated is critical as emergency workers can be expected to place their own lives in danger to save people. Thus a “floor warder” telling the fire department everyone is out will save time in fighting a fire and potentially fire fighter’s lives. The plans do not and in fact, should not, be complex. All that is really needed to be known by each employee is “what do I do” when any given type of emergency situation arises.

Proactive Planning

Planning for all types of emergency situations involving both natural hazards and human events is a vital element in and security plan. Knowledge of both historic hazards and evolving threats should be the concern of security planners. Cooperation via intelligence sharing about emerging human factor threats can prevent large scale disasters. Thus, for example, if police advise that terrorist’s plans have been identified against one sector or specific target than those facilities can use increased personnel, etc.

Basic in all these plans however, is the use of a security survey, or Target Analysis. A Target Analysis is an involved process which conducted by professionals and identifies the specific vulnerabilities or weakness in facility design and security. It is used by professionals to counter specific threats or weaknesses by the use of security upgrades. Thus, for example, if the target analysis identifies a chemical storage area as particularly vulnerable, plans could be made to “harden” this area against terrorist attack.

Summary

In short, tunnel security protocols are based on standard known principals of facility protection. Tunnel security issues are complicated by the fact that the public must be allowed entry into the facility. However, with the use of basic principals and security devices it is possible to protect tunnels and make them “safe” for both employees and public.
Concept for Fire and smoke spread prevention in mines

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ABSTRACT

This poster paper presents an ongoing project on fire safety in mines. The project is a three-year project studying fire and smoke spread in mines and the effect of ventilation and fire prevention measures. The project time is from July 2007 to June 2010. This project is part of a new research area related to fire safety in mines. The aim is to improve fire safety in mines in order to obtain safer working environment for the people working for the mining companies in Sweden or for visitors in mines open to the public. Very little research has been done in this type mines. Most of the research has been carried out for coal mines. The fire safety record in mines in Sweden is in general good with very few fire accidents occurred but there is a great awareness of the fire safety problems in mines. The awareness comes from the fact that mines are often just “an opening” in to the ground which means the “opening” is the only escape route for the people working in a specific mine sector. The reason why there is only one escape route is that it is expensive to construct extra escape routes which are not a part of the tunnel mining system. The costs to build extra escape tunnels may be better spending on different safety equipment or systems for fire prevention or evacuation. Such systems can be ventilation systems, fire fighting equipments or rescue chambers located at different places in the mines. The aim of the study is to improving the present knowledge about design fires of different fire loads in mines and to investigate how different parameters affect the fire and smoke spread inside the mine. This can be height or depth of the mine, the different type of ventilation systems with different capacities combined with different type of rescue strategies.

KEY WORDS mine, fire, smoke spread, fire spread

INTRODUCTION

The fire safety problems in mines are in many ways very similar to the problems discussed in road, rail and metro tunnels under construction. There is usually only one escape route - the entrance of the construction site - and the only safe heaven is the safety chambers consisting of over-pressurized steel containers. The experience from construction of road, rail and metro tunnels will be incorporated in the project as well as that the results from this project can be translated into conditions appropriate in tunnel construction projects and of use to companies outside the mining industry.

The main problem with mines today is that they have become more and more complicated, with endless amount of extra tunnels, and it is difficult to control the way the smoke and heat spread in case of a fire. This can be seen in Figure 1, showing a sector of a metallingerous rock mine in northern part of Sweden. The ventilation strategy is of greatest importance in combination with the fire and rescue strategies. Since there are very few fires that occur the experience of attacking such fires in real is little. New knowledge about fire and smoke spread in complicated mines consisting of transportation tunnels is therefore of importance in order to make reasonable strategies for the personnel of the mining company and the fire and rescue services. The main experience from fighting mine fires comes from old coal mines, which are usually quite different in structure compared to mines in Sweden which mainly work with metallingerous rock products. In Sweden the mines consists of either active working mines with road vehicle traffic and elevators shafts for transportation of people and products or old mines allowing visitors. In some cases it is a combination of both types. This type of “visitor mines” creates a new type of hazard. A large amount of people are visiting the mines at the same time and in case of a fire, there are no safety chambers available today that can
residence all the visitors. New strategies about how to handle such situation needs to be worked out.

![Figure 1](image1.png)  
*Figure 1  Schematic figure of a sector of a mining system in northern part of Sweden*

As the mine industry is changing and the challenging techniques developed the measures to guarantee the safety of personnel needs to be adjusted. The new technology means new type of fire hazards, which in turn requires new measures to cope with the risks. New equipment means new type of fire development. The knowledge about fire developments in modern mines is relatively limited. The fire development of vehicles transporting material inside the mines is usually assumed as from ordinary vehicles, although the vehicles may be considerably different in construction and hazard. The difference may mainly be in the amount of liquid (e.g. hydraulic oil) and the size of the rubber tyres.

![Figure 2](image2.png)  
*Figure 2 A special designed and constructed mining vehicle for transport of metalliferous rock. The vehicle name is TORO 2500E. Notice the person in front of the rubber tyre.*

In figure 2, a special constructed mining vehicle is shown using large tyres. Such tyres may create enormous amount of smoke, a hazard that is usually not considered in other applications. If a fire would occur in such a vehicle or transportation system, the situation may become very hazardous for people trapped inside the system. In order to avoid such situations, safety systems such as ventilation system or rescue chambers may be of great importance. The question is how these systems are influenced by the complicated nature of the mine systems in case of a fire. The natural draft created by the structure of the mine may easily override the power of the mechanical ventilation system. The survival of people trapped in the mine, either it is working personnel or visitors, or those who can reach to a safety chamber, is dependent on how the fire develops and how the rescue services can act
in different situations.

In Sweden the mines usually consists of a complicated system of tunnels operating by different type of road vehicles and with systems of vertical shafts where both people and metalliferous rock products are transported. Modern mines in Sweden become more and more complicated, and thereby, there is a great need to further understand the fire situation in such complicated systems. In mines open to visitors it is equally important to control the fire and smoke spread. In some cases the fire load is lower than in active mines, but in return the amount of people in the mining system can be considerably higher. In some cases active parts of the mine also, through complex pathways, can be connected with parts allowed for the public. To be able to show mines to visitors not only is a way to enlarge the business activities, but also a way to open up a part of the Swedish industrial history to the public.

**ACTIVITIES, METHOD AND TIME SCHEDULE**

**JULY 2007-SEPTEMBER 2007**
The study has started with a literature survey. The survey includes both scientific literatures as well as practical and tactical literature related to mine problems. The literature have been sought in countries which are known to be experienced in this type of problems. The literature survey has given a good overview of the problems with different type of mines. Different type of mines means different type of problems. The literature survey was principally performed by the university, but in co-operation with the participating companies.

**OKTOBER 2007-DECEMBER 2007**
The next step was to make an inventory of different type of mines, ventilation systems, shafts, elevators, vehicles that transport through the mines, safety equipment, machine halls, storages, routines of personnel, safety plans, reporting etc. These parts make the basis of the safety levels of the mines and are of importance to consider when creating a design fire scenario for different type of mine systems. The design fires scenario is the basic parameter to know in order to quantify the risk for people inside the mine. These parts of the project has been done in close co-operation between the mining companies and the university. It has provided the companies with valuable input to their documentation that is a base for their systematic fire safety work.

**JANUARY 2008-JUNE 2008**
Determination of the design fires is under process in the project. The design fire can vary depending on the type of activity and type of vehicles. The vehicles can be of different size and construction leading to different design fires. It is important the design fires are adjusted to a realistic fire risk and consequences. The design fire will be obtained by analysing different type of vehicles and using models that are adjusted to create such fires. The growth of the fire and its peak value in combination with the total energy will be the basic parameters to consider. Other important parameters to study are the risk for fires spread between vehicles and influences of ventilation on the fire conditions. Other type of fire sources, such as mechanical garages, storages, trains etc. will be considered in the derivation of the design fire. Mines that are open to visitors present other types of interiors and fire loads. In these cases the design fire and its consequences is a determining factor for the safe amount of visitors located at the same time in the mining system. The academic parts of this step will be performed by the university. Running discussions with the participating companies, regarding fire loads and the effect of changes, will regularly take place. The discussions about measures to minimize the fire load in order to change the design fire will give the companies a possibility to improve their fire safety early during the project time, but also ensure that the correct design fire is chosen for the different kinds of location and business.
MAY 2008-MARCH 2009
Based on the design fire, smoke spread calculations will be done. The smoke spread calculations will be done with both simple (one or two dimensional) and complicated (3 dimensional CFD – Computational Fluid Dynamics) calculation models. The location of the design fire will be varied as well as external parameters that can influence the smoke spread. This can be shafts, ventilation rates, blockages, external wind influences etc. Available calculation models are often derived for simpler construction systems than mines. The validity of these types of calculation models will be carried out. Comparison with experimental data will be done, see below. The calculations will be performed by the university and the mining companies will provide the researchers with relevant information about actual geometries, air movements and ventilation systems. The calculations will be compared with calculations made in earlier tunnel construction projects. This information will be provided by participation consultant companies, who also will be a valuable part for discussions translating results from this step for use in future underground infrastructure projects.

OCTOBER 2008-SEPTEMBER 2009
The fifth step includes performance of model scale and large scale fire and smoke spread models. This will be carried out in order to obtain data which can validate the models used in the project. The data will also give new knowledge on how different parameters influence the smoke spread in mines. Here it is important to maintain a simple model, and therefore it is of importance to use cheap solutions. Model scale tests have been used by SP Swedish National Testing and Research Institute for a long time. It has mainly been used for tunnel fires. These types of models are easy to work with and give very valuable information for the researcher on how things work when considering fires. The experience from these tests will be incorporated into the project. The models need to be built in a very small scale in order to take the complexity of the mines into consideration. Full scale smoke tests will also be carried out in realistic environments. The tests will be performed both in active mines and in mines open for visitors. The full scale tests will be planned and performed in close co-operation and co-ordination between the university and the mining companies.

OCTOBER 2008-SEPTEMBER 2009
The last step includes writing reports and give recommendations. The results create a new data bank and experience on how fire and smoke spreads in mines. The results will create a sound base for given recommendation on how to handle these fires in different type of mines. The type of mine, the ventilation system and fire prevention measures taken can be of greatest importance for if people can survive a fire in such a system. The system creates the hazard in combination with the design fire. The design fire is the parameter which put up the agenda for the outcome of the fire. Engineering tools for estimation of design fires and smoke spread will be some of the results in this step. To ensure that the information is passed on to the participating organisations on all levels and the recommendations and engineering tools are thoroughly evaluated this step also contains a number of internal workshops.

OCTOBER 2009-MARCH 2010
The last period APRIL 2010-JUNE 2010 will mainly consist of final dissemination of results and evaluation of the project.

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Performance Based Design for the Binyanei Ha’uma Railway Station and Tunnel

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ABSTRACT

The Binyanei Ha’uma Railway Station and Tunnel is the 1.6 kilometer underground portion of a proposed commuter subway system that will connect Tel Aviv to Jerusalem, Israel. This paper describes the detailed fire modeling analysis that was performed on the entire underground railway station and tunnel system to assess the impact of a train fire developing in either the station or the tunnel on the proposed emergency ventilation system. The performance-based design criteria from the 2003 edition of NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems, were used in the analysis. The purpose of the analysis was to quantify the impact on the station from a train fire developing in the tunnel, and vice-versa, so it was necessary to develop a fire model that encompassed the entire underground portion of the subway system. The complexity and physical size and shape of the tunnel and station presented a number of challenges during the development of the fire model.

KEYWORDS: fire model, performance-based design, computational fluid dynamics, smoke control, emergency ventilation

INTRODUCTION

The fire protection system design for the Binyanei Ha’uma Railway Station and Tunnel was to be in accordance with applicable National Fire Protection Association (NFPA) codes and standards. In particular, the design of the emergency ventilation system for the underground portions of the passenger station and tunnel was required to meet the 2003 edition of the NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems. NFPA 130 requires an engineering analysis of the emergency ventilation system, such as would result from the application of validated computational fluid dynamics (CFD) techniques. In order to provide a detailed and comprehensive study of the impact of fire on the underground tunnel and passenger station, the use of Fire Dynamics Simulator (FDS), a CFD computer model developed specifically for fire and smoke applications, was proposed. The CFD modeling of the tunnel and passenger station played a significant role in the development of the emergency ventilation system design criteria, which was established utilizing performance-based methodologies.

CFD MODEL INPUT

The computer fire model, Fire Dynamics Simulator (FDS), was utilized to simulate smoke spread throughout the underground station and the tunnel resulting from a fire developing in one or more subway passenger cars. The purpose of the analysis was to quantify the impact on the station from a train fire developing in the tunnel, and vice-versa, so it was necessary to develop a fire model that encompassed the entire underground portion of the subway system. The physical size and shape of the tunnel and station presented a number of challenges during the development of the fire model input strategy. The first challenge was the sheer physical size and shape of the tunnel system, which...
winds through a mountain up toward the passenger station at a 3 percent slope and traverses 1.6 kilometers. The rectangular volume encompassing the tunnel and station is approximately 200 million cubic meters. Considering a single mesh in FDS with 1 cubic meter control volumes, or grid cells, the fire model would require 200 million grid cells. A model of this size is well beyond the capabilities of typical desktop computers which FDS was originally intended to be run on. Most desktops can currently handle a maximum of about 2 million grid cells.

In order to reduce the number of grid cells necessary to create the underground tunnel and station in the fire model, a relatively new feature in FDS was employed. The “multi-blocking” feature allows the FDS user to create multiple interconnected meshes to create the volume surrounding the geometry. This technique can significantly reduce the number of grid cells in a model as it minimizes the number of empty grid cells that may be surrounding the geometry and not serving any computational purpose in the model. By creating multiple meshes, the number of grid cells needed to build the entire tunnel and station into FDS was reduced to 5 million grid cells. This was accomplished by using 16 grids, each with a 1 cubic meter grid cell size. 5 million grid cells was determined to be the minimum number of cells necessary to create the geometry and maintain an adequate degree of computational accuracy. Unfortunately, a model with 5 million grid cells was outside of the capabilities of any single desktop computer at the time the fire model was created.

The issue of computational resources was addressed by utilizing the recently added parallel processing feature in FDS. The parallel processing feature allows large FDS model computations to run over multiple processors. Parallel processing techniques were utilized to run simulations of the large underground tunnel and passenger station fire model on a state-of-the-art 16 processor computer cluster.

Once the issues associated with the physical size of the model and available computer power were resolved, a second input challenge arose. The challenge was how to build the curved geometry of the tunnel into FDS, which can only handle orthogonal obstructions. In general, diagonal and curved elements in FDS must be created using the “sawtooth” method where a number of small orthogonal obstructions are used to create the diagonal or curved element. The element then graphically appears “sawtoothed”, but can be computationally smoothed as to not create any unrealistic flow vortices in the simulation. There are very few aspects of the tunnel shape which are not comprised of curved or diagonal elements. The cross-section of the tunnel is arced, the tunnel winds through the mountain slightly curving left and right, and the tunnel slopes up toward the station. In order to accurately input the shape of the tunnel, the entire tunnel needed to be input as a collection of thousands of sawtoothed
obstructions. Traditionally, each sawtoothed obstruction needs to be input into FDS by hand.

The geometric input challenge was addressed by utilizing a recently developed graphical user interface (GUI) for FDS model input. The GUI facilitates the creation of FDS input files and gives the user the ability to create diagonal obstructions graphically which are then resolved into a number of small sawtoothed obstructions based on the specified grid size. The GUI software was used to create the tunnel and station with a degree of geometric accuracy that would not have been feasible if the FDS input file was created by hand. Over 40,000 individual sawtoothed obstructions were created to represent the geometry of the tunnel, which otherwise would have had to be created one by one.

**CFD MODELING RESULTS**

Ten simulations of the CFD model for the underground tunnel and station were performed in order to assess the proposed features of the emergency ventilation system in simulated fire conditions. The performance-based design criteria from Annex B of NFPA 130 were utilized to assess the results from the model simulations. The simulations varied in the number of passenger train cars that were burning, the locations and capacities of the emergency smoke exhaust fans, and the architectural design features of the passenger station. Each simulation was evaluated based on the tenability criteria recommended by NFPA 130 and included an assessment of toxicity, elevated temperature, and visibility through smoke. The intent of the emergency ventilation system for the tunnel and station is to maintain tenable conditions within areas that may be occupied.

![Figure 2](image)

*Figure 2  Smoke Movement in the Emergency Ventilation Shaft.*

Each CFD model simulation provided valuable insight into how a severe fire would impact the passenger station and tunnel. The information and data generated in each model simulation was utilized make changes to the overall fire protection design intended to increase the overall level of life safety within the station and tunnel. Some of the design changes that were made based on the CFD model results were adding additional smoke exhaust shafts and fans, adding an exhaust plenum above the station platforms, pressurizing the areas of refuge serving the concourse, and providing smoke curtains and baffles to help control the flow of smoke.
CONCLUSIONS

The CFD computer fire modeling performed for the Binyanei Ha’uma Railway Station and Tunnel provided a detailed and comprehensive performance-based analysis of the proposed fire protection features and generated valuable information related to how smoke and fire would develop and impact this particular underground subway station and tunnel. The information garnered by this type of performance-based analysis may not have been realized if the design approach was purely prescriptive. Due to recent advancements to fire model input methodologies, the performance-based concepts and criteria contained in NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems, can be evaluated using large CFD fire models. Performance-based design of fire protection systems in large building and structures, including tunnels and underground stations, is rapidly becoming a widely-accepted standard practice throughout the world. This type of in-depth evaluation of a particular space can contribute to the effectiveness and efficiency of the overall design and can often result in an increase in the overall level of life safety that will be provided.
Rail tunnels risk analysis: the UNIFI approach

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THE UNIFI APPROACH ON RAIL TUNNEL RISK ANALYSIS

The Italian standard on “Rail tunnel safety” issued in 2005 [4] identified the minimum safety requirements for each type of rail tunnel. This standard introduces two types of Risk Analysis (Base and Extended) to be performed in order to verify the fulfilment of all safety requirements and to compare the tunnel risk level with fixed acceptability thresholds. A methodology to conduct an Extended Risk Analysis was developed at the University of Florence in order to evaluate heat and toxic gasses concentration, their diffusion and their effects on passengers in function of infrastructure, train and fire characteristics and evacuation procedures. The proposed methodology allows to account for tunnel geometric characteristics (section and sidewalks number and width), vehicle characteristics (type of train and number of passengers) and fire event conditions (Heat Release Rate, Heat Release Rate time development, toxic gasses type and concentration). The application of this methodology allows to estimate the saving people likelihood and the number of expected deaths as a function of the distances covered by each passenger depending on different accident scenarios and on evacuation procedures such as scheduling of door openings and tunnel characteristics and safety measures available.

A sensitivity analysis has been conducted in order to identify the influence of the main parameters on passengers evacuation capacity, highlighting the effects of different environmental situations such as atmospheric conditions (wind speed and temperature inside the tunnels) [2]. The extended risk analysis methodology has been applied to extreme scenarios accounting for different types of trains stopped inside tunnels of different physical characteristics, with a fire occurring in the first coach located upward with reference of the airflow direction [2, 3]. The comparison between ten different scenario’s allows to identify the influence of fire design curves, tunnel section dimensions, train offered capacity.

Different fire design curves have been considered in order to evaluate the fire design effect, they are obtained both by a theoretical approach and by full scale tests results reported in literature. The tunnel sections considered represent three typical Italian railway situations: single track, double track and double track for high speed train sections. The analysis of different train capacity has been performed considering different train composition (coach number and characteristics), filling factor and doors number and position.

The new Italian high speed train infrastructures have been analyzed defining a scenario characterized by the most used Italian train composition (12 coaches) in a tunnel having the cross sections meeting the Italian standards for high speed lines.

The applied methodology has been proven highly useful as a design tool in order to identify the best design, construction and management options to increase safety levels. It could also be used to define the most effective evacuation procedures for each emergency scenario.

THE APPLIED METHODOLOGY

The Italian standard on railway tunnel safety requires to perform an Extended Risk Analysis (ERA) to fix and analyze the safety conditions occurring in tunnel longer than 9 km or longer than 2 km and characterized by high traffic or inversion slope altimetry.

A procedure to perform such an extended risk analysis with reference to accident scenarios involving fires on passengers’ train stopped inside tunnels has been proposed by Pezzati et alii in [1]. It is based
on a series of simulation models allowing to evaluate the accident probability, the number of fatalities and the tunnel risk level as function of input variables describing the tunnel geometrics, the technological facilities available inside it and the traffic characteristics. The developed models include:

- Heat release model;
- Smoke diffusion model;
- Temperature evolution model;
- Toxic smokes concentration distribution model;
- Evacuation model;
- Fatalities evaluation model.

The described ERA methodology has been applied to a typical scenario (called “reference scenario”) accounting for an ordinary train stopped inside the double track tunnel (RFI S.p.A. standards section) with a fire in the first coach located upward with reference of the air flow direction (conservative approach). The assumed fire characteristics are those provided for by the Italian standard [4] and will be called “DM curve”. The evacuation procedure applied is described in Figure 23.

![Reference accident scenario analyzed](Figure 23)

**INFLUENCE OF THE TUNNEL SECTION DIMENSIONS**

The tunnel sections considered represent three typical Italian railway situations:

- single track section \( [S_T = 42 \text{ m}^2, P_T = 26 \text{ m}] \);
- double track section \( [S_T = 74 \text{ m}^2, P_T = 33 \text{ m}] \);
- double track section for high speed train \( [S_T = 91 \text{ m}^2, P_T = 36 \text{ m}] \).

where \( S_T \) is the section area and \( P_T \) is the internal perimeter of the tunnel lining.

All the sections considered meet the “RFI S.p.A.” standards in course. Each tunnel is equipped with two lateral footpaths. For evacuation purposes, both the footpaths can be contemporaneously used in single track tunnel sections (evacuation from the train coaches occurs through the doors on both sides of the train). Instead, in double track sections only the footpath on the right side of the train will be available, in all cases the fire design curve proposed by the Italian standard has been adopted.

![Tunnel sections comparisons](Figure 24)
Increased tunnel sections, such as double track sections compared to single track ones, allow a greater number of passengers to start evacuation and to possibly complete it successfully. In fact, in a single track tunnel, 400 passengers out of 616 (67%) are able to cover a distance higher than 1 km; in double track tunnels this number rises to 472 (77%) and to 544 (88%) in the case respectively of standard or high speed lines.

The above results point out the great importance of providing coherence in defining the safety measures to be introduced in railway tunnels. In the scenario analyzed, if the coach with fire stops in front of an exit, preventing the access to it for the evacuating passengers, in double track tunnels no passenger could able to reach the distance of 4’000 m, which is the minimum distance between carriageable exits required by the Italian standards. In single track parallel tunnels, the minimum distance between passageways between tubes (which could be considered as safety exits) required by the Italian standards is 500 m and only 67% of the passengers could reach them in the conditions analyzed.

More efficient evacuation procedures and the equipping of the coaches with fire alarms allowing to reduce both the fire detection and evacuation time are required to increase life expectancy during a fire event.

**INFLUENCE OF THE FIRE DESIGN CURVES**

Different fire design curves has been adopted to consider the effects of the different approaches adopted, in all cases a double track tunnel section has been considered. The three curves considered are characterized as follows [3]:
- Fire curve adopted by the Italian standards (peak of 10 MW, time to peak 10 min, peak maintained for 30 min);
- German Intercity IC passenger railway car curve (peak of 13 MW, time to peak 25 min);
- German Intercity-Express ICE passenger railway car curve (peak of 19 MW, time to peak 80 min).

![Fire design curves effects](image)

**Figure 25: Fire design curves comparisons [3]**

The curve adopted by the Italian standards (DM curve) is the most severe one. In fact more than (616-523)=93 (equal to 15%) passengers are not able to cover a distance higher than one hundred meters. The DM curve, while having the lowest maximum HRR value (10 MW instead of 13 MW of the IC curve or 19 MW of the ICE curve) and the lowest fire overall duration, has the shortest time to reach the HRR peak value (10 min from fire ignition instead of more than 1 hour) and the longest duration at the highest heat values. Passengers are rapidly reached by life incompatible temperatures and this explains the results shown in Figure 25.

IC and ICE curves give results which are very similar: they allow all passengers to cover a distance of about 3 kilometers before falling unconscious due to toxic gasses concentration, thus leaving high possibilities to reach refuges or exits. The maximum covered distance is equal to 3’817 m for IC.
The main differences are registered for passengers nearest to the fire: applying the DM curve about 100 people don’t start evacuating, instead of the other two scenarios in which all passengers are able to start evacuating. Therefore it can be concluded that the Italian standard curve is more conservative than the real fire conditions tested during the EUREKA 499 research program.

CONCLUSIONS

The extended risk analysis methodology developed to fulfill the requirements of the new Italian standard dealing with safety in railway tunnels [1] has been applied to estimate the saving people likelihood in function of some of the variables influencing the self-evacuation possibilities of the train passengers: type of fire, tunnel dimensions, passenger capacity of the train, evacuation procedures.

The main conclusions offered by the study performed are:

- the fire design curve proposed by the Italian standard is highly conservative; it is more severe than the curves obtained by experimental activities;
- the most severe conditions have been registered for the smallest tunnel section as an effect of higher smoke concentration;
- high occupancy train require the definition of specific evacuation procedures;
- to increase passengers saving likelihood the consciousness and reaction time should be minimized. Detecting and alarm sensors installed inside the train coaches could give a chance in this direction;
- all the scenarios analyzed have shown that special evacuation procedures should be developed to increase the probability of a higher number of passengers to reach the available exits or refuges;
- four parameters having a great influence on the results have been identified and some useful indications for infrastructure and vehicle designers has been pointed out;
- the effects of a footpath between tracks installation have been evaluated, the improvement in terms of passenger’s covered distance is appreciable;

The safety measures to be included in railway tunnels should be designed according to the specific type of traffic, tunnel physical characteristics and emergency equipment available on board. The study performed pointed out the great importance of the risk analysis application to implement railway tunnel design procedures and to optimize their safety performances.

REFERENCE LIST

Journals:


Symposium proceedings:


Standards:

ABSTRACT
UPTUN is the largest European research project on fire safety in tunnels. Upgrading the safety level in tunnels with existing technology and within the legislation and guidelines frameworks of the member states is in most cases either almost impossible or too costly. Fire safety in tunnels is based on a conventional rather than a rational approach and is not examined in an integral fashion, comprising all aspects in a similar manner. This may result in adverse interaction between preventive mitigating measures or non-optimal safety investments. UPTUN project embarked in 2002 to solve these problems with the aim of investigating, examining and mainly to develop innovative technologies where appropriate and also where relevant to compare and assess existing technologies for tunnel application. Techniques in areas of detection, monitoring, mitigating measures, influence of human response, and protection against tunnel structural damage were the centre of investigation and research. Tunnel safety was thoroughly examined and new procedures for rational evaluation were developed which included criteria of acceptance and models of support to decision makers. In addition concepts for the transfer of knowledge and technology have been introduced. It is envisaged that transport systems will have further benefits from the results of this project due to the restoration of faith in transport tunnel, the removal of trade obstacles and increased tunnel utilisation. All those involved in transport systems, tunnel operators and owners will be persuaded that comprehensive research covering all aspects of tunnel safety is the right channel for undisturbed, continuous transportation. The intention was that the findings, results, innovative technologies and deliverables of this project reach all and be adopted and put into practice by all those involved in transport systems throughout Europe. An advisory group, open during the project, was established to monitor developments outside the UPTUN project allowing to anticipate on new perceptions and priorities and to provide an independent critical appraisal of the project’s progress and deliverables.

KEYWORDS: tunnel, fire, safety

INTRODUCTION
UPTUN’s objectives were:
1) Development of innovative and methodologies technologies where appropriate and where relevant comparing to and the assessment of existing technologies and methodologies for tunnel application. New technologies have been developed: water mist, water curtains, smoke compartmentation, CCTV detection techniques, training tools and programs, repair mortars and software assessment tools, including local and regional cost effect models.
2) Development, demonstration and promotion of procedures for rational safety level evaluation, including decision support models; and knowledge transfer. Safety level assessment criteria were drawn up and integrated in manual and automatic upgrade procedures/models. Knowledge transfer through dissemination on various levels: papers and presentations, international symposia (Prague, Lausanne), dedicated workshops throughout Europe and beyond (Australia, China, USA) and the establishment of a manual for good practice and an UPTUN summer course.

The desired spin-off was the restoration of faith in tunnels as safe parts of the transportation systems, the levelling out of trade barriers imposed by supposedly unsafe tunnels, and an increased awareness of stakeholders for the necessity to develop initiatives to link all relevant research. With respect to the
first, it can be said that this has not been measured prior, during or after the project. Through UPTUN and its results, undoubtedly, tunnels can be designed to be safe and reliable, and hence the risk for trade barriers due to unsafe tunnels has reduced. The awareness certainly has been enlarged on an international level.

MAIN RESULTS
The UPTUN project has led to numerous reports and publications, publically available early 2008 on the UPTUN website (www.uptun.net). In this paper some deliverables are highlighted:
- innovative detection of moving and growing fires in tunnels
- information on the development and effects of (large) fires in tunnels
- new suppression technologies to control fire growth and/or smoke spread, with a view to improve tenability conditions: watermist, water curtains and inflatable curtains
- acceptance criteria to assess new or existing fire safety measures for application in tunnels
- insight in evacuation behaviour of end-users, fire brigade and operators
- assessment of concrete spalling risk
- damage assessment and repair techniques for (concrete) tunnel linings
- integral upgrading procedures and tools for evaluation of alternative combinations of safety measures
- actual application of (combinations of) newly developed safety measures in a refurbished (TREN) road tunnel (Bolzano)
- dissemination of knowledge through summer-courses and manuals of good practice
- contribution to the establishment of the ITA committee on operational safety of underground spaces (COSUF).

EXAMPLES

3.1 Detection

One of the challenges is to detect a moving and or growing fire. A special video-detection technique was developed, to catch small, moving fires, see Figure 1. When coupled to warning and/or suppression systems, such techniques are helpful in fast and adequate monitoring and combating fires. A specific challenge was overcome to distinguish bright small lights (such as flashing lights on emergency response vehicles) from actual fires.

Figure 1 Algorithm for fast CCTV based detection of moving and growing fires.

3.2 Innovation in suppression techniques

First steps were made, using inflatable techniques and special fabrics, to mitigate smoke spread, with a view to enhance tenability during evacuation. In Figure 3, the installation of such an inflatable curtain is demonstrated. Further development is necessary e.g. for passing through such curtains and for partial curtains, which in case of accidental inflation cause less risk. As an alternative to such curtains, water curtains have also been developed. A demonstration test indicated that especially in the case of multiple water curtains, tenability significantly increases for evacuees. Because of the promising test results, these systems have actually been applied in several Italian tunnels. A collage of test pictures is shown in Figure 2. Extensive research efforts were put in and achievements were made with respect to watermist application. Because of the promising test results, these systems have
actually been applied in several European tunnels, comprising road, rail and metro tunnels. A collage of test pictures is shown in Figure 3. A design recommendation report is also available.

![Figure 2 Water curtain testing](image)

(a) Without watermist ...    (b) With watermist

![Figure 3 Watermist testing.](image)

3.3 Human factors

Research was done on driver behaviour (in simulators, in a virtual environment) and through full scale tests. Furthermore, an innovative situation dependant and versatile evacuation tool has been developed; this tool provides on the basis of on-spot measurements given the circumstances the most adequate evacuation directions. Prominent outcome is that evacuation can be significantly positively influenced through clear spoken messages and adequate driver (road tunnels) or steward (train tunnels) instructions.
Figure 4 Human factor research, from top left to bottom right: (i) and (ii) full scale evacuation tests in a new TREN road tunnel (NL-Benelux), (iii) evacuation investigation in train station, (iv)-(v) driver simulator, (vi) evacuation guidance, (vii) studying truck driver behaviour

3.4 Structural behaviour and repair

A mobile and accurate damage assessment technique was developed, as well as a highly flexible repair mortar for damaged concrete or rock sections. Critical components with load bearing functions have been identified and improvement for existing structures and new designs have been developed, using state-of-the-art numerical models for simulating the complex response of reinforced concrete structures to fire.

3.5 Integral design method

Interaction, both positive and adverse, between safety measures was also incorporated. Also an integral model was developed, allowing for comparison of different options, on the basis of tenability diagrams (lethal conditions are plotted in a location vs. time graph). The uniqueness of this model is that it incorporates also micro and macro-economic impact on socio-economy.

3.6 Dissemination of knowledge

Dissemination of knowledge was and is achieved through the UPTUN Handbook of Good Practice and UPTUN Summer Courses (Figure 5).

3.7 Actual upgrading according to UPTUN results and findings of an Italian TREN road tunnel (WP6)

The UPTUN findings were actually applied in the Virgolo road tunnel near Bolzano, on the Brennero highway in Italy. Figure 6.

RECOMMENDATIONS FOR FURTHER RESEARCH

The UPTUN consortium strongly recommends further work and continuation of some specific research items, such as: (i) (ways to adequately influence) human behaviour (ii) detection (developing fires etc.) (iii) on upgrading of rail and metro tunnels (iv) smoke compartmentation (v) actual incident investigation and evaluating (also near misses) (vi) (test protocols for) water based suppression systems (vii) interaction between (and optimization of) measures (viii) fire scenario’s of new vehicles and rolling stock (ix) establishing and / or connecting large / full scale test and demo sites (L-surF).
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