Through our international collaboration programmes with academia, industry, and the public sector, we ensure the competitiveness of the Swedish business community on an international level and contribute to a sustainable society. Our 2,200 employees support and promote all manner of innovative processes, and our roughly 100 testbeds and demonstration facilities are instrumental in developing the future-proofing of products, technologies, and services. RISE Research Institutes of Sweden is fully owned by the Swedish state.
Proceedings from the Eighth International Symposium on Tunnel Safety and Security, Borås, Sweden
March 14-16, 2018
Edited by Anders Lönnermark and Haukur Ingason
ABSTRACT

This report includes the Proceedings of the 8th International Symposium on Tunnel Safety and Security (ISTSS) held in Borås, Sweden, 14-16th of March, 2018. The Proceedings include 41 papers given by session speakers and 16 extended abstracts presenting posters exhibited at the Symposium. The papers were presented in 12 different sessions. Among them are Fire Safety Engineering: Cases & Incidents, Fire Safety Engineering: The Aims, Fire Detection, Explosions, Risk Analysis, Fire Safety Engineering: Case studies, Ventilation, Fire Safety Engineering: State of the Art, Fire Dynamics, Fixed Fire Fighting Systems (FFFS) and Evacuation and Human Behavior.

Each day was opened by invited Keynote Speakers (in total six) addressing broad topics of pressing interest. The Keynote Speakers, selected as leaders in their field, consisted of Hans Brun, the Swedish Defence University, Dr Iain Bowman, Mott MacDonald, Canada, Dr Ying Zhen Li, RISE Research Institutes of Sweden, Dr Johan Lundin, WSP, Sweden, Allan Skovlund, Greater Copenhagen Fire Department, Denmark and Prof David Purser, Hartford Environmental Research, UK. We are grateful that the keynote speakers were able to share their knowledge and expertise with the participants of the symposium.
PREFACE

These proceedings include papers presented at the 8th International Symposium on Tunnel Safety and Security (ISTSS) held in Borås, Sweden, 14-16th in March 2018. The symposium is well established in the tunnel fire community and the success of ISTSS is a tribute to the pressing need for continued international research and dialogue on these issues. These proceedings provide a state-of-the-art knowledge in the field of fire safety and security in underground structures.

This ISTSS regularly attracts over 200 delegates from all parts of the world and represents an arena for researchers to discuss safety and security issues associated with complex underground transportation systems. We see that new energy carriers (vehicles with new type of propellant) protection has become a major field of interest. Further, risk and engineering analysis continues to be an area that attract many papers. The new energy carriages will in near future become one of the most important research fields. This year there is also a specific focus on best practice engineering. Numerous renowned researchers and engineers have contributed to these and other topics at this symposium for which we are very thankful. The enormous costs for underground structures forces engineers to design alternative solutions. The sessions that have greatest focus on mitigation of fire development include those dealing with the effects of ventilation systems, active and passive fire protection, firefighting and human behaviour.

We received nearly 70 extended abstracts in response to our Call for Papers (not including our six invited Keynote Speakers) and believe that the quality of the accepted papers is a testament to the calibre of research that is on-going around the world. Of these, 41 abstracts were selected, based on their high scientific quality, for paper presentations. The poster session contains 16 posters to canvas interesting emerging research. During the symposium there is also an exhibit where businesses present their work. The selection process was carried out by a Scientific Committee, established for this symposium, consisting of many of the most well-known researchers in this field (a list can be found on the Symposium website, www.istss.se). We are grateful for their contribution to make this symposium as the leading one on fire and safety science in tunnels. At least ten of the symposium papers were selected to candidate as full journal papers in Fire Safety Journal, a special issue related to the ISTSS 2016. These papers are peer reviewed and selected by members of the scientific committee of ISTSS together with the editor of Fire Safety Journal. It is our hope that this process will continue in the future in order to raise the level of the scientific part of the symposium.

Finally, we would like to thank our organisation committee Jonatan Gehandler, who is program co-ordinator, Kaisa Kaukoranta, symposium co-ordinator, Dr Ying Zhen Li, scientific co-ordinator and Fredrik Rosén, marketing co-ordinator together with us two. We also would like to thank our sponsors who contributed with their support and engagement.

Haukur Ingason                                             Anders Lönnmermark
Chair of Organisation Committee                          Chair of Scientific Committee
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ABSTRACT

Tunnel fire safety has improved significantly over the past decade and a half. Fire occurrences have declined significantly, and the occurrence of serious fires resulting in serious casualties and/or loss of life has declined to a level where some safety regulators no longer track this type of fire in their operating statistics. This is due, at least in part, to the industry’s response to the tunnel fire tragedies of the 1990s and early 2000s, which included Baku [1], Mont Blanc [2], Daegu [3], Kaprun [4] and other incidents. The responses included measures to reduce the probability of fire (such as improvements in passenger train materials fire performance) and measures to improve the survivability for tunnel occupants in event of fire (such as the adoption of fixed fire-fighting systems within road tunnels). Today a robust framework of safety measures, including a strong hierarchy of requirements and a comprehensive set of tunnel safety systems, provides an overall level of safety within tunnels such that casualties and loss of life within such infrastructure has become extremely, and thankfully, rare. However there are new challenges. Owners and operators are beginning to determine that tunnel safety levels are now better than on many parts of their surface infrastructure. They are beginning to ask whether some of the resources that currently are expended on tunnel safety could safely be redirected to the rest of their mobility network, to improve safety levels there, with an overall improvement in both safety and sustainability. New technologies, such as alternative fuel road vehicles, autonomous road vehicles, Automatic Train Operation (ATO) and driverless trains are changing the usage of tunnels. The challenge for tunnel safety professionals is to respond to these queries responsibly, and to assess whether this is feasible, practical or desirable. To do so, it will be necessary to develop tools that are capable of providing a robust assessment of the effectiveness of various tunnel safety measures and what kind of efficiencies in tunnel safety provisions may be safely achievable.

KEYWORDS: Fire life safety, tunnel systems, sustainability, efficiency, requirements, fire statistics, future directions, effectiveness of systems

INTRODUCTION

Fire is a serious, potentially catastrophic event. Every major fire, be it the 1999 Mont Blanc tunnel [2] disaster, 2017’s Grenfell Tower [5] tragedy, or the future’s as-yet unknown major fire event, reminds us of the terrible consequences of fire if we fail to plan adequately for it. We must continually be vigilant.

However, much has changed in tunnels since that day in the Mont Blanc tunnel. Since that event, and the spate of other tragic tunnel fires that occurred at the turn of the millennium, there have been significant improvements in tunnel fire safety. In the aftermath, there developed a much stronger consensus on the need to improve fire safety within tunnels. This followed two main strands: (i) reducing the occurrence of fire, and (ii) enhancing the survivability for occupants in event of fire. The Burnley Tunnel fire in 2007 [6] was one of the first indicators that the focus on fire safety within tunnels was paying dividends. Since then, numerous other metrics have confirmed that there has been...
a real and significant improvement in tunnel fire safety.

Preventative measures, such as the development of materials fire performance standards for rail passenger vehicles, have aided in reducing the occurrence of fire. Provision of multiple layers of safety systems within tunnels, for example public address/voice alarm (PA/VA), radio rebroadcast, and enhanced signage for communication with occupants in road tunnels, has improved the survivability. Passive fire protection materials and, where adopted, fixed fire-fighting systems (FFFS) have improved the fire resistance of the tunnel structure.

Today, multiple safety systems aim to provide a robust, resilient set of fire safety measures within tunnels. Installation of fire safety tunnel systems has become ‘business as usual’ within the industry. Legislation, regulations, standards and guidance have been developed to ensure that such measures are included and satisfy specified minimum requirements.

New technologies are beginning to change the usage of tunnels. For example, the increasing adoption of alternative fuel road vehicles, such as hybrid, electric and fuel cell vehicles, bring new hazards to the road tunnel environment, while the increase in semi-autonomous vehicles and the imminent arrival of autonomous vehicles brings new challenges to road tunnel operations and incident response planning. In rail tunnels, an example is the expanding application of Automatic Train Operation (ATO) and similar associated systems e.g. Automatic Train Control (ATC) and Automatic Train Protection (ATP), and the consequent increase in the use of driverless trains. This likewise brings challenges to operations and incident response, where many of the measures rely on a driver to interact with passengers in an emergency.

Tunnel assets are now generally reliable, with good safety levels. In many cases they are safer than the associated surface assets. This is leading operators to ask an interesting question: does the industry continue to design, install, maintain, refurbish/rehabilitate and eventually replace a complex array of tunnel systems – even though the tunnel may be safer than other parts of the transportation network? Or are there efficiencies in tunnel safety measures that could be implemented to allow improvement of the overall level of safety on the mobility network? What of the challenge of new technologies that change the usage of the tunnel?

This paper examines where the practice of tunnel fire safety systems is today, and where it may be heading in the future.

**SUSTAINABILITY**

**Sustainable engineering**

Sustainability is now a critical criterion in the project approval process. “Sustainable engineering” has become a mantra. Tunnels consume large amounts of money, resources and energy, both in construction and operations. Via the project approvals process, society has decided that there is a societal need for the asset. Therefore the sustainability implications of the asset have been deemed acceptable in return for the societal benefit offered. So, it might be argued that sustainability has already been dealt with by the time most tunnel fire safety and systems engineers become involved.

But, of course, this is not the case. Sustainability remains as relevant throughout the design phase as it was during the planning phase. Engineers can significantly affect the sustainability of the asset through the design process.

η

The Greek letter, η, is the universal engineering symbol for efficiency. It is, or should be, central to everything engineers do. Efficiency represents the best and wisest use of resources with a minimum of wastage. It represents making wise choices in choosing between tradeoffs, i.e. finding the best compromise. It is fundamental to the concept of sustainable engineering and should be central throughout decision making processes, even where safety is involved. Otherwise, aspirations to be truly sustainable will not succeed.
TUNNEL SYSTEMS AND TUNNEL OPERATIONS

Overview
Operation of a tunnel asset, or indeed any transportation asset, requires due consideration of several interlinked objectives. These include safety, business continuity, commercial viability, sustainability, risk management, and others. Frequently these objectives conflict with each other. Deciding and agreeing the relative importance of each objective is key to making decisions about how to construct and operate the asset most efficiently, and how to operate it most efficiently within the wider infrastructure network.

Transportation tunnels exist within a wider mobility network. Tunnel safety is one component of the tunnel operations, and a sub-component within the mobility network operations. Tunnel systems are the design elements that help to deliver safety and permit safe operation of the facility.

Tunnel systems may be categorised by functional objectives, which are the product of the safety objectives. As an example, backbone services such as the electrical power supply and supervisory control and data acquisition (SCADA) provide the necessary framework for other systems to function. Table 1 shows one way of classifying the systems in a tunnel.

Table 1. Classification of Tunnel Systems by Functional Objectives

<table>
<thead>
<tr>
<th>Classification</th>
<th>Functional Objectives</th>
<th>Example Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backbone services</td>
<td>Provide necessary framework to support operation of other systems</td>
<td>Electrical services, SCADA</td>
</tr>
<tr>
<td>Tunnel environment</td>
<td>Provide safe environment for tunnel occupants under normal conditions</td>
<td>Lighting, ventilation, drainage</td>
</tr>
<tr>
<td>Traffic management</td>
<td>Provide safe management of traffic operations</td>
<td>Lane control signs (LCS)/variable message signs (VMS)/gates (road tunnels);</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Signalling/platform screen doors (rail tunnels)</td>
</tr>
<tr>
<td>Monitoring/incident detection</td>
<td>Provide prompt detection of incident occurrence</td>
<td>CCTV, automatic incident detection, fire detection, manual fire alarm pull</td>
</tr>
<tr>
<td></td>
<td></td>
<td>stations, emergency phones, monitoring of doors</td>
</tr>
<tr>
<td>Communications &amp; egress aids</td>
<td>Provide effective direction to evacuating persons within the tunnel</td>
<td>Public address/voice alarm (PA/VA), radio rebroadcast, signage, lighting</td>
</tr>
<tr>
<td>Mitigation of fire hazards</td>
<td>Provide tenable environment for egress; Provide ability to extinguish fires promptly; Protect tunnel structure from spalling/collapse</td>
<td>Tunnel ventilation, cross-passages, fixed-fire-fighting systems, manual fire</td>
</tr>
<tr>
<td></td>
<td></td>
<td>extinguishers, radio rebroadcast (emergency services frequencies), fire mains</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(standpipes) and hydrants, passive fire protection materials</td>
</tr>
</tbody>
</table>

It is apparent that some systems fulfil multiple objectives. For example, tunnel ventilation is used to manage the tunnel environment during both normal and emergency conditions.

The suite of fire life safety tunnel systems selected for a facility should be guided by the usage of the tunnel. Facilities where members of the public are allowed access, such as rail and road transportation tunnels, will have a different safety profile than utility and special use tunnels where only trained and
suitably authorised persons will have access. Examples of the latter type of tunnel include cable
tunnels, pipeline tunnels and special usage facilities such as the Large Hadron Collider (LHC) at
CERN [7]. There may be other requirements that drive systems decisions, such as normal operations
or environmental concerns (e.g. oil spillage risks in pipeline tunnels).

**Systems considerations**

Tunnel systems are expensive. While overall capital expenditure on systems may be relatively low
compared to the capital funding needed to construct the facility, there is nevertheless a significant
cost. Additionally, operating costs are a burden for the operator throughout the life of the facility.
When time comes for refurbishment/rehabilitation, replacement or upgrade, the cost of the systems
may amount to 80% of the total refurbishment costs.

Fire life safety systems will hopefully be required only rarely, if at all, throughout the life of the
facility. As discussed below, statistics show that fire in a tunnel is one of the lower probability hazards
within the tunnel environment. Of course, the consequences of a tunnel fire are potentially severe, and
that is why systems are installed in tunnels. Furthermore, some fire life safety systems may have other
functions unrelated to fire life safety. Future technologies on the immediate horizon (e.g. for rail,
widespread adoption of ATO/ATC/ATP systems and on-board fixed-fire fighting systems (FFFS),
and for roads, autonomous vehicles and vehicle-to-infrastructure (V2I) communications) offer the
prospect of further improvements in the safety profile with attendant reductions in fire risk. In fact,
operators of transportation tunnels are starting to find that tunnels are often the safest parts of their
mobility network.

So from the Operator’s perspective, are all tunnel systems strictly necessary? Or could there be more
efficient ways to distribute their finite resources to improve the overall safety level on their
infrastructure? How can safety within tunnels be compared with other portions of the network?

Where are we? Where do we go from here?

**THE PRESENT**

**Requirements**

Requirements represent the present ‘state-of-the-art’ mandatory standard of practice and summarise
the history of knowledge, gained through research and experience. Requirements exist in a hierarchy
as shown in Figure 1.

Legislation sits at the top and is mandatory. Legislation is typically high-level and usually lacks
details on implementation of the legal requirements. It is supported by regulations which provide
detail on the implementation of the mandatory legal requirements. Regulations can take several forms
depending on jurisdiction. Standards and codes may have a legal status equivalent to regulations,
again depending on jurisdiction. Where they are not mandatory, they fall into the next category down,
that of guidance and best practice documentation. This level of requirements may or may not be
deemed mandatory at the project level, even though they lack the legal force of the levels above.

Requirements have a tendency to be driven by historical factors. This is due to the nature of how they
are created. Fundamentally, requirements are driven by current knowledge and experience. Approval
processes to formalise requirements are conservative and it takes time for new concepts to be accepted
and adopted by the formal requirements.

New concepts may be adopted by individual projects in advance of becoming enshrined in formalised
requirements. This can happen when industry consensus is reached prior to codification of the new
concept. A well-known example of this comes from road tunnels. Following the string of catastrophic
road tunnel fires at the turn of the millennium, the industry responded by implementation of stringent
requirements that led to the installation of numerous new systems within road tunnels, a situation
which exists to this day. One of the changes was the move towards installing fixed water-based fire-
fighting systems (FFFS). However the response was not instantaneous, and as late as the mid-2000s, good practice guidance was in circulation that said activation of such systems in a tunnel would result in fatalities. The Burnley Tunnel fire in 2007 showed that, deployed within a framework of properly integrated tunnel systems, FFFS could in fact reduce the impacts of vehicle fire in a tunnel, and subsequently the requirements have changed to recognise the benefits of FFFS in road tunnels.

![Figure 1. Hierarchy of requirements](image1)

Figure 1. Hierarchy of requirements

Figure 2 illustrates the process of development of requirements. Research generates new knowledge and over time that knowledge gains an industry consensus as to its value. Here ‘research’ is used in a general sense of ‘anything that is newly found out,’ and that may encompass many things, including non-technical issues. Where justified, the new knowledge becomes codified in the requirements and then is applied into projects as it becomes mandatory, or becomes ‘good practice’ or ‘best practice’ guidance. Then feedback is received from the application and this may lead to new research or new knowledge. It is important to note that this is a continuous process.

![Figure 2. Requirements development process](image2)

Figure 2. Requirements development process

Figure 3 summarises factors, loosely referred to as ‘research’ above, that can influence the development of requirements. This includes not just history and innovation, but, critically, also includes societal attitudes. Sustainability, discussed above, is an example of a societal attitude that influences requirements. Another example would be the European regulatory attitude towards diesel vehicles. In the mid-2000s, the EU actively promoted the adoption of diesel vehicles preferentially over petrol vehicles, due chiefly to the narrow criterion of perceived lower CO2 emissions. However, following the recent scandals over emissions test manipulation, and with the emergence of electric
vehicles as a reasonably practical alternative, the authorities have altered course with respect to diesel vehicles, with both France and the UK recently having legislated the end of sale of such vehicles (and petrol vehicles) by 2040. While some of this decision is due to the changing perception of the feasibility of widespread electric vehicle adoption, some of the change is in response to changed societal attitudes towards diesel vehicles.

Figure 3. Factors influencing the development of requirements

Incident Data
A further source of information about the current state of tunnel safety is tunnel safety statistics. By looking at the most recent data, it is possible to see what trends, if any, are active and make estimates of what may happen in the near future. It is also possible to examine the relative safety of the tunnel environment compared with surface parts of the mobility network.

Figure 4 and Figure 5 show passenger rail incident data from the EU [8] and the USA [9, 10, 11] networks. It can be seen that for both networks, train fires represent a small fraction of the overall incidents. The most prevalent incidents are person-train interactions, either accidental or intentional (suicides). Train fires are relatively insignificant in comparison. It should be noted that these figures are for all types of train fires on the whole network. Fires in tunnels are a small proportion of these. Likewise serious train fires are also a small proportion. Serious train fires in tunnels are a very small proportion of the total. The data does not contain a sufficient level of detail to quantify the percentages of tunnel and serious fires. In Figure 5, note that ‘fires (other than train)’ represent all network related fires that do not occur on a train, e.g. trackside fires, station fires, etc.

Figure 6 shows data for the UK heavy rail passenger network [12, 13]. Reference [12] was an in-depth analysis of fire on the UK rail network and quantified the incidence of serious fire (leading to serious casualties and/or fatalities) as being 1x10⁻³ per million passenger train kilometres (1.6x10⁻³ per million passenger train miles) over the period 1992-2000. This compared with an overall incidence of fire during the same period that was quantified as 0.71 per million passenger train kilometres (1.14 per million passenger train miles). Since 2001, the incidence of train fire on the network has declined by over 80%, with none of the fires in that time being classified as serious. The Canadian rail safety regulator, the Transport Safety Board (TSB) of Canada publishes safety data on the Canadian heavy rail network. The most recent data [14] covers the period 2001-2015 and is of interest as until 2010 it recorded fire as a specific cause of fatalities and serious injuries. After 2010, however, the TSB decided to stop recording fire-related casualties as the incidence of these was deemed to be insignificant.

The picture from road tunnel data is similar. Figure 7 shows data on the incidence of fire in Austrian road tunnels [15] between 2006-2012, with a low rate of fire in the reporting period. Figure 8 and Figure 9 show regional road network data from the United Kingdom between 2009-2015, which includes a number of tunnels on dual carriageway highways in the data. It can be seen that fires are a
minor cause of incidents and also a minor cause of severe delays on the network.

Figure 4. EU normalised rail accident data 2012-2014 [8]

Figure 5. USA Light rail incidents (events) by type 2002-2016 [9, 10, 11]
Note: Event category reads sequentially clockwise from top, i.e. collisions, derailments, fires (other than train), fires (train), security, Not Otherwise Classified (NOC)
The UK data reveals a further insight. For tunnels on dual carriageway highways, the overall safety level of the tunnels is actually better than for the rest of the network. The highest risk areas of the road network are single carriageway roads (two-lane with no central divider), and at junctions.

A survey of Norwegian tunnel fires [17] found a similarly low incidence of tunnel fire. It further found that most fires involving personal injury occurred as a result of single vehicle accidents or collisions. The authors concluded that many of the injuries reported in these incidents were due to the traffic incident rather than the fire itself.

This data is merely a snapshot, and the references cited in this paper are examples only. However a broader survey of the available data shows similar trends to the data supplied here.
The key points from the available mobility network data are:

- Tunnel fires are statistically rare, and the rate of occurrence is decreasing overall.
- The occurrence of serious fires, leading to serious casualties and/or loss of life, is extremely rare, to the point where some safety bodies have ceased to track casualties as a function of fire.
- Most incidents that lead to casualties derive from causes other than fire, such as person-train interactions and road traffic accidents.
- Most incidents that lead to casualties occur on the surface assets of the network, rather than in tunnels.

The inference is that the focus on improving tunnel fire safety over the past decade and a half has largely achieved the intended effect. Tunnel fires are rarer now than in the past and the consequences are now comparatively minor.

Figure 8. UK Regional Roads data, incidents by type, 2009-2015, Highways England [16]
THE FUTURE

Operators are recognising that they now operate tunnels that are generally reliable and exhibit acceptable levels of safety. In many cases they observe that their tunnel assets exhibit a higher safety level than their surface assets. They also see that tunnel fires have not only become a more remote occurrence, but also that the consequences of the tunnel fires that do occur are in general not severe, with few casualties.

Consequently, operators have begun to challenge whether the expenditure of resources on tunnel systems is entirely justified. They recognise that the tunnels still need to be safe, but they must also focus on their overall network safety levels. They are therefore asking the tunnel systems industry whether it would be possible to safely redirect some of the resources now used to provide the present level of tunnel safety, and instead utilise them to improve safety in other areas, e.g. at surface level, and in improving their safety performance in the areas that currently result in the most casualties.

Additional challenges arise from new technologies. One example is the increasing use of alternative fuel vehicles on road networks. These vehicles include hybrid, electric, and fuel cell vehicles, which bring a new set of fire hazards with them. Another is the approaching deployment of autonomous vehicles on road networks, which bring new challenges to safe operations and incident response. In the rail industry one example is the expanding adoption of ATO/ATC/ATP and the consequent increase in driverless train operation, which may require a revised approach to safety operations and
incident response.

Ultimately, this could mean installing fewer safety systems, or different types of systems, within tunnels, and spending the savings elsewhere on the network. Can this be done safely? Can it be done at all? How can these questions be answered?

**Systems effectiveness**

To answer the operators’ queries, it will be necessary to examine the performance of tunnel systems more robustly. Each system’s contribution to safety should be assessed, thus allowing intelligent decisions about which systems are most essential to safety, and, importantly, whether any tunnel systems may be practically reduced or eliminated without compromising the facility’s overall safety level.

There have been efforts in the past to look at how systems interact, e.g. effects of FFFS systems on tunnel structure temperatures and the influence on passive fire protection requirements, however the attempt to quantify the effectiveness of individual systems and their contribution to overall safety levels is a new and developing area, prompted by operators’ evolving ideas about improving their overall network safety level.

There are typically many systems in modern tunnels. Ventilation, SCADA, communications, electrical services, egress, and fire mains are just a selection. Some are strictly for fire safety, while others are multifunctional. To assess the safety of a tunnel, it is first necessary to know the objectives that require the presence of the systems. Figure 10 shows a flow chart for the process of estimating the tunnel’s safety level.

First, the safety objectives are set, and these determine the functional requirements. Then, to satisfy the functional requirements, a set of tunnel systems is defined. Systems availability and effectiveness are estimated, then each system’s performance is quantified. Overall risk is evaluated and if unacceptable then changes are made and the evaluation is repeated.

![Flow chart for estimating tunnel safety level](image)

*Figure 10. Flow chart for estimating tunnel safety level*

What are the safety objectives? Each functional group of systems has one or more safety objectives. As an example, refer back to Table 1, the backbone services must function to allow other systems to be powered and to be monitored and controlled. The backbone services that satisfy these objectives are the electrical services and SCADA.

All of the systems referred to in Table 1, and others not mentioned, do not necessarily contribute equally to the overall safety level. Safety objectives may still be satisfied even when a system, although available, is not used. For example, the formal egress route, e.g. egress doors and a protected walking route, may not be used by occupants of a road tunnel. They may instead choose to walk along the roadway to the portal, that being a place they are already familiar with. In this instance the
Functional objective, egress from the tunnel, may still be achieved even though the egress system is not used by all.

Safety objectives may also still be met even if a system is not available. For example, train passengers evacuating from a train to an emergency walkway may evacuate properly from the train even if the communications between train driver, or operations control centre (OCC), and passengers is not functional. In this instance, persons still evacuate safely even though one of the systems used to aid in egress is not available.

However, some systems are completely essential to achieving the objective. For example, tunnel occupants would be unable to evacuate safely without tunnel lighting.

In order to quantify the effectiveness of individual systems, it is necessary to define a parameter to represent effectiveness, and to estimate values of that parameter for the various systems. The process should ideally be equally applicable at all stages throughout the life of the facility, from conception, through design, construction, and operations, to refurbishment, rehabilitation, replacement and/or upgrade. Figure 11 shows an example process. Using expert knowledge and stakeholder consensus, it is possible to estimate a probability that the safety objective is achieved when the system is available, and when it is not available. Details of such a method as applied to road tunnels are published in Reference [18]. The probability of success when the system is available is modified by the overall expected availability of the system, e.g. from a reliability, availability, maintainability and safety (RAMS) analysis. Failure probabilities, and consequences of failure, could then be estimated and an overall picture of the tunnel’s safety level could be built up. From this, an assessment of the value of installing, refurbishing, upgrading, reducing or even deleting individual systems could be made.

![Figure 11. Process for estimation of individual system effectiveness](image)

This could be a powerful tool for regulators, owners, operators, insurers and others with responsibility for safety on the mobility network as a whole. Funding for infrastructure is perpetually squeezed by competing priorities, and so the available funds need to be spent as efficiently as possible. Carbon usage is another key consideration, in light of global efforts to reduce carbon consumption. Figure 12 illustrates the dilemma faced by those responsible for funding decisions, i.e. how to decide where to spend the resources. As the fire risk profile in tunnels decreases as shown in Figure 13, safety funding may be redistributed to parts of the network exhibiting higher risk.
One consequence could be a reduction in the willingness to install some systems within tunnels, unless it were to be demonstrated that the system’s contribution to safety exceeds some agreed cost-benefit criteria, i.e. that there is a net increase in overall utility from the system’s contribution.

Utility is a philosophical concept that is much applied in economics. It is defined as:

1. The state or condition of being useful; usefulness.
2. Something that is useful.
3. (economics) The ability of a commodity to satisfy needs or wants; the satisfaction experienced by the consumer of that commodity.
4. (philosophy) Well-being, satisfaction, pleasure, or happiness.

Here, utility is used in the sense of an asset’s overall benefit to society. Clearly the safety of the asset is one aspect of its utility. Cost-benefit analysis is a tool that can be used to assess the utility of measures that require funding. The narrow area of safety, and the costs of providing a particular level
of safety, may be assessed by tools such as cost-benefit analysis. The utility of safety may be expressed as:

\[ U = F(P, C) \]

where \( P \) = probability and \( C \) = consequences. One representation of this concept can be found in F-N plots and the associated Expectation Value (EV). So, by applying the concept of utility, and using appropriate tools to assess the relative utility of different options, decisions regarding resource allocation may be made more efficiently, as shown schematically in Figure 14.

Figure 14. Using utility functions to allocate resources

By improving the efficiency of resource allocation, the mobility network should experience improved safety overall. The method also offers the prospect of improving the ability to adapt to future challenges, such as the spread of alternative fuel vehicles and autonomous vehicles on the road network, and the increase in usage of driverless trains on the rail network. Improved efficiency also improves the sustainability of the infrastructure by reducing waste and unnecessary usage. Resources are used more efficiently and safety remains within acceptable limits.

This may lead to reductions in the overall number of systems being installed within tunnels, with installations targeted for maximum safety effectiveness. It may lead to the implementation of new types of systems, such as V2I systems, in response to changes in mobility technology and usage. Systems that provide the most benefit would be retained and even extended in some cases, while those of lesser benefit may be reduced or even eliminated in some cases, provided the resulting tunnel safety level is deemed acceptable. The reductions, where implemented, could release additional funding and/or carbon allocations to tackle safety and sustainability issues elsewhere on the mobility network.

CONCLUSIONS

Advances in tunnel fire safety in the past fifteen years have been demonstrated to have significantly reduced the risk of serious fire in tunnels. Operators are beginning to find that their tunnel facilities now exhibit a higher level of safety than other parts of their mobility network and are beginning to ask
whether the continued level of expenditure on tunnel safety systems is fully justified. The challenge for tunnel safety professionals is to respond to these queries responsibly and to begin to develop risk-informed methods to assess the evolving needs of tunnel safety as mobility technology evolves, and to assess the value of individual systems and their contribution to the overall level of safety within a tunnel. Use of such risk-based methods could lead to more efficient use of resources across the wider mobility network, leading to transportation networks with an improved overall level of safety and sustainability in the future.

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Overview of tunnel fire research

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ABSTRACT

In the past two decades, the interest in fire safety science of tunnels has significantly increased, mainly due to the rapidly increasing number of tunnels built and the catastrophic tunnel fire incidents occurred. This paper presents an overview of research on fire safety in road and railway tunnels from the perspectives of fire safety design. The main focuses are on design fires, structural protection, smoke control and use of water-based fire suppression systems. Besides, some key fire characteristics, including flame length, fire spread, heat flux and smoke stratification, are discussed.

KEYWORD: fire safety, tunnel, design fire, structural protection, smoke control, fire suppression

INTRODUCTION

The numbers of road tunnels, subway tunnels and other railway tunnels are continuously increasing. Meanwhile, complexities of the infrastructure are also increasing, e.g. a roundabout in a tunnel, a metro transfer station connecting more and more lines etc. Despite the relatively low risk for large fires in tunnels, the increasing number of underground tunnels implies that more fire incidents may occur, unless more effective measures have been taken. A fire incident in a critical infrastructure can be catastrophic. One example is the arson fire in a metro station in Daegu, South Korea, 2003, caused 198 deaths and 146 injuries [1]. Another examples are the Channel tunnel fire incident in 1996 causing considerable damage to the tunnel lining over a length of approximately 480 m [2] and the fire incident in the same tunnel in 2008 causing the tunnel lining destroyed over a length of 750 meters [3]. In recent years, reports on arson fires and terrorist attacks appear to be increasing. Special attentions should be paid to these issues. This has forced the authority to reconsider the safety level of the tunnels and rethink the use of more active and/or passive fire protection systems. Nowadays tunnel fire safety has already become one of the key issues for any tunnel project.

In 2008, Ingason [4] made an overview of the tunnel fire research. He summarized the important work conducted in tunnel fire community concerning critical velocity for smoke control in longitudinally ventilated tunnels, correlation between heat release rate (HRR) and maximum ceiling temperatures, influence of ventilation on maximum HRR and fire growth rate and fire spread in and between vehicles. In the past decade, the interest in fire safety science of tunnels has significantly increased mainly due to the rapidly increasing number of tunnels built and the catastrophic tunnel fire incidents occurred as mentioned above. Much new knowledge has been obtained since 2008. There is a need to summarize these researches to provide sound knowledge and facilitate the foundation of the discipline of tunnel fire safety.

This keynote paper presents an overview of research on fire safety in road and railway tunnels from the perspectives of fire safety design. The main focuses are on design fires, structural protection, smoke control and use of water-based fire suppression systems. Besides, some key fire characteristics are also discussed.

DESIGN FIRES

The design fire is the most important parameter for describing the development and consequences of a
fire. In the following, the measured HRRs are summarized for each type of vehicle or fuel in graphs. The characteristics of fire development, i.e. fire growth and maximum HRR, will be depicted in detail, together with the influence of ventilation and tunnel structure.

**Vehicle fires**

For passenger cars, the measured or estimated HRRs from some fire tests are given in Figure 1. The medium and fast t-squared curves are also plotted. These tests include the Fiat 127 test by Ingason [5], the Renault test in Eureka programme by Steinert [6], the Citroen test by Steinert [7], the Trabant test by Steinert [7], the Citroen test by Shipp and Spearpoint [8], the test Car2 by Mangs and Keski-Rahkonen [9, 10], and the tests Car1 and Car 2 by Lecocq et al. [11]. It can be seen in Figure 1 that the maximum HRRs are below 6 MW for a single passenger car, and mostly below 5 MW. At the early stages, the fire development is slower than the medium curve. However, it should be kept in mind that the initial fire size can be larger if the ignition source is large, e.g. a spilled liquid pool fire.

For buses, the measured or estimated HRRs from some fire tests are also given in Figure 1. These tests include the EUREKA test 7 reported by Ingason et al. [12] and Steinert [6], SP Bus fire test by Axelsson et al. [13] and Shimizu bus tests by Kunikane et al. [14]. It can be seen in Figure 1 that the maximum HRRs are around 30 MW. At the early stages, the fire development is mostly not more rapid than the ultra fast curve. Alternatively, the typical HRR curve may be considered as a fast curve before around 3 min and a linear curve to the maximum value of 30 MW with the slope of 5.7 MW/min. The closely linear slope could be attributed to the flame spread process along the carriage, similar to that in a train carriage fire Li et al. [15, 16].

For trucks, the measured or estimated HRRs for heavy goods vehicles (HGV) are also given in Figure 1. These HGV tests include the EUREKA HGV fire test in 1992 [17], four HGV tests conducted in the Runehamar tunnel in 2003 by Ingason et al [18] and the LTA HGV test by Cheong et al [19, 20]. Most HGV tests that have been carried out in tunnels use a mock-up simulating the cargo of a HGV.

**Figure 1** Summary of experimentally determined HRR for cars, buses and trucks.

For trucks, the measured or estimated HRRs for heavy goods vehicles (HGV) are also given in Figure 1. These HGV tests include the EUREKA HGV fire test in 1992 [17], four HGV tests conducted in the Runehamar tunnel in 2003 by Ingason et al [18] and the LTA HGV test by Cheong et al [19, 20]. Most HGV tests that have been carried out in tunnels use a mock-up simulating the cargo of a HGV.
trailer. It can be seen in Figure 1 that the maximum HRRs are in a range of 60 to 200 MW. At the early stages, the fire developed even more rapidly than the ultra fast curve. The typical HRR curve may be considered as an ultra fast curve before around 3 min and then a linear curve to the maximum value with a certain slope (fire growth rate). Clearly, the fire size for a HGV is typically much greater than that for a car fire or a bus fire.

For railway and metro carriages, the measured HRRs for the tests are given in Figure 2. The solid lines are for metro carriages and the dashed or dotted lines for railway carriages. The tests include the EUREKA carriage fire tests [17], the METRO carriage fire tests in the Brunsberg tunnel [21], and the carriage fire tests carried out in a 37 m long enclosure at Carleton University [22]. A comparison of the fast and ultrafast t-squared fire curves and the test results for carriages with time up to 30 min is plotted in Figure 2. It can be known that both the ultrafast fast curve and fast curve cannot represent the fire development. In both the METRO test 2 and the Carleton subway test, the HRR maintained at a small value and grew up rapidly after around 5 – 6 min. These carriage fires are very similar to the bus fires presented in Figure 1. The closely linear slope could also be attributed to the flame spread process along the carriage, as found by Li et al. [15, 16].

For single metro carriage, the maximum HRR is found to be in a range of 35 MW to 77 MW and the energy content in a range of 23 GJ to 60 GJ. The time to reach the maximum HRR after ignition varies from 5 min to 118 min. For single train carriage, it can be known from Figure 2 that the maximum HRR is found to be in a range of 13 MW to 43 MW and the energy content in a range of 50 GJ to 77 GJ. The time to maximum HRR varies from 18 - 80 min, but mostly within 13 min. It can be known that generally higher HRRs were measured for metro carriages compared to those for train carriages. This could be attributed to larger openings in the metro carriages, which suggests that the HRRs could be higher for fully developed fires. It was pointed out that as long as the windows do not break or fall out (and there are no other large vents), the fire will develop slowly, and vice versa [23].

![Time-resolved HRR curves for the carriage fire tests.](image)

A simple theoretical model was proposed by Li et al. [15, 16] to estimate the maximum HRR for a fully developed metro carriage fire, which has been proved to be able to correlate all the test data in different scales very well. The maximum HRR in a carriage fire was found to be mainly related to the type and configuration of the fuels, effective heat of combustion, heat of pyrolysis and the openings, and the maximum HRR can be much higher than that corresponding to complete consumption of oxygen flowing into the carriage through the openings.

**Spilled liquid pool fires**

Fire tests were mostly carried out with deep (>50 mm) liquid pools that can reach a quasi-steady state after a few minutes. Typical values have been found for various fuels[1, 24]. However, in reality, these deep pool fires are rarely the cases in real incidents. It is known that when the fuel thickness is reduced to less than 10 mm, its effects on the burning rate are pronounced [25]. Putorti [26] carried out full-scale spill and fire experiments with gasoline and kerosene on nonporous subsurface (vinyl
and wood parquet) using various quantities of fuel. The peak spill fire HRRs for nonporous surfaces were found to be approximately 1/8 to 1/4 of those from the pool fires of equivalent area. The average spill thickness was less than one millimetre. In general, spill fires occurring on more conductive sub surfaces (e.g. concrete surface) resulted in peak HRR values that were lower than identical fires occurring on less conductive sub surfaces (e.g., wood). Ingason and Li [25] carried out large scale spilled gasoline fire tests, and found that the depth of the fuel is an important parameter to consider when calculating how large a fire can become, as manuals generally provide values for burning rate and HRR that are two to three times higher than those presented in this paper. For the spilled gasoline fires tested, the average HRR per unit area is about 1/3 to 2/5 of that for a deep pool fire.

Another important parameter for spilled liquid fires is the spillage area. Klein et al. [27] presented experimental results consistent with the experimental results found by Ingason [28]. Ingason [28] provided an equation showing that the spillage width correlates to the flow rate and that the spillage area correlates to the slope, and stated that the test width is nearly independent of the roadway slope [28], whereas Klein et al [27] show minor changes in the flow width between 3% and 5% of road slopes. Ingason and Li [25] carried out large scale tests to investigate release of liquids inside tunnels from fuel tanks, with varying leakage rates, leakage type, liquids and spillage sizes on sloping surfaces. Models for estimation of leakage rates and spillage sizes were proposed. The values calculated prior to the tests stated that a continuous release of water from a 1 m$^3$ IBC container would create a spill area of between 24 and 30 m$^2$, corresponding well to the tests in the tunnel, where the spills area is 22-31 m$^2$. The tests with an instantaneous release from a pool of 2 m$^3$ produced a total spillage area in the order of 138-163 m$^2$, which is approximately five times larger than that created with the continuous release. The tests with water in the tunnel show the importance of sufficient inclination across the road surface (transverse inclination), and a good surface water drainage system.

**Influence of ventilation and tunnel structure**

Ventilation condition and tunnel structure can affect the fire development, making a tunnel fire different to an open fire or an enclosure fire. From the point of view of design fire, there are two key parameters that attract special attention, i.e. the maximum HRR and the fire growth rate.

**Vehicle fires and solid fuel fires**

Important findings of the fire growth rate in ventilated tunnel fires were reported by Li and Ingason [29]. They proposed a theoretical model of fire growth rate in tunnel fires, explored the relationship between the flame spread rate and the fire growth rate in a ventilated flow, and used a large amount of data relevant to the fire growth rate from model scale and full scale tunnel fire tests for validation. The study showed that for fully wind exposed fuels the fire growth rate increases linearly with the ventilation velocity. The thermal inertia, the heat of combustion, the wet perimeter, and the mass burning rate per unit area of the fuel play important roles in the fire growth rate [29]. For fuels not directly exposed to wind, the enhancement effect of ventilation on fire growth rate is expected to be less. In case that the ignition source was on the downstream side of the fuel in a tunnel with forced ventilation, the fire may even grow more slowly than in a free burn test, see for example the car fire tests carried out by Lemaire and Kenyon [30].

Another important parameter is the maximum HRR. For vehicle fires in road tunnels, fixed design fire values can be found in different guidelines or standards for road tunnels, depending on type of the vehicle. Although it is known that the tunnel geometry and tunnel ventilation have influence on the maximum HRR, there is no consensus on this. Carvel et al. [31] performed an analysis of HRR enhancement in a tunnel fire compared to corresponding fire situation in the open. Results from a number of experimental test series published in the literature were collected and analysed using the Bayes’ theorem concerning conditional probability to study the effect of various parameters on HRR. It was concluded that the tunnel width had a very significant influence on the HRR and a power law correlation was proposed. But the test data concerning solid fuels used in the study are rather limited. Tests with natural ventilation or forced ventilation at velocities less than 1 m/s were considered, which may be under the ventilation controlled regime. Therefore, as also stated by Carvel et al. [31], there are insufficient experimental data available to support or deny the theory. Ingason and Li [32,
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33] carried out model scale tunnel fire tests with both longitudinal ventilation and point extraction ventilation to investigate the effect of ventilation and tunnel geometry on the HRR. The fire sources used were wood cribs, corresponding to one or several HGV trailers. The results showed that for well ventilated fires, the maximum HRR in a tunnel is only 1.3 to 1.4 times that in the open. It was also found that when the tunnel is not well ventilated, the maximum HRR could depend on the ventilation flow, that is, the fire tends to be ventilation controlled. Kayili et al. [34] carried out an experimental study on the effect of blockage ratio and ventilation velocity on the HRRs from wood crib fires in a 1:13 model scale tunnel. Their results showed that the HRR increases with ventilation velocity. However, the corresponding porosity in the tests is mostly less than 0.7 mm, indicating the porosity also has strong influence on the burning rate [32]. Lemaire and Kenyon [30] presented results from large scale fire tests in the Second Benelux tunnel and showed that for car fires the maximum HRR with a ventilation velocity of 6 m/s is closely the same as that without ventilation (despite a long delay for 6 m/s), and for truck fires the maximum HRR is around 1.2 to 1.5 times that without ventilation. This correlates very well with Ingason and Li’s test data [32, 33]. Li et al. [35] analyzed data from a series of tests with varying geometries and ventilation conditions and found that for well ventilated tunnel fires (fuel controlled) with solid fuels (wood crib, or wood/plastic crib), the HRR increases by approx. 25% relative to a free burn test, however, it is not sensitive to either tunnel width, tunnel height, or ventilation velocity. For tunnel fires with solid fuels that are not well ventilated or closely ventilation controlled fires, the HRRs could be less than those in free burn tests. Further, the scenarios for ventilation controlled fires are close to cases with natural ventilation and the HRRs approximately lie at the same level as for cases with natural ventilation. More specifically, the ratio of HRR to that in a free burn should be in a range of around 1 to 1.25 for the crib fires. Li et al. [15, 16] found that a simple theoretical model can be used to predict the maximum HRRs in all the tests under various conditions, not considering the effect of tunnel ventilation and structure. Li [36] further carried out a series of CFD modelling of the full scale carriage fires and found that the tunnel structure and ventilation on the fire development is insignificant for well ventilated fires.

In summary, for well ventilated tunnels fires with vehicle carriages, the influence of tunnel ventilation and structure on the maximum HRR is insignificant. This explains why single design values for the vehicles are reasonable to a certain extent. In most cases, the influence of tunnel ventilation on fire development is also insignificant, but it can have some influence if availability of vehicle openings (e.g. windows, doors or fallen roofs) forms a longitudinal flow inside the carriage which can stimulate the fire spread. For exposed solid fuels (e.g. open truck loads) in a tunnel fire, the maximum HRR could slightly increase (by around 25 %) compared to that in the open, but the fire growth rate increases approximately linearly with the tunnel ventilation velocity. If fire spread to other vehicles or vehicle carriages occurs, the total HRR depends on how fast the fire spread occurs and how many fuels can sustain burning simultaneously. In such cases, higher tunnel ventilation indicates more vehicles or vehicle carriages may be involved in burning simultaneously, i.e. a higher HRR. This, however, is not the commonly assumed case, as it is generally supposed that intervention from fire fighters should prevent such a scenario.

Spilled liquid pool fires
As mentioned previously, there is rather limited research on spilled liquid fires in tunnels. The only relevant information on influence on ventilation and tunnel structure comes from the researches on deep pools. Apte et al. [37] performed pool fire tests with aviation oil in a full scale mine tunnel with a velocity of 0.5 to 2 m/s. They found that the effects of wind were relatively small but there was a tendency of decrease with the velocity. Ingason [38] found the similar trend in their model scale tunnel tests with helptane, methanol and xylene. Carvel et al. [31] analysed test data for pool fires from the literature using the Bayes’ theorem and used a power law correlation to express how the HRR in a tunnel significantly increase with tunnel width and ventilation. However, by analyzing the test data that they used in their analysis, it can be found that the ratio of HRR in a ventilated tunnel to that in the open is mostly below 1.4 for pools with diameter exceeding 0.5 m. In contrast, small scale test data for HRR vary more significantly. By analysing the test data of burning rates of pool fires obtained by Roh et al. [39] in a 1:20 model scale tunnel, Li et al. [40] found a linear correlation between the ventilation velocity and mass burning rate. This enhancement effect of wind on HRR was
also reported by Hu et al [41]. Li et al. [35] investigated the effect of tunnel cross section as well as tunnel ventilation on the HRR for liquid pool fires, by analyzing the results from a series of model scale tunnel fire tests. They found that for well ventilated heptane pool fires (fuel controlled), tunnel width has limited influence on the HRR. Instead, a lower tunnel height corresponds to a slightly greater HRR, i.e. a decrease in tunnel ceiling from 0.4 m to 0.25 m results in an increase of approx. 30% in HRR. For heptane pool fires, the HRR in a tunnel is approximately 3 times that in a free burn laboratory test. They pointed out that the factor of 3 cannot be directly extrapolated to large scale pool fires due to the scale effect of pool fires [35].

In summary, for well ventilated fires with deep liquid pools, influence of ventilation and tunnel structure on burning of pool fires is not very significant for large scale pools, but very significant for small pools. The burning of pool fires is highly dependent on the scales of the pool pans. Therefore the findings from small scale pool fire tests cannot be directly extrapolated to large scales. There is an urgent need for more research concerning spilled liquid fires in tunnels.

**STRUCTURAL PROTECTION**

Although the probability of a large fire incident may be low, a large fire is a possible incident in tunnels. In such a case, the stability of the tunnel structure is a key design parameter concerning the fire safety in tunnels. For example, a tunnel may be the key transportation line between two countries as in the case of the Mont Blanc or the St Gotthard tunnels, where several fires have occurred, some with significant consequences. A large fire can jeopardize the tunnel construction if the fire becomes too intense over a long period of time. Our knowledge of the impact of thermal exposure from the fire on the tunnel construction and how to calculate the stability of the structure is, therefore, critical.

**Standard time-temperature curves**

Traditionally, evaluation of heat exposure to a tunnel construction is based on the use of standardized time-temperature curves. Indeed, standard fire temperature curves, such as ISO 834 [42], the hydrocarbon curve (HC) [43] or the RWS curve [44], are widely used to test the fire performance of tunnel linings. These temperature curves are discontinuous and cannot be represented with a single mathematical expression as the ISO 834 and the HC curves. All these curves are derived in different ways and usually based on large scale or small scale tests or by consensus of technical committees working in this field. This method is accepted by most authorities around the world and means that the analysis will be critically dependent on the choice of the time-temperature curve. When choosing different curves, there is no single guideline document concerning how to choose one curve in relation to the HRRs, longitudinal ventilation velocity or the ceiling heights compared to others. The method is crude and prescriptive and therefore not applicable to performance based design. Due to this fact, there is a clear need for a reliable engineering tool based on theoretical analysis that can predict the gas temperature as a function of the tunnel geometry, HRR and ventilation conditions.

**Performance-based time-temperature curves**

The gas temperature is highly dependent on the HRR, velocity and effective tunnel height, and tunnel structure itself. In reality there exists no single time-temperature curve. Extensive research has been conducted on maximum ceiling gas temperatures in tunnel fires. Kurioka et al. [45] proposed an empirical equation to predict the maximum gas temperature rise below the tunnel ceiling. However, the maximum gas temperature cannot be predicted correctly when the ventilation velocity is low, and the value is around 750 °C for a large tunnel fire, which is much lower than the data obtained from large scale tests. Li et al. [46, 47] conducted a theoretical analysis of the maximum excess gas temperature below the ceiling based on an axisymmetric fire plume theory. They found that the maximum ceiling excess gas temperature can be classified into two regions, depending on the ventilation velocity. Each can be divided into two sub-regions. The first sub-region exhibits a linear increase which transits into a constant period, depending on the fire size, ventilation and effective tunnel height. The proposed equations for the maximum excess gas temperature beneath the ceiling fit the data from both model scale tests and large scale tests. The correlations for the maximum excess gas temperature, Δ$T_{\text{max}}$ (°C), proposed by Li et al. [46, 47] in reality can be simplified into the
\[
\Delta T_{\text{max}} = \min\left(17.5 \frac{\dot{Q}^{2/3}}{H_{\text{ef}}^{5/3}}, \frac{\dot{Q}}{u_{o} b_{\text{fo}}^{0.6} H_{\text{ef}}^{2/3}} \cdot 1350\right)
\]  

where \(u_{o}\) is the longitudinal velocity (m/s), \(H_{\text{ef}}\) is the effective tunnel height and \(b_{\text{fo}}\) is the equivalent fire source radius (m).

Note that in the above equation, a maximum possible excess gas temperature of 1350°C, which was the highest measured tunnel ceiling excess gas temperature obtained, was set. However, this gas temperature in reality is also dependent on the tunnel linings. Li and Ingason [48] further developed the model factor in the effect of tunnel structure and lining on the maximum ceiling gas temperature. The improvements made to the previous MT models, has enabled and facilitated more accurate predictions of the maximum possible excess gas temperature beneath tunnel ceilings during large fires. More details refer to the literature [48]. The knowledge on gas temperature can also be used to assess heat exposure to humans, fire detection time and risk for fire spread, and to design ventilation systems.

SMOKE CONTROL (TUNNEL FIRE VENTILATION)

Smoke control is of the utmost importance for evacuation and rescue service. In buildings and railway or metro stations, fire compartmentation by use of physical or other fire barriers is a common measure to divide a large area into individual zones to avoid a fire in one zone affecting the others. In metro stations, fixed or movable smoke curtains or smoke barriers are also commonly used at the upper spaces to separate the platform region from the track tunnel in case of a fire in a carriage. In case of a tunnel fire, fire ventilation systems are required to control smoke flows and create paths for evacuation and fire fighting.

Longitudinal ventilation

Longitudinal ventilation systems have been widely used in both road and railway tunnels. There are two key design parameters for tunnels with longitudinal ventilation, i.e. critical velocity and backlayering length.

Critical velocity

There are mainly two types of models to estimate the critical velocity, i.e. the critical Froude model and the non-dimensional model. The critical Froude model was proposed by Thomas [49, 50] and use of a critical Froude number of 4.5 was proposed by Danziger and Kennedy [51, 52] based on one data point from Lee et al.’s experimental work [53]. The critical Froude model was developed based on the assumption of full mixing between the heat and the incoming air flow immediately at the fire site. This cannot be true for a wide tunnel. Oka and Atkinson [54] carried out fire tests and proposed a non-dimensional model for the estimation of critical velocity using tunnel height as characteristic length. Wu and Bakar [55] also carried out fire tests with various aspect ratios and correlated their results using the hydraulic diameter instead of tunnel height. Vauquelin and Wu [56] further investigated the influence of tunnel width on the critical velocity and found that in both series of tests, for aspect ratios greater than unity, it is noticed that the critical velocity decreases when the width increases. It should be kept in mind that in Wu and Bakar’s [55] tests, the use of water sprays in the vicinity of the fire source could result in large error, especially for wide tunnels, and in Vauquelin’s tests [56] the cold gas was used which could differ significantly from a realistic fire. Kunsch [57] conducted a theoretical analysis of smoke movement in a tunnel under no ventilation based on the theory of ceiling jets under unconfined ceilings, and proposed a simple mathematic equation. To propose the explicit solution, the energy equation for weak plumes was used, which could not be appropriate for large fires. Despite the theoretical weakness, the proposed equation is interesting in that it shows how critical velocity varies with HRR and tunnel geometry. Li et al. [58] carried out theoretical analyses and fire tests in two model scale tunnels to investigate the critical velocity together with the backlayering length in tunnel fires. Fire tests in two model scale tunnels were carried
out and full scale tunnel fire test data were also used for comparison, and a correlation was proposed. Recently, Li an Ingason [59] carried out theoretical and numerical work to investigate the effect of tunnel cross section on critical velocity for smoke control in longitudinally ventilated tunnels, and also systematically investigated and compared the critical Froude model and various non-dimensional models. Their results showed that the critical Froude model with the Froude number of 4.5 does not appropriately account for the effect of tunnel width and tunnel height, and its predicted results are generally too low. Oka and Atkinson’s model [54] systematically underestimate the critical velocities. Wu and Bakar’s model [55] overestimates the effect of tunnel width on critical velocity for small and large fires, and the predicted results are generally low for small fires but can potentially be high for large fires in wide tunnels. Kunsch’s model [57] does not appropriately account for the effect of tunnel width. The critical velocity slightly increases with increasing tunnel width, which is contrary to numerical results. In reality, in Kunsch’s model the critical velocity is insensitive to the tunnel width. Li et al’s model [58] predicts the data well for both small and large fires, but the effect of tunnel width needs to be considered for a tunnel with a large aspect ratio. Li an Ingason [59] also found that for small fires, the critical velocity decreases with both the increasing tunnel height and tunnel width. For large fires, the critical velocity significantly increases with the increasing tunnel height but is closely independent of tunnel width. Based on their previous model [58], they proposed a new correlation for critical velocity, which is expressed as follows:

\[ u^*_c = \frac{u_c}{\sqrt{gH}} = \begin{cases} 0.81\phi^{-1/12}Q^{1/3} & Q^* \leq 0.15\phi^{-1/4} \\ 0.43 & Q^* > 0.15\phi^{-1/4} \end{cases} \] (2)

where

\[ Q^* = \frac{Q}{\rho_o c_p T_o g^{3/2} H^{5/2}}, \quad \phi = \frac{W}{H} \]

\[ \frac{u_c}{\sqrt{gH}} = \frac{u^*_c - u^*_c,ob}{u^*_c} \] (3)

where the subscript \( ob \) indicates vehicle obstruction. The reduction ratio indicates how much the critical velocity is reduced due to the vehicle obstruction. Li et al. [58] found that the reduction ratio of critical velocity due to obstruction approximately equals the blockage ratio, i.e. the dimension ratio of model vehicle to model tunnel, \( A_{ob}/A_c \), regardless of the fire size [58]. In other words, the local critical velocity is almost the same, regardless of the vehicle obstruction [58]. Similar trend can be found by analysis of the test data obtained by Oka and Atkinson [54]. Li et al [58] concluded that as a conservative rule of thumb, the blockage ratio could be regarded as the reduction ratio of the critical velocity due to obstruction near the fire site, \( \varepsilon \), from which the critical velocity for smoke control in an obstructed tunnel can be extrapolated. This has further been verified by Lee and Tsai [60]. In their experimental work, the obstructions were placed immediately upstream of the fire source, which also significantly increases the local velocity across the fire source and similar results were obtained.

**Backlayering length**

The backlayering length, \( L_b \) (m), is defined as the length of the smoke backlayering upstream of the fire when the ventilation velocity is lower than the critical velocity. Thomas correlated the backlayering length with the Froude Number. Vantelon et al. [61] found that the ratio of backlayering length to tunnel height tended to vary as 0.3 power of a modified Richardson Number. However, the HRRs were very small. Deberteix et al. [62] made detailed measurements of the backlayering length.
as well as the critical velocity in a model of the Paris metro with 0.163 m height, and related the backlayering length with a Richardson Number. Li et al. [58] carried out two series of tests in model scale tunnels based on a dimensional analysis, and found that the backlayering length increases with the HRR for low HRRs, and dependent only on the ventilation velocity at higher HRRs. According to a dimensional analysis, the dimensionless backlayering length, \( L_b^* \), was correlated with the ratio of longitudinal ventilation velocity to critical velocity [58]. It was found that the relation between the ratio of longitudinal ventilation velocity to critical velocity and the dimensionless backlayering length approximately follows an exponential relation. When the dimensionless HRR \( (\dot{Q}^*) \) is less than 0.15, the backlayering length varies as one-third power of the modified Richardson number and is almost independent of the dimensionless HRR, which is expressed as follows [58]:

\[
L_b^* = \frac{L_b}{H} = \begin{cases} 
18.5 \ln(0.81 / u^*), & \dot{Q}^* \leq 0.15 \\
18.5 \ln(0.43 / u^*), & \dot{Q}^* > 0.15 
\end{cases}
\]

where \( u^* = u_c / \sqrt{gH} \).

The effect of vehicle obstruction on the backlayering length was also investigated by Li et al. [58]. The results show that the backlayering length was reduced when the vehicle was placed inside the tunnel for a certain dimensionless confinement velocity. In other words, a small change in velocity will result in a greater change in backlayering length. Zhang et al. [63, 64] modified Li et al.’s model for backlayering length without blockage [58] to account for the effect of blockage in a metro tunnel. Note that in reality the vehicles upstream are generally not so close to the vehicle on fire, and the blockage ratio is normally a small value except in the single-track subway tunnel. In most cases, the effect of blockage on the backlayering length could be neglected, which tends to be conservative.

**Smoke extraction**

When designing an extraction system in a tunnel or in a metro station, the traditional method is to estimate a “smoke release rate” corresponding to the maximum design fire size, and then use this value to determine the capacity of the extraction system. However, the smoke flow rate is not only dependent on the HRR, but also strongly depends on the ventilation and tunnel geometry. In other words, the smoke flow rate is not constant. The smoke extraction systems can be categorized into single point extraction system, two point extraction system, three points extraction system, etc., by the number of opened extraction vents during a fire. The configurations of these systems are different. However, the concept is essentially the same. Ingason and Li [33] found that in order to efficiently control the smoke flow, an extraction ventilation system must be powerful enough to create longitudinal flows with sufficiently large ventilation velocity from both sides. Otherwise the smoke flow will continually travel along the ceiling until finally the smoke front is trapped by the incoming flows, which could results in high risk of fire spread in a large tunnel fire. Ingason and Li [33] and Ingason proposed the correlation for the critical total extraction mass flow rate, \( \dot{m}_{ex} \), :

\[
\dot{m}_{ex} = 2\rho_o u_c A
\]

where \( \rho_o \) is fresh air density (kg/m\(^3\)), \( u_c \) is critical velocity (m/s) and \( A \) is tunnel cross-sectional area (m\(^2\)). Chen et al.[65], Tanaka et al. [66] and Tang et al. [67] also investigated the performance of single point extraction ventilation with a focus on the smoke back-layering flow length on the upstream side of the fire. Their results provide additional support for use of the backlayering length equation proposed by Li et al. [58] in such a point extraction system.

**Natural ventilation**

Recently a natural ventilation system with intensive large short shafts or vents was proposed for use in urban city tunnels and metro tunnels close to surface. This natural ventilation system consists of large amounts of short shafts connected to outside with a short spacing distance. The operation costs under normal case can be reduced. The main drawbacks are the installation costs and the need for places for large amounts of external vents. In case of a fire, the system extracts smoke flows by use of smoke buoyancy, in comparison to an extraction system by use of mechanical fans. Wang et al. [68] carried
out three full scale tests in a road tunnel with short shafts and a fire size of around 7.5 MW, and presented some valuable temperature data. Yuan et al. [69] and Kashef et al. [70] carried out small scale tunnel fire tests and proposed simple models to estimate the total mass flow rate extracted by the shaft and the temperature distributions. Yao et al. [71] studied the characteristics of smoke movement in a 1:10 scale tunnel with vertical shaft and by introducing a concept of virtual fire source below the shaft, they proposed a new empirical model to predict the smoke back-layering flow length based on Li et al.’s work [58]. There are also studies on local smoke behaviors at the shaft, e.g. the smoke separation and plug holing phenomenon. Ji et al. [72] experimentally investigated the effect of vertical shaft height with varying fire sizes and shaft heights in a 6 m long tunnel model and found that the increasing shaft height, the boundary layer separation becomes inconspicuous and the plug-holing occurs. Despite many researches on this topic, the global performance of such a natural ventilation system in control of smoke flows for various fire sizes and tunnel geometries are still unclear.

Cross passages
A tunnel cross-passage connects the main tunnel to a safe place, and provides a safe route for evacuation and rescue operations in a tunnel fire. The minimum ventilation velocity through a door to prevent smoke flow is defined as the critical velocity for smoke control in a cross-passage. Tarada [73] proposed a performance-based method to calculate a specific critical velocity for a cross passage located downstream of the fire, and simply regarded the critical Froude number as 4.5. Li et al. [74] conducted a parametric study of critical velocity in a tunnel cross-passage, taking the fireproof door geometry, HRR, longitudinal velocity and fire source location all into account. It was found that the critical velocity in a tunnel cross-passage varies approximately as 3/2 power of the fireproof door height, as 1/3 power of the HRR and as exponential law of the tunnel ventilation velocity, and is almost independent of the fireproof door width. A non-dimensional equation to predict the critical velocity for smoke control in a cross-passage was proposed [74].

Rescue station
The safety level in a very long tunnel can be significantly improved by use of a rescue station which consists of numerous cross-passages with a short spacing for efficiently evacuate the passengers. The main method of smoke control is to supply fresh air towards the incident tunnel to keep the cross-passages free of smoke. The smoke flow in the fire tunnel could also be exhausted through vertical shafts or blown out by the longitudinal flows. Li et al. [75] carried out 54 model scale rescue station fire tests to investigate the effects of HRR, train obstruction, fire source location and ventilation condition on smoke control of the cross-passages in a rescue station. Their found that the critical velocity in the cross-passage beside the fire source is the highest, and the critical velocity in cross-passages decreases with the distance away from the fire source. The critical velocities in the cross-passages approximately vary as 1/3 power law of the HRR and decreases due to the obstruction of the train. The average reduction ratio of critical velocity due to vehicle obstruction is about 14 % on average, i.e. slightly lower than the blockage ratio of the vehicle. The results of the critical velocity for smoke control in the rescue station correlate well with that in the normal cross-passages [74].

USE OF WATER-BASED FIRE SUPPRESSION SYSTEMS

The main purposes of a water-based fire suppression system are to limit the fire size, cool the smoke and prevent fire spread to other vehicles, for protection of tunnel users and structure. Water-based fire suppression systems can be subdivided into water spray systems and water mist systems, both with and without the use of foam additives. All of these systems have been applied to tunnels, although water spray systems without additives represent the vast majority of the installed systems. The main differences between them are the operating pressure and droplet size. There are also other water-based fire suppression systems, e.g. the automatic sprinkler system that directly uses thermally activated sprinklers in tunnels [76] and the foam systems [1]. These, however, are seldom used and thus not
A tunnel is normally divided into large amounts of longitudinal zones (deluge zones) each having a length of around 20 to 50 m. In case a fire, 2 or 3 zones in the vicinity of the fire site will be activated. The mechanism of fire suppression using water-based systems can be classified into two types: condensed phase suppression and gas phase suppression. In the condensed phase, surface cooling is the main mechanism. In the gas phase, the extinguishment mechanisms can be categorized into gas cooling, heat capacity and dilution effects, and kinetic effects [1].

Water spray systems typically require a minimum operating pressure of 1.5 - 5 bar and they discharge a uniform pattern of water droplets with droplet sizes less than 2 mm in diameter. The water discharge density over the length of the deluge zone is in the range of 6 to 12 mm/min (l/(min·m²)). The K-factor of the nozzles is typically 80 L/(min bar²). Water mist systems are fundamentally similar to water spray systems. According to the definition given in UPTUN guidelines [77] the general principle of the low pressure water mist system is to produce a fog (or mist) of small water droplets at a nozzle pressure of 3-10 bar. The high pressure water mist system produces a fog (or mist) with a mix of different sizes of water droplets at a nozzle pressure of 60-120 bar. The water discharge is in the range of 1 to 4 mm/min (l/(min·m²)). The K-factor of the nozzles is typically 4 to 6 L/(min bar²). The majority of water droplets should have a diameter smaller than 1 mm. The median diameter is mostly much less. The water mist systems use less water than water spray systems but significantly higher pressure. As a result, pipes, tanks and pump capacities can be smaller, and the water demand be lowered.

**Suppression of solid fuel fires**

The suppression of solid fires normally takes a certain time due to the three-dimensional characteristics of the solid fire source. The time that is required for extinction of a fire is correlated to the water flow rate. A higher water flow rate can reduce the extinguishment time and less fuel will be consumed. Kung and Hill [78] investigated the extinction of wood crib and pallet fires and obtained some useful empirical equations. It was shown that a single empirical correlation, for three types of cribs with the same stick size, but different crib height can be established between the ratio of crib mass consumed during the extinction period and combustible material remaining at the beginning of the water application, \( R \), and the ratio of true water application rate and the fuel burning rate at the activation of water application. Tamanini [79] found that the mass consumed during extinguishment varied with a power law of the water flow rate, where the power of -1.55 was used by Kung and Hill and was in the range of -1.86 to -2.18 according to Tamanini [79]. The time to extinction was also correlated with the corrected water flow rate and the activation parameters which suggests that the time to extinction prolongs significantly as the water flow rate decreases. Yu et al. [80] made a theoretical analysis of extinguishment of rack-storage fires by cooling of the fuel surface. A fire suppression parameter, \( k \), was identified to correlate the fire suppression results obtained from large-scale tests conducted using two different commodities arranged in steel racks of different height. Xin and Tamanini [81] also conducted a series of fire suppression tests using representative fuels to assess the classification of commodities for sprinkler protection. An empirical correlation was proposed for a ceiling clearance of 3.05 m to estimate the actual water flux discharged to the fuel surfaces, which was correlated with the sprinkler discharge flux and the convective HRR. Based on Kung and Hill’s work [78], Ingason [82] proposed a new equation to correlate the energy content with the HRR. Ingason [82] also correlated the non-dimensional ratio of HRR, excess gas temperature, fuel consumption, oxygen depletion and heat flux to the non-dimensional water flow variable, and good agreement was found. In summary, some useful equations have been obtained, however, most of these equations are empirical and they must be used with caution.

**Tunnel fire suppression tests and system performance**

There have been many FFFS tests conducted in full scale or large scale tunnels. Several tests were carried out in Japan, e.g. Kakeitou Tunnel fire tests in 1980, however, technical information was very limited [1]. After 2000, several series of large scale fire suppression tests have been conducted in tunnels, most of which were performed in Europe. The deluge water spray tests include the Second Benelux tunnel tests during 2000 and 2001, Land Transport Authority (LTA) Singapore tests during 2011 and 2012 and the Runehamar tests in 2013. The water mist tests include the IF tunnel tests
carried out in the UPTUN project during 2002 and 2004, the IF tunnel tests by Marioff in 2004, the VSH tunnel tests by Marioff in 2005, the San Pedro de Annes tests by Marioff in 2006, the Runehamar tests in 2007, the tests in the SOLIT project and the SOLIT2 projects, the SP Runehamar suppression tests in 2013 and 2016. More information can be found in the literature [1].

In the tests recently carried out, water spray systems normally use a water flow rate of 10 to 12.5 mm/min, while water mist systems normally use a water flow rate of 1 to 4 mm/min. The ratio of the water flow rates used in these two systems is in a range of 3 to 4. However, these values of water flow rate are mainly applied from fire suppression in residence and industrial buildings. The main mechanisms of fire suppression using these two types of systems are different. A deluge water spray system suppresses a fire mainly by fuel surface cooling; a water mist system suppresses a fire mainly by dilution and gas cooling. Compared to normal building fires, the fuel load density for a HGV tunnel fire is much higher. Further, ventilation reduces the dilution effect significantly. Therefore, in suppression of fires in tunnels with longitudinal ventilation, the systems with low water flow rates and small droplets, which extinguish fire mainly by dilution, cannot perform as well as in building fires in a quiescent environment. Further, in most of these tests, the fires were neither extinguished nor suppressed, and instead were only controlled, especially for the water mist systems tested. There have been some popular arguments that fire suppression systems cannot suppress tunnel fires, but only mitigate the fire effect. However, we can only conclude that most of the systems tested cannot successfully suppress or extinguish the tunnel fires. This is mainly due to the low water flow rate, especially for the water mist systems. In other words, in order to successfully suppress tunnel fires, the performance of fire suppression systems needs to be improved. There are also arguments that the performance of a water mist system is better than a water spray system. However, under the water flow rates tested, the performance of the water sprays systems appears to be better than the water mist systems in suppression of the fire development for solid fuels, e.g. [83]. Further, it should always be kept in mind that the water spray systems and water mist systems discussed here use significantly different water flow rates. Therefore, it is apparently not fair to make the comparison so simply.

The use of fire suppression systems in a tunnel is always a cost-effectiveness issue. The capability of fire suppression systems needs to be improved to effectively suppress the fires, rather than only control the fires. However, the cost will definitely increase. Research on the minimum capacity to suppress the fire is of special interest from an economic point of view.

**FIRE CHARACTERISTICS**

**Flame length**

Relatively large fires are needed in order for flames to extend along a tunnel ceiling. This corresponds to HRRs that are usually over 20 MWs for most tunnels [1]. Due to the confined tunnel space, the ceiling flame length is normally longer than that in an open fire or a room fire. This horizontal extension results in higher risk for fire spread to the neighbouring vehicles. Limited research has been carried out on the flame length in tunnel fires, with the focus on downstream flame lengths. Rew and Deaves [84] presented a correlation, which included HRR and longitudinal velocity but not the tunnel width or height. They defined the horizontal flame length, $L_f$, as the distance of the 600 ºC contour from the centre of the HGV or the pool, or from the rear of the HGV. However, no geometrical parameter has been taken into account, which makes it impossible to predict the flame length for other tunnels due to different geometries of tunnel and fire source. Ingason and Li [32] analysed their test data and proposed a simple correlation for the downstream flame length under high ventilation conditions. Li and Ingason [85] further carried out theoretical and experimental study of the flame lengths in tunnels under different ventilation conditions, and found that when the dimensionless ventilation velocity, $u^*$, is less than 0.3, flames exist both upstream and downstream of the fire. At larger velocities there are only downstream flame lengths. The flame length increases linearly with the HRR, but decreases with the increasing tunnel width and tunnel height. The downstream flame length is insensitive to the ventilation velocity, while the total flame length, i.e. sum of upstream and downstream flame length, can be as long as twice the downstream flame length. Correlations for downstream, upstream and total flame lengths in tunnel fires are proposed [85].
Fire spread

Fire spread is one of the most important processes during fires in tunnels, and it determines the duration of a fire and the possibilities for the fire and rescue services to fight the fire [1]. As pointed out previously, the total heat release rate would be much higher than a single vehicle fire. Rew and Deaves [84] identified five different types of mechanisms for fire spread between wagons in a rail tunnel, i.e. flame impingement, flame spread, remote ignition, fuel transfer and explosion. If the vehicles are very close to each other or the initial fire size become very large, the flame may directly impinge on and ignite the neighboring vehicle, while the remote ignition or ignition by radiation could be more common. Newman and Tewarson [86] argued that in duct flow the material at a location will ignite when the average temperature has obtained a critical ignition temperature. Beard [87] developed a non-linear model called FIRE-SPRINT to predict fire spread in tunnels and assumed that a sudden increase in temperature of the gas volume (thermal instability) will result in a fire spread. Lönnermark and Ingason [88] tested and investigated the fire spread in full scale tunnel fires and the results show that an average temperature of approximately 500 °C seems to give the best correlation with fire spread. However, the data are rather limited. All the above work is based on the assumption of one-dimensional flow, however generally there is a strong stratification in the vicinity of the fire where the fire spread potentially occurs. Furthermore, the assumption of one-dimensional flow is completely invalid under low ventilation. Ingason and Li [33] found that fire spread to a neighboring wood crib occurs when the ceiling gas temperature above the wood crib rises to about 600 °C. However, the materials may also be a key parameter in fire spread and different materials perform very differently while exposed to the flame radiation. Li and Ingason [85] carried out a series of model scale tunnel fire tests and obtained hundreds of data points to identify the criterion of fire spread to wood and plastic samples and they concluded that fire spread occurred when the incident radiation heat flux is greater than approximately 20 kW/m² and the net heat flux on the fuel surface at the ignition state was found to be a positive value.

Gas temperature distribution

There have been numerous researches on longitudinal temperature distribution along the tunnel, mostly for rather small fires. For example, Ingason [89] presented an exponential correlation to estimate the average downstream temperature. Hu et al. [90] carried out large scale pool fire tests to study the longitudinal temperature distribution and found that distribution of the dimensionless excess ceiling temperature fell into good exponential decay. Ingason and Li [32] found that a dimensionless distance has to be introduced to correlate the test data, and they correlated the dimensionless temperature with the dimensionless distance using sum of two exponential functions. Further, they found that there is a virtual origin for large fires, that is, the gas temperatures between the fire source center and the virtual origin decrease very slowly. They postulated that this is due to the fact that the continuous flame continually introduces a large amount of heat into the smoke flow although the smoke flow releases heat along the tunnel. Li and Ingason [85] further proposed a correlation to estimate the distance between the virtual origin and the fire source. Li et al. [91] proposed an interesting model to express the distribution of ceiling temperature along the tunnel. They assumed that the lumped heat transfer coefficient equals the convective heat transfer coefficient and introduced the Stanton number in the model, but this could be valid only for low temperatures and small fires. Li and Ingason [85] discussed this issue in detail in their work and pointed out that the lumped heat transfer coefficient is not constant along the tunnel. Instead, it should be greater close to the fire but less far away from the fire. Similarly it should be greater at the early stage of the fire and less as time goes on. There are also some researches on the transverse temperature distribution, i.e. temperature distribution between the fire source and tunnel walls. For example, Fan et al. [92] carried out small scale tests to study this and also compared the transverse and longitudinal temperature distribution.

Smoke stratification

Due to the buoyancy forces, the hot smoke flows upwards and occupies the upper region of a tunnel cross-section. Therefore a clear stratification may exist in some cases. But smoke stratification is not only dependent on the buoyancy forces created by the fire but also the longitudinal ventilation velocity. In general, buoyancy force tends to maintain the smoke stratification while the inertia force tends to destroy the smoke stratification. A global Richardson number can be used to describe the
balance between these two forces [1]. Newman [93] has shown for duct fires that there is a correlation between the local temperature stratification and the local mass concentration of chemical compounds. Newman [93] used a specific Froude number, Fr, to distinguish three distinct regions of smoke stratification, and identified the distinction point as Fr=0.9 and Fr=10. Newman [93] also proposed correlations for estimation of temperatures in each region. Nyman and Ingason [94] investigated Newman’s temperature correlations [93] based on a large amount of data from small scale and large scale tunnel fire tests. It was concluded that Newman’s equation [93] for ceiling temperatures in Region II did not fit the large scale data and a new equation was proposed for estimation of the temperature difference between the ceiling and floor. Based on this finding, Ingason et al. [1] found that the value of the Froude number at the Region II - III interface should be 3.2 instead of 10. Therefore, they concluded that the first region (Region I) corresponds to Fr ≤ 0.9, results in severe stratification. Region II corresponds to 0.9 ≤ Fr ≤ 3.2 where strong interaction between imposed horizontal flow and buoyancy forces exists. Region III corresponds to Fr>3.2 where smoke stratification is insignificant. It was recommended that for practical use, the calculated Froude number should be less than 0.9 to ensure severe stratification.

CONCLUDING REMARKS AND FUTURE TRENDS

For well ventilated tunnels fires with vehicle carriages, the influence of tunnel ventilation and structure on the maximum HRR is expected to be insignificant. In most cases, the influence of tunnel ventilation on fire development is also insignificant, but it can have some influence if availability of vehicle openings (e.g. windows, doors or fallen roofs) forms a longitudinal flow inside the carriage which can stimulate the fire spread. For exposed solid fuels (e.g. open truck loads) in a tunnel fire, the maximum HRR could slightly increase (e.g. by around 25 %) compared to that in the open, but the fire growth rate increases approximately linearly with the tunnel ventilation velocity. If fire spread to other vehicles or vehicle carriages occurs, the total HRR depends on how fast the fire spread occurs and how many fuels can sustain burning simultaneously. In such cases, higher tunnel ventilation indicates more vehicles or vehicle carriages may be involved in burning simultaneously, i.e. a higher HRR. This, however, is not the commonly assumed case.

Concerning spilled liquid fires in tunnels, rather limited researches have been carried out. For well ventilated fires with deep liquid pools, influence of ventilation and tunnel structure on burning of pool fires is not very significant for large scale pools, but very significant for small pools. The burning of pool fires is highly dependent on the scales of the pool pans. Therefore the findings from small scale pool fire tests cannot be directly extrapolated to large scales. Further researches are necessary.

Smoke control in longitudinally ventilated tunnels has attracted much attention and much knowledge has gained on the two key parameters, i.e. critical velocity and backlayering length. There are also some researches on smoke control in cross passage and in rescue station but lack of full scale test data.

Interest in use of water-based fire suppression systems in tunnels has increased. A deluge water spray system suppresses a fire mainly by fuel surface cooling, while a water mist system suppresses a fire mainly by dilution and gas cooling. In tunnels with longitudinal ventilation, the water mist systems are not expected to perform as well as in building fires in a quiescent environment. The design values for water flow rate presently used are relatively small. The capability of fire suppression systems needs to be improved to effectively suppress the fires, rather than only control the fires. Research on the minimum or optimum capacity to suppress the fire is of special interest from an economic point of view.

There are still huge gaps in knowledge on fire characteristics inside tunnels. Most researches focus on maximum ceiling gas temperatures and ceiling temperature distribution, mostly for rather small fires and low temperatures by use of model scale testing. More efforts need to be put on other fire characteristics including flame length, smoke stratification and etc.
Nowadays, the use of alternative fuel vehicles such as electric battery vehicles has been widely spread worldwide. Special attention should be paid to the fire and explosion safety of such vehicles, especially when they are running in urban underground tunnels with heavy traffics.

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Risk Evaluation and Risk Control in Road Overbuilding of Transport Routes for Dangerous Goods

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ABSTRACT: Overbuilding, i.e. capping or decking, of roads assigned for the transportation of dangerous goods in major cities is being considered more often in Sweden. This type of facility introduces a number of risks and challenges related to rare events, such as dangerous goods accidents in tunnels, with a potential to cause substantial damage, e.g. collapse of buildings on the over site development. Many argue that the major problem associated with risk evaluation of such risks is the lack of commonly agreed acceptance criteria and regulations. Approaching the problem from a scientific perspective suggests that the root cause of this problem has not been adequately identified. However, there are strong indications that it is because the nature of the risk is not adequately addressed in risk analysis. In this study, we have structured the problem and propose ways of making progress in the evaluation of risk exposure and risk control. It is concluded that several challenges are inherent in the risk management of decking over routes for the transport of dangerous goods, and that these must be addressed in order to be able to control the risk. One of the complicating factors is that it is practically and economically impossible to construct the overbuilding so that it can withstand the maximum permissible explosion load. The main conclusions of this study are that overbuilding of dangerous goods routes has the potential to lead to catastrophic events, that the transport of dangerous goods in the future is associated with considerable intrinsic uncertainties, and that the possibility of supervising and controlling the transport of goods is limited once the route is in use.

KEYWORDS: capping, overbuilding, dangerous goods, tunnels, categorization, risk management

INTRODUCTION
Dangerous goods are not only encountered in industry, but in other activities, for instance, at petrol stations, sewage treatment works, construction sites and hospitals. It is necessary to transport dangerous goods to and from these facilities by road or by rail, inducing risks to the environment and to health and safety. For society to accept the transport of such goods, it is important that the public is not exposed to unnecessary or unacceptable risks. The transport of dangerous goods is therefore governed by extensive regulations [1], and a requirement that potential risks are considered in the planning of roads and developments [2] [3] [4]. In order to balance the need for transportation of dangerous goods with safety aspects in land use planning, dedicated routes are recommended for the transportation of dangerous goods. Land suitable for development is becoming limited, which means that areas previously not deemed suitable for development due to noise, emissions and other risks associated with heavy traffic, are now being reconsidered. One way of increasing the amount of land is through over site development, e.g. by decking over existing road or rail infrastructure.

Interest in overbuilding has increased considerably in large cities in Sweden in the past decade [5] [6], as it is believed to have several advantages within the framework of sustainable city development, such as increased accessibility, increased traffic safety for pedestrians, reduced noise and a general improvement in the urban environment [7]. The principle is illustrated in Figure 1. However, the main driver is commercial, in that it enables densification of urban environments and development of central areas, which is often necessary for financing these major projects. Bearing in mind that there is a housing shortage in many Swedish towns and cities, the possibility of developing new areas is of high interest to local authorities, developers and, not least, those who need somewhere to live. Housing is high up on the Swedish Government’s agenda. For example, the City Planning Division in Stockholm
is assigned to conduct a survey of places suitable for overbuilding in order to provide new opportunities for development [8].

However, overbuilding is associated with several challenges; for example, the cost of laying foundations and the CO₂ footprint are much higher than in other types of construction. Furthermore, a number of safety issues must be addressed. Complicated and extensive agreements are also required between several parties for the financing and execution of the project.

Overbuilding is not necessarily regarded as a sustainable practice in urban development. It depends on the perspective from which the project is analysed. However, it is clear that it has the potential to play an important part in sustainable urban development.

One consequence of these challenges is that the presumptions on which the planning of an overbuilding project is based are uncertain. There is a risk that it will not be possible to assess the feasibility of the project, or the suppositions on which the business case is based until a relatively late stage in the planning process. This poses a threat to the whole project as the uncertainties in the return on investments are too great.

One of the greatest project risks in decking over roads has been found to be the issue of safety when the route is used for the transport of dangerous goods. Uncertainty concerning risk evaluation and risk control is a major factor, i.e. how we can ensure that an acceptable level of safety is achieved and maintained over time. The uncertainty is, in fact, so tangible that it may cause a major threat to the feasibility of projects, despite the societal benefits it offers in terms of urban development.

AIMS AND OBJECTIVES
The aim of this study was to apply scientific principles to investigate the conditions for, and to provide recommendations on, the risk evaluation of overbuilding of routes intended for the transportation of dangerous goods, with the ultimate aim of making risk control possible. The intention is that this study will allow planning to be conducted in a transparent and credible way in the early stages of the project, in order to reduce the project risk, and to improve its feasibility. The following approach was adopted for the study:

- Identification of critical aspects of the nature of risk and risk control associated with overbuilding.
- Development of recommendations regarding the information used to inform decisions makers regarding risks.
- Clarify the conditions for risk management to ensure risk control over time.

BACKGROUND
This section presents a short background on the underlying reasons why the question of safety in the present case is perceived as being so complex that it poses a threat to the feasibility of overbuilding projects. Overbuilding of roads is perceived as problematic by both developers and supervisory authorities, i.e. authorities having jurisdiction. The planning process takes time, and delays resolving the safety issues are common; there is often a lack of transparency, and the level of predictability is low. The way in which authorities deal with the question of safety is sometimes perceived as being arbitrary, which affects the credibility of the planning process and the supervisory authority (AHJ). This is
completely contrary to the objectives of the planning and construction processes. The uncertainties in the planning process are highly undesirable from the perspective of the project management and the investors. Examples of these uncertainties are the floor-space index, constructability, the cost, the involvement of the authorities, and final approval.

The problems identified in dealing with safety issues in overbuilding projects from a number of previous projects and in studies of the current knowledge base commissioned by national and regional authorities [6] [7] can be broadly summarised as follows: unclear regulations, the lack of a clearly defined acceptable level of risk, indecision on the part of authorities regarding design values of blast, and the fact that it is not financially reasonable to design for scenarios with very low probabilities. None of the above challenges are unique to overbuilding, but they apply in principle to all kinds of risk management. Unfortunately, little progress has been made in this area during the past decades and little or no research initiatives have been taken. We therefore deemed it necessary to investigate the problems more deeply, and structure them, before attempts were made to provide solutions.

Experiences of overbuilding in Europe are limited. According to one of few inventories [9], it appears that overbuilding has only been carried out along routes where the transport of dangerous goods with the potential to affect overlying constructions is not permitted. This simplifies the problem of risk management considerably. In several regions and countries, for example, in many states in the USA, the transport of dangerous goods through highway tunnels close to urban areas is restricted or forbidden. Overbuilding of long road routes on which dangerous goods are transported is a relatively new concept in Sweden. Little empirical data are therefore available regarding both the project as such and accidents. Worth noting is that in Sweden, at least in the area of Stockholm, seems to be less restrictive of these types of overbuilds compared to other countries.

MAJOR RISK-RELATED PROBLEMS
In order to structure the problems and suggest solutions, the risk analytical context in question, which affects both the actual risk and risk management, is described briefly below, based on a literature study and the author’s experiences from previous projects.

Many parties and a high level of complexity
Risk management in cases of overbuilding is complicated in many respects as several parties are involved, and the abilities, costs and risks associated with each party are affected by the way in which the risk management strategy for the project is resolved. Any project is dependent on several planning processes simultaneously, mainly road planning and physical planning. Knowledge is limited regarding the problems concerning safety and which measures are required to solve or mitigate them. As the incentives, responsibilities and abilities regarding risk management vary among the parties involved, there is a need for coordinated measures and collaborative solutions in order to carry out the project. In the case of several public authorities, this may mean a change in role from being a supervisory authority, to becoming an active partner who is required to facilitate the realisation of the project. The greater the number of the parties involved, the greater the complexity of the planning process. Examples of authorities often involved in such projects are various committees in local authorities, e.g. for traffic planning, town planning and development, the emergency services, as well as national and regional authorities such as the Swedish Transport Agency, the Swedish Transport Administration and the relevant County Administrative Board [6]. The need for supervision, approval and consultation is large.

Geographical demarcation
Problems may arise if the risk mitigation strategy at a specific place, for a given detailed development plan, requires measures to be taken outside the physical area covered by the plan. Such measures may mean that the effects of the risk are moved to other locations, for example, the rerouting of traffic. It is very difficult and complicated, both administratively and practically, if the kind of measure required has not been prepared in advance, e.g. in masterplanning. It may be necessary for different parties at local, regional and national level to reach agreements. In some cases, measures that would provide an
optimal solution from the local perspective may be difficult or impossible to realize in a specific project due to regional or national considerations. Clearly there is also the risk of sub-optimisation if different risk management strategies are applied along the same route, without taking the whole picture into consideration.

**Conflicts of interest between transportation authorities and developers**

There are basic conflicts of interests between the needs and objectives of infrastructure managers (roads and/or tunnels) and the local authority in charge of development, or another local party such as a developer, wishing to develop the land over or adjacent to the transportation route. The infrastructure manager will want to avoid restrictions on the type and amount of dangerous goods that can be transported, while the land owner will want to avoid development restrictions in order to maximize the exploitation potential. A crucial factor in overbuilding projects is how this conflict of interests is dealt with in the development and application of risk-reducing measures. If no restrictions are placed on the dangerous goods or land use, there is an evident risk that this will result in a lack of risk control. This may give rise to a critical uncertainty as we do not know what kind and frequency of dangerous goods transport will be necessary in the future. Depending on the tolerance deemed necessary, the prerequisites for the design and use of the overbuilding are can be significantly impacted and therefore compromise the project business case. Overestimating the requirements for future transport of dangerous goods will lead to an unnecessarily expensive construction, or underuse of the facilities, for example, if the number of apartments built is restricted. On the other hand, if the future needs for dangerous goods transports are underestimated, then the level of risk will be higher than deemed acceptable by society, or it may be necessary to repurpose the over site development, which can be cumbersome and rarely done. It is possible to predict the needs of dangerous goods transport a few years hence, but this kind of development is expected to have a technical lifetime of 100-150 years.

**Uncertainties may lead to future surprises**

If decisions are rushed, and inadequate solutions are implemented, or if conditions change in unpredicted ways, can cause problems. The development is expected to be in use for many years, and there is little scope for changing the nature of the risk or the risk mitigating strategy after the development has been completed, and then only by a small number of parties. Unfortunately, the acceptable level of risk may be exceeded without our being aware of it, as there is no regular control or supervision of the amount of dangerous goods transported. This means we will have constructed a potential “black swan”, at least for some stakeholder. This phenomenon has been the subject of discussion in risk research in recent years (for further details see [10]). In the present context, a black swan is a surprising extreme event relative to one’s knowledge/beliefs. These can be classified into three different types: a) unknown unknowns, b) unknown knowns (we do not have the knowledge but others do), and c) events that are judged to have a negligible probability of occurrence and are thus assumed not to occur. All three types may arise in the present type of development.

A black swan is the kind of risk that, in most contexts, we want to avoid, or protect ourselves against, but which is perceived as being difficult. As this kind of risk is difficult to imagine before it happens, it is difficult to prepare for it or deal with it. Research in risk in many areas involves developing strategies to identify black swans, and methods of managing this kind of risk. Therefore, when creating overbuildings, we run the risk of creating black swans for future generations, by inadequate risk management. This is controversial and hard to align to sustainable development if not dealt with.

**ANALYSIS OF THE NATURE OF THE RISK**

To provide a more detailed picture of the nature of the risk related to transport of dangerous goods and overbuildings and the requirements for risk evaluation, a number of important factors are analysed, based on an inventory and study of recent research and experience in other areas.

**Risk exposure above the overbuilding**

People in the vicinity, or on top, of the overbuilding covering a transport route for dangerous goods can be exposed to risk from an accident inside or outside the tunnel, mainly at the tunnel portals. Peo-
People near ventilation openings, including tunnel ventilation shafts, may also be exposed following accidents in the tunnel. Both these types of risk exposure have been relatively well investigated and proven measures are available.

The kind of risk that gives rise to the greatest problems in risk assessment and control is the transport of goods that could result in explosions. One of the complicating factors is that it is practically and economically impossible to design the overbuilding so that it can withstand the maximum permissible explosion load, i.e. 16 tons. As a result, an accident can lead to an unacceptably high risk in a development where the density of people within the area affected is limited due to effects of progressive collapse. In previous projects (see e.g. [11]), it has been deemed to be technically and economically feasible to design a tunnel with over site development, such that damage in the event of an explosion of 1-2 tons in the tunnel is severe, but the impact to the apartment buildings above is limited. If a development is designed for such blast loads, and an explosion equivalent to 16 tons occurs, it is estimated that the damage to the tunnel will be so severe that the buildings on top would collapse. Guidelines have been developed for the construction of air-raid shelters and similar buildings that can withstand explosions of considerably higher force, but the basic principles for this kind of construction are not compatible with a road tunnel with an overbuild. It is thus not possible to construct the tunnel and the development to withstand this kind of accident with only limited damage. Unfortunately, loads of this size are not uncommon when explosives are transported, even though the frequency of transports can be relatively low [12] [13].

The kinds of goods that can cause such scenarios are explosive materials (ADR Class 1), oxidants and organic peroxides (ADR Class 5). Accidents with combustible gases (ADR Class 2.1) such as LPG and LNG, can lead to gas explosions consisting of a rapid increase in pressure as a result of combustion of the gas/air mixture. Such an explosion usually results in so-called deflagration, i.e. a high-pressure shock front, but lower than that resulting from a detonation. There is a theoretical possibility that a gas explosion in combination with high turbulence could lead to detonation, but this has not yet been observed in a road or rail tunnel. This means that, in practice, it is possible to construct a tunnel able to withstand an explosion involving a Class 2.1 substance.

Although the transport of large amounts of explosive goods can be expected to be limited, an accident in which buildings on top of the overbuilding are affected cannot be ruled out unless transportation is restricted. The probability of such an accident is low, but still possible. The possibility of serious consequences, i.e. resulting in a large number of fatalities, cannot be excluded. The worst case scenario for a single load involves the explosion of 16 tons of material, and it is not practicable to construct the overbuilding so as to prevent damage to buildings on top of it. The extent of the residual risk is determined by the structural consequences, as well as the number of people affected, for a fixed number of transports. This will depend on the extent of the overbuilding and the type of over site development. (For further information on accident scenarios the reader is referred to the extensive study presented in the report for the Northern Link project at Hagastaden in Stockholm [11].)

**Comparison with the open road network**

Extensive damage and injuries can also be expected as the result of an explosion on the open road, but there are a number of important differences between this and an explosion under an overbuilding, which will be discussed below. Firstly, the pressure build-up in a confined space such as a tunnel will be considerably greater than on the open road. The effects on the tunnel and the foundations of the buildings above will thus be much higher. Another important difference is that the probability of an accident resulting in an explosion is higher in a tunnel than on the open road because trucks carrying dangerous goods can affected by a fire in another vehicle in the tunnel, which possibly increases the probability of such an accident.
Presentation of the risk

The effect of an accident in a tunnel on the development above can be simply expressed using F-N curves. This provides information on the spread in probability and the consequences of the various scenarios that together represent the total risk. The method has been thoroughly described in the literature (see e.g. [14] [15]). A common way of expressing and presenting acceptance criteria in such a graph is to use the ALARP (as low as reasonably practical) region. This is not the only way of presenting risks, but it provides a good way of illustrating the risk contributions from the various scenarios considered. The use of the ALARP region to evaluate the risk has both advantages and disadvantages, but it is commonly used to describe most kinds of major hazards. The ALARP region has been determined to be more suitable for evaluating the risk in this particular case than a pure cost-benefit analysis [14].

Figure 2 shows an example of the use of the ALARP region for the evaluation of risk in vicinity of dangerous-goods routes (light full lines). The dashed parts of the light lines are extrapolations to the region where risks are not normally acceptable on only a risk-based evaluation, e.g. due to the catastrophe potential. In case of an accident with explosives, it can not be ruled out that the F/N-curve is close to the grey shaded area due to the magnitude and uncertainty in the probability and the consequences.

Potential for catastrophe

The potential for accidents in tunnels leading to a catastrophe due to fatalities in the surrounding buildings may be much higher than on the open road. The extent of material damage and personal injuries may, therefore, be of such a magnitude that society will not have the capacity to deal with them in terms of emergency services and health care. The potential for catastrophe is strongly dependent on the planned land use and development. Risk evaluation is therefore a central aspect in determining the type of land-use, buildings and floor-space index to be permitted on and around the overbuilding.

The potential for catastrophe in a scale where one can question if such risk is reasonable or not, even if the probability is very low, arises if the following three factors coincide: 1) dangerous goods are transported in the tunnel, 2) the construction cannot be designed to prevent structural damage or fatalities in the buildings above the decking for an explosion involving the maximum permissible load of 16 tons, and 3) the degree of exploitation above the deck is high, leading to the risk of a large number of people being affected by an accident.

Such a catastrophic risk is often characterised by high uncertainty, low probability, and very severe consequences. It is far from clear whether the acceptance criteria for these kinds of risk scenarios can be extrapolated according to the light lines/F-N curves in Figure 2; rather, the opposite. In the criteria developed in several countries, an activity is not permitted if the risk exposure exceeds a certain size, e.g. 1000 fatalities, based solely on quantitative criteria [16] [17]. It is stressed that the decision making must be risk-informed rather than risk-based. In the criteria proposed for the chemical industry in Sweden, which are used in many applications, it is clearly stated that: “No upper limit for the consequences has been proposed as part of the criterion for societal risk”. This kind of issue should be addressed qualitatively [15]. The question remains as to how this should be done. In practice, very little attention is paid to this at the present time.

One of the main threats to overbuilding projects described at the beginning of this paper is illustrated by the bold dashed line in Figure 2, i.e., a risk scenario with very low probability but very severe consequences. Another situation that can cause a similar threat is if the risk analysis results in a risk pro-
file represented by the bold line in Figure 2, but uncertainties are present that can shift the risk profile towards the bold dashed line. The representation of the risk profile by the lines is highly dependent on the assumptions and limitations applied in the underlying risk analysis. Examples of these are whether explosive materials are transported along a certain route, or if only limited quantities are transported, for which the tunnel and over site development is designed. The development above the decking can also be restricted so that the number of people that can be affected at the same time is limited. In such cases, there is a good possibility that the residual risk will not exceed what is considered to be acceptable. The dilemma arises when the size of the design blast load is derived from the size of the cargo load and number of transports based on current conditions, and there are no restrictions on future loads. If the maximum permitted load and/or frequency should increase in the future, then the risk would extend into the region indicated by the grey cloud.

The extent of the risk
One of the questions that arises is whether the level of the acceptable risk is correct. Shouldn’t the benefit to society allow a higher level of risk than that applied in other kinds of exploitation? A brief assessment of the risk profiles arising from substances that can cause an explosion (mainly ADR Class 1 and Class 5) shows that the average risk in terms of expected fatalities per year is very low, far below the average risk from other hazards not exceeding the acceptance criterion. This means that the problem does not lie in the fact that the proposed development would lead to a higher number of expected fatalities per year than in others kinds of developments. The individual risk does not pose any problem either, as the probability of this kind of accident is generally very low. Based on experience from a number of projects, it is deemed very probable that for most of the buildings above the decking, the individual risk without any protective measures will be lower than that accepted in other contexts, e.g. exploitation within 100 m of a railway or housing estates near airports. The problem, as mentioned above, is the severity of the consequences associated with a very serious accident.

This means that the problems associated with project planning and risk management would not be alleviated to any appreciable degree by increasing the acceptable risk level. This would not lead to the acceptance of a facility with a risk profile that borders on the grey shaded area in Figure 2. To achieve such an alleviation it would instead be necessary to increase the acceptance of catastrophes – not unlike the kind caused by the tsunami in Fukushima in Japan in 2011. This would mean the deliberate construction of a facility with the potential for a catastrophe of such dimensions, for future generations. The effects of the tsunami in Fukushima have been discussed in the scientific literature from many perspectives. It has been questioned why the protective walls were not dimensioned so as to offer protection against the highest previous tsunamis in the area, rather than being satisfied that the height chosen was adequate according to design praxis [18]. The same applies to overbuildings and how much foresight we need to have is unclear.

Large uncertainties
For obvious reasons, few empirical data are available on the effects of explosions in tunnels in the urban environment. There are considerable uncertainties in the estimation of the probability and the extent of the consequences. However, the physical effects, in terms of pressure, temperature and vibrations, are relatively well known, and both simple and more complex models are available to study the phenomena. Despite the fact that these models are based on simplifications and assumptions, they provide useful information for the assessment of the extent and severity of such accidents. It could be argued that the tools are still too crude, but in general, they are quite well developed, and this particular kind of accident is not exceptionally problematic compared to other decision-making situations associated with risk management. The uncertainties involved are considerably lower, for example, than in the assessment of the effects of solar storms on IT infrastructure, or the spread of pandemics in society. However, it is important to understand there are uncertainties, and that attention is drawn to them so that decision makers are made aware of them. A number of sources of uncertainty have already been mentioned above, but a summary is given below of the parameters associated with uncertainty that will affect the probability of an accident of the kind considered here;

- Transportation and future traffic developments
• Transportation patterns (which are affected by developments of the road network and possible future restrictions)
• Regulations governing transportation, market conditions and authorisation for the production and use of substances that can cause explosion
• Political decisions the affect the proportion of traffic on roads and on railways
• Cargo capacity, i.e. increased allowances in cargo capacity
• Economic conditions that affect distribution patterns including transportation costs
• The location of production plants and distribution centres for explosive goods
• The number of purchasers/users of explosive goods
• The state of the economy (the transport of goods is strongly correlated to the GNP)
• Security risks and antagonistic threats
• The enforcement and compliance of restrictions

Even if we have some idea of how goods are transported today, conditions will change with time in a way that we cannot predict or control. This means that the uncertainty associated with future transportation patterns and size and frequency is high. This constitutes an intrinsic uncertainty that affects not only the nature of the risk, but also our ability to evaluate it. The only way to reduce this uncertainty is to ensure that the residual risk is not exceeded, even when the maximum amount of explosives is transported. This amount of goods can be reduced by tunnel restrictions so that it is possible to reduce the risk by designing the tunnel construction to withstand an explosion.

Uncertainties, and the way in which they have been considered, as well as the consequences of not taking them into account, thus constitute an important component in the information on which decisions regarding risk are based.

Low probabilities
It is sometimes argued that when the probability of a certain kind of accident is extremely low, it can be disregarded. But on what basis can we define a negligible probability or risk in relation to a particular scenario? We need to be careful about ignoring scenarios on the basis of isolated risk and probability assessments, as even very unlikely events may occur [19].

Explosions are rare in the transport sector, but there are examples of serious accidents (see, e.g. [20]). One such accident occurred at an open-cast mine in Norway in 2016, when a truck carrying 16 tons of explosives exploded on the surface road. The driver was miraculously uninjured. Other examples can be found in the literature [21] [22]. If an increasing number of urban tunnels are constructed, each with a negligibly low probability of an accident, the overall probability of an explosion in such a tunnel will steadily increase. Serious industrial accidents are characterised by a series of unfortunate circumstances, where the probability of a single event may be very low. According to Perrow (and Aristotle), “It is probable that the improbable will happen” [23]. One can, therefore, not simply ignore the potential for such accidents merely because their probability is low. From the point of view of decision-making theory, the weight that decision makers place on fear and uncertainty, and the weight afforded serious consequences in relation to minor consequences, will be decisive in risk evaluation. The monetary value placed on human life will ultimately determine which measures are deemed necessary to reduce the risk to an acceptable level.

DEALING WITH THE PROBLEM OF RISK CONTROL
Maybe a little bit contradictory, decking and overbuilding is generally an effective risk-reducing barrier, e.g. for existing buildings near the tunnel. However, problems arise when dangerous goods are transported through the tunnel, combined with a high density of people in the vicinity. Analysis of the nature of the risk also shows that in such situations: risks that are not dealt with can lead to a catastrophe, albeit with a low probability; that the uncertainties associated with the risk are high; and that implementing risk-reducing measures that allow risk control is complicated. Recommendations can be developed by comparison with other so-called major hazard industries (e.g. nuclear power, chemical,
dams in power industry, etc.) and a survey of recent research into risk analysis in this area.

**Strategies for risk management**

The problems and frustration experienced in real projects seem to be due to the belief that it should be possible to solve problems by so-called risk-based decision making. A quantitative risk assessment produces values expressed as probabilities and expected values that are compared to acceptance criteria. Such a risk management strategy is suitable in cases where there is sound knowledge and the uncertainties are small, which is not the case with overbuildings, mainly regarding future transports and severe damage. This appears to be a fundamental reason why no progress is being made in practical projects in this area. A growing number of researchers and analysts have found probability-based approaches to understanding risk to be too narrow [24]. The main reasons are:

1. assumptions can conceal important aspects of risk and uncertainties,
2. the probabilities can be the same, but the knowledge on which they are based may vary,
3. the approaches are often based on historical data,
4. surprises occur (black swans),
5. there is too much reliance on probability models and frequentist probabilities, and
6. probability is just one of many tools that can be used to describe uncertainties.

In other words, uncertainties are not properly reflected when using this risk assessment procedure. Uncertainty assessments extending beyond probabilities and expected values are necessary in making informed decisions on the acceptability or tolerability of risks [25]. Since technical risk analyses represent a narrow framework, they should not be the sole criterion used for decision making regarding risk [26]. Thus, different foundations are required in decision making for the management of catastrophic risks that complement traditional decision analysis and expected utility theory [27].

The strength of the knowledge on which the probability assessments are based is not reflected in the probabilities used in comparisons with acceptable levels [28]. The crucial question here is what degree of uncertainty and ignorance the main stakeholders and public interest groups are willing to accept or tolerate in exchange for a potential benefit. The use of such criteria can easily lead to the wrong focus, namely meeting the criteria, rather than finding the best possible solutions and measures, taking into account the limitations of the analysis, uncertainties not being reflected by the analysis, and other concerns important in the decision-making process.

As a reaction to risk-based decision making, various risk management strategies or approaches have been developed with emphasis on different complimentary aspects. Research initiatives highlight three approaches that are commonly used to manage risk: risk-informed, cautionary/precautionary, and discursive strategies [26] [29] [30]. Emphasis is put on arriving at a suitable risk management strategy by combining three pillars according to the nature of the risk:

1. The use of risk assessment.
2. Robustness, resilience and cautionary principles.
3. Building trust and participation in the decision-making process.

In order to achieve this it is necessary to balance the risk-informed, cautionary/precautionary (robustness, resilience, adaptive) and discourse-based approaches. This is the general approach and is fundamental for risk management. The results of quantitative risk analyses must be considered in relation to the assumptions made and the knowledge on which the analyses are based [10]. The dimension uncertainty, knowledge and surprise in risk analysis must be adequately reflected, but this has not been addressed until recently.

A risk assessment could provide useful decision-making support, although emphasis must also be placed on the uncertainties. According to the literature (e.g. [31] [32]), the precautionary principle reflects the idea that if the consequences of an activity could be serious and are subject to scientific uncertainties, then precautionary measures should be taken. In extreme cases, the whole activity should be forbidden or terminated. So the critical criteria used to establish whether the precautionary principle should be applicable in the present case is both the possibility of catastrophic outcomes and
the existence of scientific uncertainties. It is stated in the literature that the ALARP region is in line with this concept, i.e. cautionary approach, but that traditional cost-benefit analysis (CBA) and the expected value are inadequate [28].

The so-called precautionary-based strategy is suitable, when scientific uncertainty is so significant that precautionary or adaptive measures are required. In other cases additional risk reduction measures are sufficient. A detailed risk assessment providing predictions and characterization of the uncertainties can provide input for such a judgement of suitable strategy. The more uncertain the consequences are, the more decision makers are driven to apply the precautionary principle even if the expected value for each risk dimension is rather low [25]. The above reasoning can be exemplified by the decision of the County Administrative Board of Stockholm to apply restrictions on the transport of dangerous goods that could lead to serious explosions along parts of the Northern Link tunnel in Stockholm [33].

The management of uncertainties
Two important conclusions can be drawn from the survey of recent research that differentiate the suggested approach from the traditional risk-based approach. The first is that the uncertainties themselves are an important part of the information on which decisions are based, and affect the decisions made. The other is that part of the risk management strategy involves taking measures to reduce the uncertainties. It is acknowledged that risk analysis as a tool has limitations and robust approaches are required to deal adequately with uncertainties. The PSA-N nuclear regulations state, for example: If there is insufficient knowledge concerning the effects that the use of technical, operational or organisational solutions can have on health, safety or the environment, solutions that will reduce this uncertainty shall be chosen [28]. This strongly indicates that efforts must be made to reduce uncertainty, and not only the risk. In the same manner, measures must be taken to increase knowledge, without necessarily reducing the risk.

Assumptions
Several risk analysis researchers have highlighted the need to consider the results of risk assessments in the light of the assumptions made [34] [35]. Another important aspect closely linked to the strength of the knowledge available is the underlying assumption applied in the analysis. Aven proposes the following framework [36]. First, the assumptions must be identified and listed. This task in itself is challenging. The next task is to perform a qualitative risk assessment of these assumptions, highlighting and presenting deviations from these statements (assumptions), the implications of such deviations, judgements of the probabilities and the strength of the related knowledge. Attention should also be paid to questions such as: “Do we understand the phenomena involved?”, “Do we have evidence supporting our judgements?” and “Have our beliefs been checked by others?”.

The first stage of the analysis should include the following elements in particular: (a) a qualitative assessment of the information value of the metrics in relation to informing the decision maker about risk; (b) a qualitative assessment of the risk related to deviations from the assumptions made (this assessment covers deviations and the effects of these deviations, probability judgments, and strength of knowledge judgements (see c); and (c) a qualitative assessment of the strength of the knowledge.

The strength of the knowledge
The need to link risk with knowledge is also highlighted. This is a relatively new concept, but has nonetheless been investigated by, for example, Aven [24]. Risk descriptions are not objective, but are developed based on data, information and justified beliefs. This basis is analyst dependent, so even if the information on which it is based is the same, this will not necessarily lead to the same risk descriptions by two different analysts. There is no way of ensuring that two assessors having the same background knowledge would assign the same probabilities [15]. Hence there is no alternative that allows for some type of process that can see beyond the quantitative results of a risk analysis. The values obtained provide information for the decision maker, but do not prescribe what to do.
One way of making use of knowledge is to divide it roughly into strong and weak knowledge, and report these separately so that decision makers can take this into account. The dimension of knowledge, at least, should be taken into account in the choice of measures. For example, if knowledge is limited, the decision could be made to acquire better knowledge before any decision is made. Various ways of doing this have been reported, e.g. by Aven, who presents a crude method of incorporating the strength of knowledge in decision making using the ALARP principle [37], which can be regarded as a relatively straightforward tool that can be applied in practice.

**Surprises**

Another concern is the common use of probabilities. Although the aim of a probability is to express the uncertainty or variation in relation to future situations, it is often used simply as a function of historical empirical data. Thus, important aspects of change and potential surprise are not taken into account. Furthermore, if the probability of a certain event is calculated from a finite amount of existing data, this may have little value in predicting the probability of a future event. A checklist is provided by Bjerga and Aven [13], highlighting potential surprises relative to the analysts’ knowledge to provide a good starting point for the decision maker to analyse the situation in question.

1. The possibility of unknown knowns. Have special measures been implemented to check for this type of event (for example, an independent review of the analysis)?
2. The possibility of events being disregarded due to their very low probabilities, although these probabilities are based on critical assumptions. Have special measures been implemented to check for this type of event (for example, signals and warnings influencing the existing knowledge basis)?
3. Risks related to deviations from the assumptions made.
4. Changes in knowledge over time.

The reason for addressing surprises is to obtain a stronger focus on issues not covered by the traditional risk perspectives, which are based on historical data, probabilities and expected values. At the same time, it is crucial to address known events in the risk analysis whose probability of occurrence is judged negligible, and are thus not believed to occur.

**Nuancing of Risk Control**

The conditions affecting risks can vary considerably, e.g., between high-density through traffic on an urban motorway and local traffic on smaller roads. Knowledge of size and frequency of expected future transport may vary for different kinds of roads at different locations. Examples of this are a secondary road for transport of dangerous goods where the customer does not have a permit for the handling of certain dangerous goods types compared to a dual carriageway used as thoroughfare. Another example is if a primary route intended for the transport of dangerous goods, although it is mainly used by local traffic, and no dangerous goods, or at least explosive goods, are transported and there are no producers or customers for dangerous goods. It is therefore important to address the possibility of the adaptation of protection by using risk analysis approaches specially adapted to the specific situation. Bearing in mind the construction in question, an attempt is made below to nuance risk control in three cases, based on the analysis of the nature of the risk, and the tools available for risk control presented in the previous section. These cases have not been studied in detail, but are intended to illustrate the potential of this approach. The conditions for risk evaluation and the risk management strategy, and thus for risk control, differ in these cases, which are denoted: “off the scale”, “potential black swan” and “low-risk”.

**Case 1: The off the scale case**

This case exemplifies high-density traffic on an urban motorway, classed as a primary route for the transportation of dangerous goods. The stretch of road in question is used by both through traffic and local traffic. The nature of the risk can be influenced by applying risk-reducing factors, as shown by the bold dashed line in Figure 2. Risks can, in general, be reduced by measures that reduce the probability or the consequences of an accident, or a combination of both. Two possible strategies can be identified to evaluate the risk described above: by reducing the consequences to the extent that the
level of risk is inside the boundaries for established risk criteria, or by accepting a low probability of a
catastrophe.

Consequence-reducing measures
From the perspective of traffic safety in tunnels, probability-reducing measures are usually given high
priority. It has been made clear in the European regulations for tunnels (TSD, [38]) that this is a basic
component in the development of safety concepts in tunnels. Examples of measures taken in tunnels
are reducing speed limits, prohibiting overtaking, and installing safety systems such as sprinklers in
combination with a drainage system. Sprinklers significantly reduce the probability that a fire in a
tunnel, for example, in a truck, will spread and involve other vehicles transporting explosives. Despite
the positive effects of sprinklers, they will not solve the problem of risk evaluation in the present case,
as the risk of catastrophe would remain, even if the level of risk were reduced. Consequence-reducing
measures should therefore be considered in addition. The consequences can be reduced by designing
and adapting the tunnel (overbuilding) and the development on top of the tunnel, and by restricting the
kind of traffic allowed in the tunnel. The choice of measures is strongly related to the way in which
conflicts of interest between the infrastructure manager and developers are dealt with.

The design of the tunnel
Risk reduction can be achieved through a combination of measures to increase the resistance of the
structure to the effects of an explosion, e.g. by limiting the effects of a blast through the decking, or
reducing the risk of progressive collapse. This may call for measures to be taken in the construction of
the overbuilding, its foundations, and the overlying buildings.

Traffic
The type of goods transported in the tunnel can be restricted, but his means that it must take other
routes. Restrictions can be designed so that they apply only at certain times of day. For example, only
allowing the transport of certain types of dangerous goods during the night-time, when shops or offic-
es built on the decking are empty. Most dangerous goods can be transported through the tunnel at any
time, even during the day, provided the restrictions are adapted to the design load of the construction
works or vice versa. It may then be necessary to provide a secure base for trucks carrying dangerous
goods in the vicinity of the tunnel.

The use of tunnel restrictions places high demands on a holistic approach, as these measures may have
effects outside the geographical boundaries of the detailed development plan. Risk exposure will be
moved from one location to another. Also, the transportation needs of the producer and consumer
must be met, which may necessitate measures elsewhere. Other ways of influencing traffic and/or the
implementation of restrictions include the provision of new routes, the supply of goods from another
location, or the relocation of businesses. Another important aspect is the enforcement to take place.

During the operation of a tunnel, it is generally necessary to temporarily divert traffic along a route
used for rerouting during renovation etc. This route can sometimes also be considered as an alterna-
tive route if restrictions are applied. In any case, it will be necessary to consider the risk exposure
along the new route, which requires an overall assessment to determine whether it is suitable or not.
Examples of frameworks for such assessments have been presented previously [39]. As the exposure
to risk above the tunnel will be mainly affected by explosions, it is possible to adapt the restrictions so
that they only cover classes of dangerous goods that can result in powerful explosions. It is also worth
pointing out that those restrictions generally only apply to a small proportion of the transports. Such
restrictions on the transport of goods that can cause serious explosions are available according to the
ADR classifications, i.e. if a tunnel categorized as a B-tunnel. From a societal viewpoint the impact
on transport work should have little or no effect, but should be considered in each individual case.

Buildings
The kind of buildings constructed on top of the decking should be determined by the nature of the
risk. Risk reduction measures will affect the type of buildings as limitations will be placed on their
design, type and volume. This may make the building of car parks or shops more suitable than apartments, as the former are generally only occupied during the daytime. The desired effect of measures is to limit the number of people simultaneously exposed to a risk. If a multi-story car park is required in the area, it could be built on top of the decking, as could a recreational area or a local road.

An extreme example of a measure is not to allow any kind of buildings on the decking. Such a measure would naturally affect the potential for development, but land would still be made available close to the tunnel. It should be noted that considerable demands may still be made on the construction to ensure that it can withstand an explosion of a certain force.

Accepting the potential for catastrophe
Another way of dealing with the “off the scale” situation is to consider reducing the probability of an accident as far as is reasonably practicable, and then accepting that there will be a low probability of an extreme event occurring. The knowledge base is often weak, and the probabilities are subjective (judgmental, knowledge-based), and more or less strongly founded. There is no clear correspondence between the probability assignments and the actual occurrence of the events, and it is therefore necessary to scrutinise the judgements concerning acceptable risk and negligible probability, and the background knowledge on which these assessments were based. For this alternative to be possible, important assumptions and uncertainties must be clearly presented in the original analysis.

There are examples of areas where this kind of approach has been applied, mainly in cases of bursting dams and landslides, where the approach has been formalised [16] [40]. For example, the tolerability limit for the maximum number of fatalities (arising from a single event) should be increased from 1000 fatalities to 5000 fatalities (see Figure 3).

Vertical lines are drawn in the F-N graph in Figure 3 at 1000 fatalities and 5000, up to the line, above which the number of fatalities is unacceptable. The region between 1000 and 5000 fatalities is regarded as an “intense scrutiny” region. According to Aven, there is no clear correspondence between the probability assignments and the actual occurrence of the events [10]. Hence, it is appropriate to scrutinise the judgements concerning both the acceptable risk and negligible probability, and the background knowledge supporting these judgements. Therefore, such a scrutiny must be based on the following acknowledgements: that the acceptable risk should not be determined by a judgement of probability alone; that events may occur, even if the probabilities is very low; and that cautionary and precautionary principles constitute essential pillars of the risk management associated with such events. The reason for including an “intense scrutiny” region in the risk guidelines is to provide regulators with the option to permit certain types of developments. Such developments may not necessarily be associated with an unacceptable level of risk, but could be examined with special scrutiny bearing in mind societal needs and additional requirements that reduce the probability further.

As it has been possible to formulate this kind of acceptance criterion in other areas, it is not impossible that this may be applicable to the case of overbuilding, bearing in mind that the benefit of the development to society is very high. However, this would be controversial in Sweden, as we have no
general tradition of this type of application of risk evaluation and no application has been found for overbuildings in any other country. Such an agreement should therefore be carried out using a discourse-based risk management strategy among relevant stakeholders and authorities.

**Case 2: A potential black swan**
This case is exemplified by overbuilding of a stretch of secondary road or a primary route without through traffic or local producers or consumers of explosives. Under such conditions, the uncertainties will be smaller, and knowledge concerning the goods being transported is better, as it will be based on the needs of local producers and consumers. The challenge lies in the uncertainty in how explosive goods will be transported in the future. The nature of the risk and its challenges is characterized in Figure 2. This should be suitable for situations where the risk-based on the planned construction and the predicted transport of dangerous goods does not exceed the acceptance criteria, but where unexpected developments in transportation lead to uncertainties in the judgements, resulting in it being impossible to exclude the potential for catastrophe.

**A robust solution**
One way of achieving risk control is to take the corresponding measures from the “off the scale” case, but this may involve unnecessary limitations and restrictions, or less than optimal exploitation of the opportunities offered by overbuilding, i.e., a waste of public finances. However, this provides a margin for future changes and a robust solution, and is not depending on monitoring or control.

**An adaptive solution**
An adaptive solution should also be possible for the construction in question. In this case, risk management should be directed towards having control over the risk in order to be able to take measures, e.g. restrictions, only when the amount of dangerous goods being transported approaches the limit for an acceptable level of risk. This kind of risk management places demands on dialogue and cooperation, and requires that good knowledge be maintained, for example, by monitoring the amount and type of goods transported and/or taking an active part in the planning and processing of applications that affect the kind of goods transport in question. This means that future planning and processing of applications should be connected to this strategy. Future handling and transport of dangerous goods can be supervised and controlled in connection with the issuing of environmental permits and authorisation for the handling of combustible and explosive goods. Regulations and mechanisms for controlling such goods are available, but are not yet used for this purpose in local planning and authorisation. Methods must be developed to use this knowledge and risk control instrument correctly in the management of the kind of risks discussed here. For example, environmental permit to operate should not be granted for a business if the transport of explosive goods cause negative effects or another location of the business might be necessary to consider in city planning. Some initial thoughts on this are presented in the final report on the project Urbana Stråk in Stockholm [12]. Demands are also placed on techniques for the monitoring of the transport of dangerous goods. Techniques have been developed, but are not in regular use today. It is also necessary to have a “Plan B”, in case future developments are not as expected (i.e. a surprise). One way of ensuring this could be to make provision for a future re-categorisation of the tunnel, if and when necessary, by planning an alternative route and ensuring that the risk exposure along this route could be managed before the route is taken into operation.

**Case 3: The low-risk case**
The third alternative is characterised by stretches of road in urban environments on which no dangerous goods, or at least explosive goods, are transported and will never be. This should be the most common situation in large cities. In such cases, overbuilding will not be a problem, and can be regarded as a risk-reducing measure. This is a completely different case to that described in this paper. Overbuilding of such routes should be considered, in the first place, when the aim is cost-effective solutions with low project risk.
CONCLUSIONS

Overbuilding in urban environments should, in general, not pose problems, notwithstanding the risks for tunnel users. An exception is in rare cases when applied to routes used for the transport of dangerous goods, together with overlying developments in which large numbers of people are simultaneously exposed to risk. In such cases, challenges are unavoidable. Knowledge and the results of research on the management of major hazards and other risks that have been obtained in recent years are not fully exploited when considering overbuilding of dangerous-goods routes. There is thus a considerable potential to make better decisions and reduce the risks associated with future overbuilding projects. This knowledge can also serve as the basis for the development of practical tools.

Knowledge concerning conducting risk analysis and a lack of data appears to not be a serious problem. Neither is it necessary to perform more extensive risk analyses in order to evaluate the risk. If anything, a better, more adapted risk management strategy should be developed for the matter in question. Information on which decisions are based should be improved, for example, by shedding light on the strength of knowledge, uncertainties, surprises and assumptions used in the analysis, to give decision makers a better understanding of the nature of the risk. Furthermore, it was found that concrete measures, other than generic risk-reducing measures, may be necessary to deal with these dimensions, e.g. to increase knowledge and/or reduce uncertainty.

Two critical issues were identified regarding risk evaluation and risk control, which concern two fundamentally different situations. The first issue concerns whether it is justified to accept the risk of an accident with a very low, but finite, probability that may result in a very high number of fatalities (e.g. >1000). The effects of an accident involving the maximum amount of explosive goods that can be transported cannot be adequately reduced by building an explosion-proof construction. It is possible to deal with a relatively high blast load (~2 tons), but not the maximum (16 tons). In order for the risk of a catastrophe to be acceptable, agreement must be reached on suitable criteria for determination of impact significance, i.e. acceptable risk, with the County Administrative Board on the implementation of measures to reduce the probability of such a catastrophe as much as possible. Also, application of protective barriers is necessary to reduce the damage and injuries that could arise from accidents involving most of the transportation of explosive goods. It will still be difficult to determine which, and how many, measures and protective barriers are reasonable. To the best of the author’s knowledge, no such risk has yet been accepted in practice.

If the risk of a catastrophe is not accepted, then the main risk management strategy should be the reduction of the consequences. Examples of this include restrictions on transportation, possibly combined with protective barriers, or that the development on the overbuilding and the area surrounding it is designed such that the risk of serious consequences is acceptable (for example <1000 fatalities). Other technical means of reducing the consequences are possible, but will lead to limitations on the development or the transport of goods, which may be costly and difficult to implement.

The other critical issue is how risk control can be ensured when the transport of explosive goods is not currently envisaged, but cannot be excluded in the future. If the risk evaluation does not take into account possible future transport of such goods, a so-called precautionary approach will be necessary. This requires measures such as measuring and supervision of dangerous-goods transport in order to determine the margins, and whether further measures are necessary. Techniques and means of doing this are available. Attempts have been made to do this in pilot projects, but there are currently no demands for this kind of survey. It may also be necessary to monitor and assess the way in which future development plans and environmental permits affect the need for goods transport. Continued development and testing in this area can help realize developments with cost-effective safety concepts.

The management of both these critical issues will require the cooperation of a number of parties in a way that is not common today. In practice, this means that many challenges will be encountered in the planning and execution of such a development. However, there is no need for further scientific efforts to make this possible, rather deeper cooperation between the public and private sectors, and the expe-
dient application of the knowledge and research results currently available. Sustainable urban development should be based on the realization of developments for which the level of risk can be controlled, despite future changes in use. Such guidance and control is essential.

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ABSTRACT

A continuously growing number of complex infrastructures are being built underground in larger cities around the world. The degree of complexity and the demand for innovative architectural structures and functions often result in a corresponding demand of the emergency services to adopt an equal innovative and tactical intervention behavior and use of specialized equipment.

The result is often a considerable diversion from standard operation procedures (SOP) in the emergency services and implementation of specialized equipment that besides a demand of maintenance and service establishes a need for specialized competences and training of the fire crew, who are expected to be familiar with the equipment. This inflicts a maintenance-operational- and training cost in the emergency services that is a contrast to the continuously demand of savings and optimization of the emergency services.

When designing the extension of the Copenhagen metro, the Metro Cityring, Greater Copenhagen Fire brigade learned how an early involvement of the emergency services and collaboration between the emergency services and all key stakeholders within the project ensured a high level of safety to the metro. This included the fire brigade accepting and adopting specialized equipment and Technical tradeoffs (TTOs).

Besides this Greater Copenhagen Fire brigade experienced the need of ensuring that the implementation of TTO did not transfer parts of the responsibility of the fire strategy/safety level from the facility owner to the emergency services.

This emphasized the need of an sincere and open dialog, clear and specific agreements and the owners will to be an active part in raising competences and ensuring relevant training within the emergency services.

KEYWORD: Early involvement, fire brigade, intervention, smoke diver, training, underground structures, tunnels, technical trade-offs, operative bindings, robustness, infrastructure, stakeholder, joint training, EFSTG.

INTRODUCTION

Innovative and complex buildings and structures have become increasingly common, since building materials and technical installations are being developed and allow the boundaries of architectural and building developers performance capability to expand.

To cope with this, the demand for fire brigades flexibility and specialized knowledge on fire strategies and unique details about separate and specific objects increases.

Implementation of specialized tools and equipment by fire brigades are more often than before seen as
the only mean of achieving a sufficient safety level when certain special and unique architectural
details are desired.

This increasing demand on fire brigades gaining and maintaining specialized skills combined with the
increasing cost to maintain specialized material and equipment essential for interventions in structures
and buildings is a direct contrast to the continuously demands of savings and financially cut backs in
the public sector/fire brigades.

When fire brigades accept implementation of specialized equipment as a technical trade off against
traditional fire related installations, they apply an operative binding that will “burden” their
organization as long as the structure exists, and will most likely experience great difficulties getting
rid of the binding.

Greater Copenhagen Fire Department has, like so many other fire brigades, accepted a series of these
bindings which they, in widest possible extend, try to adjust in the pursuit of a wider (and to some
extend necessary) operative flexibility.

Does all the savings and financial cut backs forced upon fire brigades produce a degradation in
competencies, training level, resources etc. to an extend where the capability to intervene in certain
specialized objects with specialized equipment etc. is no longer present?

Right now the Copenhagen metro is undergoing a massive expansion and will within a few years be a
very significant provider of public transport within the Copenhagen area.

Intervention in the metro network is (as for most underground structures) associated with great
challenges, it is very resource- and logistically demanding and complex.
A high safety level in the extension to the metro, known as Metro Cityring, including intervention
capability of the fire brigade was being secured by a close, early and honest cooperation between all
stakeholders such as police, ambulance service, fire brigade, owner and advisory.

Experiences from Metro Cityring have proven that technical tradeoffs (TTO) cannot ”stand alone”,
that implementation of such increases the demand of raising the level of competence and
differentiation in training within the fire brigade and that this, in a time of financial focus within the
public sector, increase the need to solve this in cooperation, meaning that the owners accept their part
of the responsibility to ensure the continued maintenance of necessary training and ensuring a
sufficient level of competence within the fire brigade, applied by the agreed TTO’s.

PLANNING PHASE

a. Early involvement of the fire brigade

The safety level including the fire related installations etc. in the Metro Cityring is defined in a
separate legislation which meant that the Greater Copenhagen Fire Department did not hold the
authority, when dealing with underground structures. Nevertheless the owner, in an early stage of the
project, established an emergency group with representation of all rescue services involved, including
police, ambulance services, fire brigade etc. The formation of the group was a consequence of
experiences from the construction of the first metro line in Copenhagen where a similar common
forum had proven itself valuable to the final safety level in the metro.

The purpose of the group was to ensure all stakeholders a common forum to discuss and analyse point
of interests regarding fire and rescue related topics and dilemmas related to the upcoming project.

The group was given the name MSURR which in Danish was the abbreviation for Metro Safety
Incident Rescue and Clearance and was given the major mandate in fire and rescue related decisions
regarding the Metro Cityring project.
b. **MSURR group members / the strong network**

Every stakeholder involved with MSURR was obliged to deliver a competent and authorized member who had the relevant technical and organizational knowledge which allowed the member to analyze and prioritize pros and cons regarding different technical and strategical dilemmas and challenges along the project, ensuring that the group had the precondition working fast, effectively and competent.

The fire and rescue services as well as the organizations representing the owner mostly consisted of persons who had already been involved in other projects related to underground structures. Hence most of the members had already been associated in previous projects and established personal relationships at different levels. This itself proved a great asset to the group dynamic and efficiency and created an unformalized, honest and sincere environment which contributed to a flexible, agile and innovative management of often complex and controversial challenges and solutions.

c. **The professional network of the fire brigade / EFSTG (European Fire Service Tunnel Group)**

Because a lot of important fire related installations and considerations were decided and concluded based on analysis and reflections by individuals, and not upon clearly defined legislation, competencies as well as a high level of technical insight among representatives from each organization proved crucial to the final level of safety for the metro line that became one of the major infrastructures in the Danish Capitol.

To gain the sufficient level of competencies and being able to discuss certain matters and collect experiences and inspiration from other similar underground projects, the fire brigade turned to its European network of tunnel specialists within fire brigades across Europe, the EFSTG (European Fire Service Tunnel Group). EFSTG was established in 1995 at a tunnel-seminar in France where the need for a non-commercial and independent network was discussed by a small group of fire officers sharing a dinner. This was the birth of a network of representatives from European fire brigades which hold a tunnel within their district. In 2017 EFSTG is represented by 17 fire brigades from 13 European countries, has 1-2 annual meetings to discuss and share information regarding safety related to underground structures as well as performing field trips to relevant objects. For a short introduction to the EFSTG, see links in [1] and [2].

**SPECIALIZED AND RESOURCE DEMANDING INTERVENTION**

Metro Cityring as well as the existing Copenhagen metro is being constructed in a way that only allows passage between the two tubes at station- and emergency shaft areas. This leads to restrictions regarding the possibilities of evacuation from the tube and fire brigade intervention routes.

Especially in fire scenarios the possibilities are limited because the ventilation of hot smoke and gasses in fires of a certain size are expected to exclude the stretch of a tunnel on one side of the train as evacuation route and set extended restrictions in fire brigade ability to use that same stretch as intervention route. That means that evacuation and fire brigade intervention route are being dimensioned from the following:

a. **Fire ventilation**

Given the train- and tunnel geometry, movement of the train within the tunnel will produce a "piston effect” that in a fire scenario in a stranded train in a stretch of the tunnel will be supported by the mechanical fire ventilation that has been dimensioned to keep the stretch of the tunnel behind the train free of smoke.
If the planned ventilation strategy (supporting the movement of the train forward) in a specific scenario is obvious unsuitable and/or associated with the risk of losing lives, it will be possible for the control room supervisor to reverse the ventilation direction.

b. Evacuation

Evacuation of the up-to 300 passengers is hence paragraph a. above expected to take place in the opposite direction from the driving direction of the train (rear). A total evacuation of a full metro train carrying 300 passengers is expected to be completed in less than 6 minutes. The evacuation is expected to take place via the 0.71 m wide emergency walkway to the nearest station or emergency shaft. Experiences from evacuation studies under similar or semi similar circumstances indicate that a certain percentage of the passengers are expected to leave the emergency walkway and proceed by the tracks at the bottom of the tunnel. This must of course be taken into consideration when planning the intervention.

c. The firebrigade intervention route

A consequence of the ventilation strategy described in paragraph b. above the fire brigade intervention route is expected to be from the nearest station/shaft behind the involved metro train (referred to as “the primary point of attack”). This allow the firefighters to progress with the wind coming from behind, ensuring a non-smoke filled intervention route. Experiences and studies from ex. Stockholm indicate a great variation of the speed of the intervening firefighters in smoke filled/smoke free environments.

Because of tactical reasons the nearest station/shaft in front of the train is also maned by firefighters (referred to as “the secondary point of attack”).

Figure 1 Evacuation/intervention route and ventilation in a fire scenario in metro the tunnel

Because of the limitation to only one usable evacuation and intervention route which also serves as the only path of retreat for firefighters, should this be necessary, securing this stretch of the tunnel was of course of highest priority when planning the safety level etc.

EXAMPLES OF TTO’S AND THEIR ORIGIN

The great experiences from the first metro in Copenhagen meant that a big effort was put into planning and building the new Metro Cityring from the same frame as it had proven itself robust and wellfunctioning. Different circumstances resulted in a few differences which lead to a lower level of fire safety in some important fire and rescue related areas compared to the first metro.

This paper only focuses on consequences related to the extension in longest distance between stations/shafts (intervention and evacuation route) from initial approx. 650 meters to approx. 1250 meters. The extension resulted in, the emergency group agreeing upon the need for improvements, in a series of fire and rescue related areas compared to the existing metro line, to achieve the same high
level of safety as the existing metro line with the longest distance of approx. 650 meters.

This resulted in a series of TTO’s of which this paper describes 3 of high value to the overall fire safety level:

a. **Battery assisted rescue trolleys**

To assist the fire brigade in transporting firefighting equipment, manually assembled and pulled rescue trolleys were implemented on the first metro line in Copenhagen. These were simple aluminum frames with wheels and a piece of cloth for equipment to be put on.

The trolleys had proven themselves useful but time consuming and heavy to assemble in the tunnel and were to be brought to the scene of incident by a vehicle from the fire brigade and later to be carried by firefighters to the tunnel. The speed with which the trolley was able to be deployed with, were slow and depended greatly upon the load carried on it. Because of the slopes within the tunnels, pushing and working with the trolleys had proven physically exhausting which caused a problem since firefighters performing that job were the same few firefighters who were expected to do the hard and complex duty of fighting the fire itself.

Due to the extended intervention route of approx. 1200 meters and the above described considerations described above, MSURR agreed upon implementing battery assisted rescue trolleys. These where to be stored in a compartment at the stations on each side of the platform allowing the fire brigade to deploy a trolley within 5 minutes in each of the tracks by the platform.

Besides this, the trolley would be designed in a way which would allow firefighters carry it to the neighbor track if necessary. In this way it would be possible to deploy 2 trolleys from each station within a few minutes after arriving, assisting fire brigade carrying equipment as well as patients.

![Figure 2](image)

*Figure 2  An early sketch of the battery-assisted rescue trolley*
b. Equipped “fire stations” on every platform

Different areas that were agreed to improve, with the aim of saving the strength of the firefighters who were to address the fire, and to improve the handling and preparation speed of equipment needed for the intervention inside the tunnels.

Until this arrangement the fire brigade was expected to bring the equipment from their vehicles on the surface, to the underground platforms and carry it further inside the tunnels, up to a distance of approx. 600 meters.

It was estimated that storing this equipment on platform level would potentially reduce the time consumption prior to an intervention with several minutes if stored at stations. This resulted in the group agreeing upon a storage of a specific amount of relevant firefighting material on every platform at all stations to relieve firefighters from carrying the equipment from the surface, allowing them to address the fire faster and saving valuable and potentially lifesaving minutes, in the total time leading up to an intervention.

c. Rebreathing apparatus for all firefighters

As mentioned in paragraph 2.c – the fire brigade intervention route, firefighters doing an intervention in a metro tunnel were considered endangered, compared to most other interventions because of the presence of only one single useful retreat route. If a failure in the fire ventilation would occur, the firefighters would have to escape as far as 1200 meter and depend on one single route.

Therefore an guarantee had to be made, that every firefighter working inside the tunnel would have access to air supply, allowing him/her to escape through smoke filled environment as far as 1200 meters after addressing a fire for some time.

Based on an analysis on the air consumption of firefighters, fighting a fire inside tunnels, the emergency group decided that this guarantee could not be met using a standard breathing apparatus with a single bottle of compressed air.

From the different alternatives (available at the that time) it was agreed upon, that the fire brigade should have access to rebreathing apparatuses which should be mandatory equipment for firefighters working inside the metro tunnels.

NECESSARY COMPETENCE GAINS AND TRAINING MAINTENANCE

By implementing the TTO’s agreed upon, the emergency group considered the original safety level in the metro was fulfilled including the conditions necessary to perform a safe and effective intervention in the metro tunnels.

Several of the TTO’s including the ones covered by this paper would have bigger or smaller consequences to the fire brigade because they demanded special knowledge, education and gaining new and specialized competences.

Especially objects and structures that differs a lot from other objects and are of great infrastructural value as the metro and are vulnerable to a major incident that could prove devastating to a large number of people, the readiness of the fire brigade is of great importance.
a. Rebreathing apparatuses

The decision on implementing rebreathing apparatus as a mandatory part of the equipment when conducting an intervention in a metro tunnel resulted in a need for raising the competences among the operative part of fire brigade personnel who is potential to intervene in metro tunnels.

The fire brigade performed an analyses of the resources (manpower) required for a potential fire in the metro tunnels compared to the logistic involved when replacing personnel intervening/maintaining a sufficient amount of personnel to address the fire/incident. Based upon this analysis the fire brigade decided that all personnel should be able to use a rebreathing apparatus on a level that made them able to perform a safe and sufficient intervention in the metro tunnels.

This means that approximately 360 firefighters have to undergo the sufficient education and training in the use of a rebreathing apparatus prior to the opening of the Metro Cityring. To minimize both the economical and logistical cost to a realistic level covering both education and specific competences in this part of the operative force, the education was differentiated dividing the education in 2 modules and only giving both modules to the necessary part of the force.

Since educating personnel on this scale is associated with a considerable cost (not including the logistics involved) it was agreed that the owner (Metro Company) would cover a sizable part of the costs associated with the initial basic competence gaining training and a part of the following operating costs.

Besides this, implementing a new breathing apparatus lead to related costs, rebuilding of vehicles, equipment workshops, education of service staff etc. Costs that were all covered by the fire brigade.

Figure 3 Exercise in the Metro Cityring tunnel. Greater Copenhagen Fire Department use Dräger BG4 breathing apparatus.

b. Object knowledge / differentiation in competences / competence matrix

The fire brigade experienced an increasing number of buildings, structures and project of architectural diversity within their district. This meant that a considerable part of the new structures differed largely from traditional buildings and had to be characterized as complex structures if looked upon from a fire preventative point of view. This would also be the case for the metro and its successor, Metro Cityring. This increasing growth in diverse and innovative structures produced several challenges to the fire brigade readiness and demanded specialized knowledge on specific and numerous objects.

In recognition of this Greater Copenhagen Fire Department launched a project that aimed at clarifying
the possibilities of efficient and realistic training to prepare for intervention in metro tunnels and scenarios.

The project was a consequence of the recognition, that an intervention in a fire scenario in the metro tunnels would be associated with great resource- and logistical challenges and that success would depend on sufficient training of the entire operative organization and not limited to training of the firefighters attending the scene solely. Therefore the variety in educational skills would vary considerably from operative, administrative personnel such as personnel operating in the dispatch central to the smoke diver intervening and operating inside the tunnels.

To clarify the educational needs in every part of the organization a skill/competence matrix was produced, listing every possible and necessary action and task involved in an intervention in a metro fire scenario. Then the relevance of theoretical and practical knowledge/educational need of each action/task was considered for every group of personnel in the organization and put into the matrix given a value from 1-3, see figure 4 and 5.

With a final consideration of time (hours) needed to educate the different groups of personnel the different tasks/actions etc. the total estimated time (hours) needed to educate and bring the sufficient competences to the entire operative organization was given.

The Copenhagen metro lines operate a 24/7 schedule. Therefore the skill matrix also proved a valuable tool in clarifying in what part of the operational force, specific, physical and realistic training inside the actual tunnels were mandatory. In this manner the amount of staff needing to visit the tunnels could be reduced to a minimum, reducing inconvenience and disturbance of the metro to a minimum.

The majority of the operational personnel were, with basis in the described analysis considered to gain sufficient training and acquire the needed competences using training methods other than actual visiting the object/tunnels.

Educational tools such as e-learning, classroom lessons and video were decided sufficient tools for fast, efficient and cheap methods for gaining relevant competences and educational skills.
### Metro and metro City Ring Copenhagen

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SC=Chief of staff, OC=Chief of operations, ISL=Incident commander, ISL assist.=Assistant to the incident commander, TL=Team leader, Crew=Firefighter, Dispatch=Dispatch central, Spec.=Specialist firefighters, BG4=Teams using rebreathers, BA= Teams using compressed air bottles.

**Figure 4** Example of one page of the metro skills matrix

**Figure 5** Explanation of theoretical and practical levels used in the skills matrix

$P=$ Practical competence (hands-on), $T=$ Theoretical knowledge
c. Common responsibility for specialized competences within the fire brigade

After calculation/evaluation of the total estimated time consumption etc. required for gaining the necessary competences within the operative part of the fire brigade personnel it was realized that the task ahead would require a lot of resources and would be extremely time consuming and require for other prioritized tasks, drills etc. within the fire brigade to be abandoned or postponed.

After discussions with the owner of the structure regarding the task ahead and their relevance to the overall safety level of the metro, the fire brigade, the Metro Company and the Metro operational management agreed upon a sharing of the relevant education of operative personnel within the fire brigade.

As an example the operational management offered to customize their newly developed e-learning module, dedicated to their own personnel to meet some of the requirements and needs to the part of the fire brigade personnel who was expected to be able to gain sufficient competences and education thru e-learning. Besides this the operational management offered to facilitate some of the other parts of the necessary operative education of personnel from the fire brigade on their facilities that was found best suited.

As described, the total need of improving competences within the different fire and rescue services involved in securing the metro was discussed and recognized as a common task to secure an appropriate and high level of safety and served to give a common picture on the level of readiness and competences among the services expected to perform a safe and secure intervention if called upon and thereby ensuring the end-users of the structure, the citizens

“A chain is no stronger than its weakest link”.

RELEASE OF CONTROL AND MAINTANANCE OF PARTS OF THE OVERALL SAFETYLEVEL?

Implementation of specialized equipment (often related to as TTO) to be able to perform a safe and effective intervention in specialized structures is a commonly known phenomena among fire brigades worldwide throughout history.

As described in this paper, this way of ensuring the fire safety with TTO’s in a specific structure are often related to direct or indirect consequences to the fire brigade accepting implementation of specialized equipment often motivated by immediate and shortsighted economical gain.

Accepting specialized and innovative solutions must be considered carefully with focus on a wide string of parameters such as operative bindings, long-term operational costs, maintenance of specialized skills and knowledge regarding the specific structure.

If a satisfactory level of safety in the structure is based upon the TTO/specialized equipment, consequences to the structure should be considers carefully, should the fire brigade eventually decide (or forced upon) not to use the equipment. Could this potentially result in the safety level of the structure being reduced to an unacceptable level? What consequences would this have to an object potentially being an important infrastructure?

It should also be of great consideration how the necessary level of competences among the staff, expected to be able to handle and use the specialized equipment is ensured and documented.
LESSONS LEARNED / FUTURE CHALLENGES

There is a tradition among emergency services to be solution oriented and to focus on possibilities instead of limitations. This means that there has been a willingness to deviate from standard operating procedures (SOP) to ensure that intervention plans and fire strategies could be implemented commonly motivated by the consciousness of the fire brigade role as a servant of society.

When emergency services accept- or are forced to implement specialized equipment or are being forced to divert from SOP they often accept an increased cost related to training and maintenance of equipment, transferring some of the responsibility of the fire strategy/total safety level from the owner of the infrastructure to a public emergency service, being financed from tax funds.

Experiences from the Metro Cityring project have shown that it is crucial that the emergency services are being involved in the project at an early stage and that it is important to have clearly defined agreements and contracts describing important aspects regarding implementation of specialized equipment and diversions from SOP, particularly in matters related to operating costs and gaining competences.

Besides that experiences have shown that a clearly defined agreement of expectations should be established describing how to deal with situations where specialized equipment or specialized intervention tactics can no longer be used. Allowing changes in legislations related to working environment or inexpedient operational bindings to be altered without inappropriate negative consequences to the infrastructure nor the emergency services.

In a situation were sufficient agreements cannot be obtained the emergency service must retain itself from accepting specialized equipment and diversions from SOPs that inflict costs to the emergency service or transfer parts of the responsibility of some of the safety level from the owner to the emergency service.

CONCLUSION

Implementation of specialized equipment expected to be a part of the overall safety level/strategy must be considered to fulfill its purpose, only if it is used properly in its right context and maintained as described by the manufacturer. Is it appropriate / possible to release yourself from the responsibility to control and maintain an essential part of the overall safety level of your structure?

The owners of the structure must take upon them their part of responsibility ensuring that the necessary competences and resources (economically as well as human) are obtained within the emergency services if the emergency service are expected to take upon them tasks that divert from SOP or inflicts extraordinary costs to the emergency services.

The share of responsibilities as well as the economical shares in the agreements must be clear and secure flexibility within the emergency services making sure they don’t result in inappropriately fixed operational bindings.

REFERENCES


How to Determine Toxic Effects and Human Behaviour when Exposed to Fire Smoke in Underground Facilities – Challenges and Possibilities

David Purser
Hartford Environmental Research, Hatfield, Hertfordshire AL9 5DY, United Kingdom.

ABSTRACT
The impact of different individual Available Safe Escape time (ASET) and Required Safe Escape time (RSET) parameters has been examined for three serious fire incidents in tunnels and underground facilities (Mont Blanc, Daegu and Channel Tunnel fires). The event timelines have been obtained from incident reports, and for the Mont Blanc tunnel fire these have been compared with fire hazard development and escape behaviour modelling to determine the extent of hazards and effects on occupants. For these incidents, detection and emergency management responses were processes involving chains of investigation and reporting leading to serious delays in taking remedial action and warning occupants to escape. Escape failure also occurred because vehicle occupants were reluctant to leave trains or vehicles to enter escape routes, emphasizing the need for high levels of affordance for exits, but some occupants did succeed in moving many metres through dense smoke. Using data on smoke and toxic gas yields from mixed materials combined with Fractional Effective Dose (FED) modelling, it is concluded that subjects can move through smoke down to 2 metres visibility (reflected light) for up to ~20-60 minutes before collapse from asphyxia, depending on their susceptibility.

KEYWORDS: tunnel fire, toxicity, burns, escape, behaviour, smoke, evacuation, management

INTRODUCTION
Fires in underground facilities such as sub-way stations and tunnels may present particular hazards and risks to occupants beyond those encountered in buildings above ground [1,2]. These arise mainly from fires involving road or rail transport vehicles in tunnels. They may involve large fuel loads and in a number of incidents [1,2] and tests [3] have shown rapid fire growth within a few minutes to large fires of 50-100+ MW. In the confines of tunnels these can produce very hot environments over hundreds of metres with dense smoke spreading rapidly over even greater distances. Depending on the fuel load, ventilation and combustion conditions, the smoke is likely to contain high concentrations of irritant and asphyxiant toxic gases, which may overcome trapped or escaping occupants needing to walk significant distances in difficult conditions to reach refuges or emergency exits. Further issues arise where subway train tunnels pass through station complexes. Fire effluents from burning trains may flow up into station enclosures before being extracted or emerging at ground level. Underground station facilities are often complex spaces, with interconnecting lines, platforms, ticketing, exchange and retail halls at different levels, presenting long escape travel distance and significant wayfinding challenges for escaping occupants. They may find themselves moving up into hot and heavily smoke-contaminated areas, further compounding wayfinding escape and survival hazards. It is therefore important in the design and management of underground facilities to evaluate and take measures to mitigate the particular fire survival risks associated with such systems.

Methods for evaluating fire hazards
Tunnels and underground facilities are designed with a range of fire safety systems including fire detection, emergency traffic management procedures, firefighting and rescue services, compartmentation, suppression and smoke extraction systems, protected refuges and escape routes for occupants. The performance of these systems in response to specific fire scenarios can be evaluated by modelling design fire growth and effluent spread in relation to the timing of detection and implementation of emergency response procedures. The effects on occupants can then be evaluated.
as they remain in place, seek refuge or escape. In any scenario the life safety outcome is time-related, depending on the outcome of two parallel processes [4]: Available safe escape time (ASET) = time from ignition to that when conditions in each location become untenable (conditions under which occupants can no longer perform the actions required to escape safely) and Required Safe Escape time (RSET) = time from ignition to that when all occupants reach a place of safety. For a safe outcome ASET must be longer than RSET by an appropriate margin of safety. Where occupants remain in place or in a refuge the conditions must remain tenable until the fire is extinguished.

ASET depends on the time concentration curves of smoke, toxic products and heat to which occupants are exposed throughout a scenario, and their incapacitating effects. Inputs for ASET calculations include the heat release rate curve for the fire, heats of combustion of the fuels and mass yields of toxic products. The effect on occupants depends on the behavioural and physiological effects of exposure [4] in terms of:

- Behavioural effects of seeing smoke or flames on willingness to enter smoke-filled escape routes or pass flames.
- If occupants decide to enter smoke, the effects on walking speed and ability to move through smoke, navigate escape routes and find exits (wayfinding), willingness to continue or turn back and seek refuge. These concentration-related aspects depend initially on visibility impairment (optical density) and irritancy of the smoke (due to the presence of acid gases and irritant organics) causing pain to the eyes, nose and throat, with breathing difficulties, and the sensation of heat.
- After a period occupants may be incapacitated by dose-related effects of asphyxiant gases (mainly CO, HCN and CO₂) or heat exposure. For asphyxiant gases tolerance is limited by doses resulting in collapse and coma, while for heat tolerance is limited “doses” of radiant and convected heat resulting in pain to the skin or throat followed by burns.

From the perspective of design and management of underground facilities tenability aspects to consider with respect to these fire hazards include:

- The limits of exposure during a potential incident considered acceptable and consistent with all occupants escaping in safety.
- The probabilities and likely consequences of exposures beyond these limits in terms of potential injury and death.

The basic RSET expression is as follows [2]:

\[
\text{RSET} (\Delta t_{\text{esc}}) = \Delta t_{\text{det}} + \Delta t_{a} + \Delta t_{\text{pre}} + \Delta t_{\text{trav}}
\] (1)

Where

\[
\text{RSET} (\Delta t_{\text{esc}}) = \text{escape time (time from ignition for all occupants to reach a place of safety)}
\]

\[
\Delta t_{\text{det}} = \text{time from ignition to detection}
\]

\[
\Delta t_{a} = \text{time from detection to alarm}
\]

\[
\Delta t_{\text{pre}} = \text{pre-travel time (or pre-movement time): time from alarm to when each occupant begins to move towards an exit}
\]

\[
\Delta t_{\text{trav}} = \text{travel time: time taken of each occupant to walk to an exit and through escape routes}
\]

Note: Evacuation time (\(\Delta t_{\text{evac}}\)) is the time from alarm to safe escape, which is the sum of pre-travel and travel time.

ASET and RSET calculations and comparisons involve the application of models and input data derived mainly from fire dynamics and human evacuation experiments. Some of these inputs are well established and validated, but others are subject to considerable uncertainty and difficulty in obtaining well-validated data or functional relationships. Also, when different scenarios are evaluated, it becomes evident that outcomes may be heavily dependent on values and effects of some parameters, while others may have little effect on outcomes. It is therefore important to identify the key parameters affecting outcomes and evaluate or control them. A particular issue is aspects of human behaviour and escape when faced with unexpected and uncertain situations with limited knowledge of the conditions. It is therefore useful to study outcomes of serious incidents to determine how hazardous conditions developed and how occupants behaved and were affected, in order to learn vital safety lessons, obtain data on occupant responses and develop improved systems. This approach can be particularly powerful when aspects of incidents are recreated experimentally or by ASET-RSET...
modelling, in which case the forward predicted modelling outcomes can be compared with the actual outcomes of incidents in terms of occupant survival. In this paper the ASET-RSET modelling and incident data from the Mont Blanc road tunnel fire [1,2], and incident data from two rail tunnel fires (Daegu subway and Channel Tunnel) [2] have been used to highlight aspects of different ASET and RSET parameters having a major impact on safety outcomes. The finding are used to suggested approaches to better evaluate and control these aspects for future design and management.

**METHODS**

Reports of three major incidents in road and rail tunnels and underground facilities (Channel Tunnel train and tunnel fire 18th November 1996, Mont Blanc Road Tunnel fire of 24th March 1999, Daegu train, tunnel and subway station fire 18th February 2003), have been examined to construct timelines and identify key events and parameters affecting ASET-RSET and effects on occupants. The conditions during the Mont Blanc tunnel fire were modelled using a version of the JASMINE computational fluid dynamics (CFD) code developed for application to tunnel fires (TUNFIRE), calibrated against sensor data for smoke movement and temperatures from the incident, and test fires carried out in the tunnel [5]. Smoke and toxic gas yields were estimated from small and large scale tests on different materials similar to those involved in the fire [6]. Predicted effects on occupants in terms of time to incapacitation and death were calculated using Fractional Effective Dose methods [1,4]. Further details of the Mont Blanc study methods and results are presented in [1]. The sequence and timings of key events in this and other incidents have been obtained from published reports and are described in more detail in [1] and [2]. Some features of the Mont Blanc tunnel fire investigation were used to illustrate the application ASET-RSET modelling to evaluating the conditions and effects on occupants during the actual event and for different alternative scenarios.

Estimated time to collapse from exposure to asphyxiant gases as a function of smoke density has been calculated from the ratios between yields and concentrations of smoke, CO, HCN and CO2 measured during flaming combustion of four materials (a cellulosic material - medium density fibreboard, polymethylmethacrylate (PMMA) and two nitrogen-containing foams (a combustion modified medium density polyurethane foam and rigid polyisocyanurate foam [PIR]) commonly used as insulation [6-8] . The smoke and gas yield data used for these calculations have been chosen as indicative of a burning “mixed fuel” package representative of the approximate mix in an heavy goods vehicle (HGV) fire. Yield data were used for two combustion conditions, well-ventilated flaming (equivalence ratio $[\phi]=1$) and under-ventilated combustion ($\phi =1.5$). For each of these the relationship between smoke density and its reciprocal (visibility for reflected light) and time to incapacitation has been calculated as the time to reach FED=1 (representing time to incapacitation for 50% of an exposed population) for asphyxiant gases using the FED expressions in [4]. Times to FED=0.3 were also calculated as the estimated incapacitation threshold for the most sensitive 1% of an exposed population. The results from the four different materials were averaged to give an indication of the effects of exposure to smoke from a mixed fuel package.

**PARAMETERS AFFECTING AVAILABLE SAFE ESCAPE TIME (ASET)**

**Heat release rates and fire size for tunnel vehicle fires – time window available for suppression**

Both road vehicles and trains consist of large fuel loads which can produce fires growing rapidly to a very large size within the narrow confines of tunnels or stations. The time window available after detection for active suppression before conditions become unmanageable may be only a few minutes. The Mont Blanc tunnel fire initially involved a small fire in the engine compartment of a heavy goods vehicle carrying a load of margarine. From the time when the driver stopped in the tunnel at 10:53 hours on 24th March 1999 the fire grew very rapidly. During this incident, the tunnel ventilation conditions were such that the effluent plume from the burning vehicle was carried mainly toward the French Portal of the tunnel. It rapidly became impossible to approach the fire from the France, although it was possible from the Italian Portal. In addition to the effects of the tunnel ventilation settings, the rate and extent of effluent spread, which was recorded by the tunnel systems, was found to depend on the meteorological conditions between the tunnel portals and the fire size. The model scenario developed for the CFD analysis providing the best representation of the conditions during the
early minutes of the actual incident (Scenario 0) involved a 10 Pa pressure differential between the tunnel portals and a fire in the first vehicle estimated to have reached 40 MW within 7 minutes, which then plateaued for several minutes. Alternative scenarios considered included a 40 Pa pressure differential and continued fire growth to 70 MW within a further 2 minutes, spreading to involve the next vehicle. Scenario 0 gave a better fit with the measured meteorology and tunnel conditions for smoke spread and temperature. The CFD model was also validated against experimental pool fire tests carried out in the tunnel [1,5].

The findings were that occupant survivability in this and similar incidents could be greatly enhanced by early fire suppression, and an issue considered was up to what time might it have been feasible for the tunnel fire service to have approached the fire to fight it. Figures 1 and 2 show the conditions in terms of visibility through smoke, temperature and heat flux during the early minutes after the vehicle on fire (PL0) stopped at 10:53 hours. Vehicles are referred to as PL (Poids Lourd) representing heavy goods vehicles or VL (Vehicule Legère) representing light vehicles, numbered according to their final positions in the tunnel between the fire at PL0 and the French Portal.

To fight the HGV fire it would be necessary to approach it within a maximal distance of 25 metres using 1 or 2 jets of 250 L/min or 300 kg of powder. Around 11:05 the fire developed to 40-70 MW, with a radiant flux ~5 kw/m² at 150 m from PL0 and 30 kW/m² at 50 metres. The conditions were too severe for an effective intervention. If the fire had been attacked from the Italian end from around 10:58-59 with three jets it might have been possible to control the fire within a few minutes, but this allowed only 5 minutes for the fire fighters to reach the fire location from the Italian tunnel portal.

Similar short response times for suppression can apply to train fires. The Daegu subway train and station fire in South Korea 18th February 2003 was deliberately ignited on the train at 09:22 using a lighter and cartons containing a flammable liquid, becoming a significant fire as the train stopped at Jungangno station. The doors then opened and the passengers escaped in good conditions. The fire then grew rapidly spreading throughout the train within two minutes, growing to a large conflagration involving another adjacent stationary train. Within a few seconds of the train’s arrival the automatic smoke detectors and alarms in the station were triggered but there was very little time for any firefighting response unless there had been an automatic suppression system on the train or an immediate manual response at the station, neither of which occurred.
For automatic suppression systems it is also important to obtain a rapid response to extinguish the fire or maintain control while the fire is small. While occupants can survive exposure to halon or inert gas release at concentrations capable of extinguishing fires, it is usual to delay activation by around 30 seconds to enable occupants to evacuate to adjoining carriages before release (as in the Channel Tunnel vehicle shuttle carriages). If fires continue to burn there can be additional hazards from vitiated combustion or decomposition of halogenated suppressants releasing acid gases [9]. While sprinklers and water mist systems can be effective in suppressing or extinguishing fires, thereby greatly reducing the hazard to exposed occupants, tenability issues to take into account are:

- Sprinkler activation reduces visibility by cooling and down drag of buoyant smoke layers from above head height down to floor level, impairing escape efficiency and increasing escape times during the early stages of a fire incident.
- Where the fire is not rapidly extinguished occupants may be exposed to smoke saturated with water vapour. Due to the high latent heat content, the highest temperature at which saturated air or smoke can be breathed is 60° [4]. In a design context it is therefore important to demonstrate that escaping occupants will not be exposed to saturated air or smoke above this temperature.
- In experimental sprinklered fires it has been found that although occupants may suffer early visual impairment, “sprinklered” smoke is generally of very low irritancy and toxicity, so that although walking speeds and wayfinding of evacuating occupants may be impaired, the time available for escape should be considerably increased.

Effective heats of combustion, smoke and toxic gas yields for input to Fractional Effective Dose modelling

The developing toxic hazard in a compartment fire depends upon the time-concentration curves for the toxic products. This in turn depends on:

- Fire growth curve (mass loss rate of fuel [kg/s]) and dispersal volume (kg/m³)
- Yields of toxic products under a range of combustion conditions (e.g. kg CO/kg material burned)

In fire engineering calculations and computer models the size of the growing fire is often expressed in terms of a HRR (Heat Release Rate) curve. The mass pyrolysis rate of the fuel is then given by HRR (MW)/heat of combustion (MJ/kg) = kg/s fuel mass pyrolysed. The values used for the heat of combustion are often the constant heats of complete combustion [6,7], which may be appropriate during the early stages of well-ventilated fires, but decrease as combustion becomes under-ventilated,
so that for a given HRR a greater mass of fuel is pyrolysed at fuel:air equivalence ratios above stoichiometric ($\phi>1$) (Figure 3). Similarly, while the values for yields of toxic products used as input are often those for well-ventilated combustion, these can increase considerably as combustion becomes less efficient. This applies particularly to smoke particulates, irritant organic species, CO and HCN (Figure 4). For example at a fuel:air equivalence ratio of 2, the heat of combustion is halved, which doubles the pyrolysis rate for a given HRR, and the CO yield may increase by a factor of 10, resulting in a 20x increase in the mass production rate of CO at a given HRR.

![Figure 3. Equivalence ratio ($\phi$) and effective heats of combustion for 14 materials [6,7].](image)

![Figure 4: Relationships between $\phi$ and yields of CO and HCN for different materials [6,7]](image)

For fires such as those involving vehicles or trains in tunnels, the equivalence ratio will vary with the combustion conditions in relation to the fire size and ventilation, which can be computed using CFD analysis. When fires occur inside vehicles or rail carriages, these may rapidly become under-ventilated with increased yields or toxic products [10], but when the entire vehicle become involved and conditions in the tunnel are considered, then combustion outside the vehicle may be relatively well-ventilated, at least initially, depending on the fire size. For a fire involving a single light vehicle in a road tunnel, the maximum fire size is likely to be less than ~3 MW, with no deep upper smoke layer penetrated by flames [10]. For an HGV fire of 40-70 MW in a single bore tunnel as at Mont Blanc, with flames penetrating the upper layer, the combustion becomes more vitiated so that based on the computed fuel:air ratio a CO$_2$/CO volume ratio of 4:1 was estimated, with the CO:HCN concentration ratios based on the carbon:nitrogen content of the vehicle fuel load and the finding from tests such as those illustrated in Figure 4 [6,7] that during combustion, the conversion of fuel nitrogen to HCN is directly proportional to the efficiency of conversion of fuel carbon to CO.
Fractional Effective Dose (FED) modelling and tenability limits for exposure to smoke

The recommended method for tenability assessment for any fire scenario is to carry out a Fractional Effective Dose (FED) analysis using the time-concentration curves for smoke obscuration, irritants, asphyxiant gases, convected and radiant heat for all occupants throughout their exposure, using the methods described in [4]. These have been applied to the modelled Mont Blanc tunnel fire to estimate the hazards to vehicle and tunnel occupants. The results are described in [1] and summarized later in this paper. The aim is to calculate the time at which the exposure concentrations of smoke and irritants, and the exposure doses of asphyxiant gases and of heat, reach FEC (Fractional Effective Concentration) or FED (Fractional Effective Dose) levels predicted to significantly impair escape efficiency, or at higher levels prevent escape or cause incapacitation, (collapse) or death.

Another and somewhat simpler approach for tenability assessment from smoke and toxic gases is to set tenability limits in terms of smoke concentration and visibility. The basic approach for a design limit is summarized in Table 1, with a detailed description in [1 and 4]. The basic concept is that the design has failed if the visibility is insufficient for occupants to make an efficient and timely escape. Based on the consideration that smoke in tunnel fires is likely to be derived from burning vehicles or trains, or tunnel facilities such as cables, and therefore likely to contain a significant content of acid gases and organic irritants from burning polymeric materials, it is recommended that smoke from all tunnel fires should be considered irritant. On this basis occupants are likely to move as if in darkness in smoke optical densities exceeding \(\alpha 0.2 (\alpha_k 0.5)\) (where \(\alpha\) is the linear decadic absorption coefficient [or optical density] per metre and \(\alpha_k\) is the light extinction coefficient per metre [\(\alpha_k = 2.3\alpha\)]. At this density, although the nominal visibility of light reflecting objects in diffuse illumination would be around 5 metres \((\sim 1/\alpha)\), visibility is further impaired by eye irritation and reflex closure. It has also been found that in fire incidents, approximately 30% of people turn back rather than enter smoke with a density of 0.33 (around 3 metres visibility). For this reason \(\alpha 0.2\) (visibility 5 m) is recommended as a maximum acceptable smoke density for safe escape from small enclosures (such as from a bus or railway carriage). For a large enclosure, or travel distance to a tunnel or station exit, occupants need to be able to see at least 10 metres to orient themselves and navigate escape routes and exits, giving a tenability limit of \(\alpha = 0.08\) (Table 1).

<table>
<thead>
<tr>
<th>Smoke density and irritancy (\alpha) (extinction coefficient (\alpha_k))</th>
<th>Approximate visibility in diffuse illumination</th>
<th>Reported effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>None 0.2 (0.5) irritant</td>
<td>Unaffected reduced</td>
<td>Walking speed 1.2 m/s Walking speed 0.3 m/s</td>
</tr>
<tr>
<td>0.33 (0.76) mixed</td>
<td>3 m approx.</td>
<td>30 % people turn back</td>
</tr>
<tr>
<td>0.5 (1.15) non-irritant</td>
<td>2 m</td>
<td>Walking speed 0.3 m/s</td>
</tr>
</tbody>
</table>

Suggested tenability limits for buildings with:
- small enclosures and travel distances;  
- large enclosures and travel distances.

\(\alpha = 0.2\) (visibility 5 m)
\(\alpha = 0.08\) (visibility 10 m)

Some occupants exposed above these levels will enter smoke and may be able to escape. Ability and willingness to enter and move through smoke therefore depends on the following aspects:
- Scenario related: subjects are more likely to attempt to move through smoke if already immersed in it, but may turn back or remain where they are if they can avoid entering smoke. Movement is easier and faster if guided by a handrail or wall.
- Behaviour related: depends on the experience and sensitivity of the individual subject
- Visibility related: visibility distance and irritancy affects willingness to enter and move through smoke and walking speed once exposed.

These have been issues in tunnel fires such as Mont Blanc when by far the majority (76%) of vehicle occupants between the fire and the French portal remained in their vehicles when these were enveloped in smoke and died there from smoke intoxication rather than attempt escape through the tunnel. Those close to the fire who did leave their vehicles are likely to have been in relatively clear conditions during the early stages of the fire, due to the buoyancy of the plume keeping the smoke
layer near the ceiling, while at the same time they could see and were exposed to the heat from the flames of the rapidly growing fire, which may have caused them to abandon their vehicles and attempt escape along the tunnel [1]. Vehicle occupants in clear conditions on the Italian side all escaped.

For occupants attempting to move through smoke away from regions of extreme heat, tenability ultimately depends on the concentrations of asphyxiant gases, especially CO, HCN and CO₂ in the smoke or on heat and burns. The ratios between yields and concentrations of smoke particulates and these gases depends on the composition of the fuels and especially on the combustion conditions (as illustrated in Figures 3 and 4). From data on these ratios measured for different fuels in bench-scale or large-scale fire tests [6-8] it is possible to determine gas concentrations for different smoke densities and calculate times to incapacitation (collapse) from exposure to asphyxiant gases for these gas mixtures using FED analysis. As a simple limiting value it can be established that for smoke from any flaming fire involving any fuel mix, at a visibility distance of 10 metres, the concentrations of asphyxiant and other toxic gases will be low enough to have no significant deleterious effects on escape or survival for exposure periods of up to approximately 60 minutes. At higher smoke concentrations the estimated exposure time before a person walking along a tunnel would collapse from asphyxiant intoxication is shown in Figure 5. Escape below a smoke layer requires a maximum upper layer temperature of 200°C so as to limit downwards heat radiation to a tolerable level.

Figure 5 shows plots for a “mixed fuel” package considered representative of the approximate mix in an HGV fire, for two combustion conditions: reasonably well ventilated combustion (ϕ ~ 1) and under-ventilated combustion conditions (ϕ ~1.5). Two plots are shown for each condition, one representing time to incapacitation for 50% of an exposed population (FED=1) and one for the estimated incapacitation threshold for the most sensitive 1% of an exposed population (FED=0.3), which is recommended as a limiting design value to enable safe escape of almost all occupants. In practice the relationships between visibility and times to incapacitation were similar between the different individual materials in the fuel package (average coefficient of variation 28%).

Taking 2 metres visibility as an example, the results show that even under the worst condition of an under-ventilated fire, occupants of average sensitivity would be able to walk through the smoke for 40 minutes before collapsing, while the most sensitive subjects would be able to walk for 13 minutes.
PARAMETERS AFFECTING REQUIRED SAFE ESCAPT TIME (RSET)

Pre-warning delays in major fire incidents. Detection of fires and escape warnings to occupants are generally thought of as discrete events occurring at specific times during an incident, as represented in Equation 1. Examination of events occurring in major fire incidents, particularly those occurring in tunnels and underground stations, shows that in practice “detection” and “warnings” are often processes involve a number of stages between the first detection event and the final provision of an evacuation warning to affected occupants and implementation of other emergency responses. Larger built systems usually have two-stage alarms. Detection activates a pre-alarm to security after which a general alarm may be provided to all affected occupants. In many larger and more complex facilities, when the initial detection of the fire (either automatically or by a person) provides a pre-alarm to security staff, they have to decide if and when to activate a general evacuation alarm. Sometimes there is an automatic protocol for a general alarm (for example after a fixed delay unless cancelled, or if more than one detector is activated by the fire), but in some serious incidents either there has not been such a back-up or it has been cancelled. When staff receive the pre-warning they enter their own behaviour sub-routine, taking time to recognise that an alarm has been received and then responding in some way. In almost all cases the first response is to send someone to investigate. Further time is then spent for investigators to travel to the fire site, appraise the situation and report back, with information and instructions passing up and down a management chain. Investigation and reporting may take a significant time as the fire grows before it may be considered sufficiently serious to recommend evacuation. In some incidents warnings have been too late, so that occupants died attempting to escape. In such a situation the RSET expression might be represented as follows:

\[
RSET (\Delta t_{esc}) = (\Delta t_{det} + \Delta t_{prew}) = \Delta t_{a} + \Delta t_{pre} + \Delta t_{trav}
\]  

(2)

Where

\[\Delta t_{prew}\] represents the pre-warning time

In such incidents the sub-routine consists of a sequence of different “detection” stages or events leading to a sequence of different “pre-warning” events before finally resulting in an alarm [2].

Mont Blanc Road Tunnel fire 24th March 1999: A prolonged detection-warning process introduces delays in taking appropriate action during which rapid fire growth and a seriously deteriorating situation can occur, resulting in life loss. The Mont Blanc Road Tunnel fire provides an example [1,2,11] (Table 2). The fire occurred in the engine of a road freight vehicle (PL0), which entered the 11.6 km, two-way tunnel from the French end at 10:46 hours. The tunnel contained 40 video surveillance cameras, opacimeters and carbon monoxide detectors every 1450 m (intended for monitoring air quality), and a fire detection system (temperature sensors in the French half of the tunnel and a pressure sensing system in the Italian half). The opacimeter system gave a continuous display reading in the control room and also sounded an alarm if the opacity exceeded 20%. Lay-bys (Garages) are situated by the side of the tunnel every 300 m, with refuges at alternate Garages. When the vehicle entered the tunnel it released white smoke, gradually increasing in density. An operative recorded seeing smoke from the vehicle entering the tunnel, but no action was taken. This first detection event is shown as time 0 (10:46 hours) in Table 2. A sequence followed involving different tunnel management operatives receiving, discussing and exchanging information from various sources before the first action taken to close the tunnel at 10:54:30 as the French controller set the traffic lights throughout the tunnel to red. At 10:55 the alarm siren was sounded and péage closed at the tunnel mouth as the last two vehicles from France entered and the Italian portal lights were set to red.

Daegu train, tunnel and subway station fire 18th February 2003: A similar series of detection and warning events and delays occurred during the underground train fires in the Daegu Subway (Table 3) and the Channel Tunnel (Table 4). Despite the presence of automatic detection systems the Daegu incident, as with the others, combined early detection by occupants of train 1079 (even before the fire was fully ignited!), followed by confusion, with conflicting cues and information passing up and down the chain of command between the Station Control Centre (SCC) and the Operational Control Centre (OCC), losing 6 minutes during which preventative action might have been taken. Both detection and warning processes occurred in stages taking several minutes each.
Table 2: Timeline for Mont Blanc road tunnel fire 24th March 1999

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:46</td>
<td>Freight vehicle (PL0) entered tunnel pêage. Followed by two other vehicles</td>
</tr>
<tr>
<td>10:48</td>
<td>Two more vehicles enter tunnel</td>
</tr>
<tr>
<td>10:49</td>
<td>PL1 and PL2 enter tunnel</td>
</tr>
<tr>
<td>10:50</td>
<td>Tunnel staff recorded white smoke escaping from a lorry (no action taken)</td>
</tr>
<tr>
<td>10:51</td>
<td>Six more vehicles enter the tunnel</td>
</tr>
<tr>
<td>10:51:30</td>
<td>Four more vehicles enter tunnel</td>
</tr>
<tr>
<td>10:51:30</td>
<td>Vehicle PL0 driver sees smoke in rear view mirror but keeps driving</td>
</tr>
<tr>
<td>10:52</td>
<td>Four more vehicles enter the tunnel</td>
</tr>
<tr>
<td>10:54:15</td>
<td>Opacimeter No 5 reading 29.07% at Garage 18 (5.6 km), sounds alarm and lights up screen in French control room. Four more vehicles enter tunnel</td>
</tr>
<tr>
<td>10:54:30</td>
<td>Burning vehicle stops near Garage 21, 6.5 km from the French portal in Italian half of the tunnel, driver gets out and attempts but fails to reach extinguisher – fire grows rapidly producing black smoke. The Italian fire alarm system had been turned off due to a malfunction. French control acknowledges receipt of opacimeter alarm and check camera views Garage 16, 17, 19 seeing smoke in tunnel.</td>
</tr>
<tr>
<td>10:55:37</td>
<td>French controller contacts Italian Tunnel controller to discuss smoke but conversation inconclusive although smoke was visible on screens</td>
</tr>
<tr>
<td>10:56:10</td>
<td>Four vehicles coming up behind PL0 in dense smoke with great difficulty seeing where they were going, but 1st manages to overtake the stationary vehicle</td>
</tr>
<tr>
<td>10:57:32</td>
<td>French controller puts tunnel traffic lights to red throughout tunnel.</td>
</tr>
<tr>
<td>10:58:10</td>
<td>3rd vehicle passes PL0</td>
</tr>
<tr>
<td>10:59:37</td>
<td>Last of four vehicles manages to overtake the stationary PL0, after this the fire conditions are too extreme. Italian pêage closed, French official drives into tunnel from French portal to investigate</td>
</tr>
<tr>
<td>11:00:37</td>
<td>PL1 arrives behind PL0, stops 12 metres behind and tries to escape by running back along tunnel towards France – dies in tunnel</td>
</tr>
<tr>
<td>11:01:37</td>
<td>PL2 arrives behind PL1 driver gets out and tries to escape along tunnel</td>
</tr>
<tr>
<td>11:02:37</td>
<td>PL3 arrives behind PL2 driver gets out and tries to escape along tunnel</td>
</tr>
<tr>
<td>11:03:37</td>
<td>PL4 arrives 91 m behind PL0 driver collapses while trying to get out of cab</td>
</tr>
<tr>
<td>11:04:37</td>
<td>PL5 arrives but does remains in vehicle 111 metres behind burning vehicle</td>
</tr>
<tr>
<td>11:05:37</td>
<td>French Control calls Fire Service from Annecy</td>
</tr>
<tr>
<td>11:06:37</td>
<td>Italian Control calls Italian Fire Service from Courmayeur</td>
</tr>
<tr>
<td>11:07:37</td>
<td>French temperature fire detectors activate</td>
</tr>
</tbody>
</table>

Table 3: Timeline for Daegu subway train and station fire Korea 18th February 2003

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:52</td>
<td>Passenger tries to start fire on train leaving Daegu station</td>
</tr>
<tr>
<td>09:52:12-17</td>
<td>Station smoke alarms activated and displayed SCC CCTV but ignored</td>
</tr>
<tr>
<td>09:54:17</td>
<td>SCC informs OCC of station fire, OCC instructs train to proceed with caution</td>
</tr>
<tr>
<td>09:54:42</td>
<td>Train 1080 leaves BanWallDang station</td>
</tr>
<tr>
<td>09:55:37</td>
<td>Jungagno platforms smoke-logged</td>
</tr>
<tr>
<td>09:55:57</td>
<td>1080 approaches Jungagno station</td>
</tr>
<tr>
<td>09:56:10</td>
<td>Automatic fire shutters shut on floors 1 and 2</td>
</tr>
<tr>
<td>09:57:17</td>
<td>Driver of 1080 informed of station fire – proceed with caution</td>
</tr>
<tr>
<td>09:58</td>
<td>Train 1080 entered Jungagno station and stopped alongside blazing train 1079.</td>
</tr>
<tr>
<td>09:58:45</td>
<td>The doors opened briefly, but were immediately closed by the driver</td>
</tr>
<tr>
<td>09:59-10:03</td>
<td>Attempts to reconnect power, then train driver escapes but passengers trapped as doors remain closed – some manage to force open doors and escape train. Some overcome by smoke on platform and upper levels of station</td>
</tr>
</tbody>
</table>
Train and tunnel fire: Channel Tunnel freight train 18th November 1996: [[2,12] (Table 4)] A fire occurred under one of the road freight vehicles being carried on open flatbed rail wagons. Road vehicle crews were in an amenity coach behind the engine. The fire was seen as 2 metre high flames by tunnel staff just before the train entered the tunnel (21:47 hours). Fire detectors (optical, ionic and carbon monoxide) are located at 1.7 kilometre intervals along the tunnel. Activation of any one type raises an unconfirmed alarm at the Fire Equipment Management Centre (FEMC), while activation of any two raises a confirmed alarm to both the FEMC and RCC (Rail Control Centre). Table 4 shows the events.

**Table 4: Timeline for Channel Tunnel fire 18th November 1996**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>21:47</td>
<td>Security staff see 2 metre flames under freight vehicle as it passes towards tunnel, reported to supervisor who called the Terminal Control Centre (TCC).</td>
</tr>
<tr>
<td>21:48</td>
<td>1 Train enters tunnel from France.</td>
</tr>
<tr>
<td>21:49</td>
<td>2 TCC called Rail Control Centre. Smoke activates kilometre detector – indicating unconfirmed possible fire, train 2.2 km into tunnel.</td>
</tr>
<tr>
<td>21:50</td>
<td>3 Further detection activations to Fire Equipment Management Centre as train proceeds</td>
</tr>
<tr>
<td>21:51</td>
<td>4 RCC inform train driver of possible fire and to continue through tunnel (the prescribed emergency procedure), train driver cab alarm of unconfirmed fire at rear of train.</td>
</tr>
<tr>
<td>21:52</td>
<td>5 Second train enters tunnel behind first, and the driver soon encounters thick smoke</td>
</tr>
<tr>
<td>21:53</td>
<td>6 A confirmed fire alarm is activated on the first train, and in the tunnel. RCC begin to prepare for a fire in the tunnel.</td>
</tr>
<tr>
<td>21:54</td>
<td>7 A third train enters the tunnel from France. RCC instructs fire train driver to stop near cross passage.</td>
</tr>
<tr>
<td>21:55</td>
<td>8 19 km into tunnel first train driver stopped with amenity coach next to an escape cross passage. Train spanned three escape passages. Fire was at rear of train but air flow carried smoke forward filling tunnel at front of train so driver could no longer see cross passage door and Control did not know which of two was near the amenity coach. Tunnel closed to further trains.</td>
</tr>
<tr>
<td>21:57</td>
<td>10 More faults on fire train, tunnel crossover doors closed.</td>
</tr>
<tr>
<td>21:58</td>
<td>11 Power to fire train lost. Driver could not see cross passage door due to smoke.</td>
</tr>
<tr>
<td>21:59</td>
<td>12 Driver informs RCC he has lost power, but cannot say which cross passage he is near.</td>
</tr>
<tr>
<td>22:01</td>
<td>14 Driver informs RCC he had tried to leave cab but failed due to smoke, tried again with respirator but prevented again by smoke. Smoke starts to enter amenity coach. Chef du train opens amenity coach door, but could not see cross passage, closed door but coach full of smoke. Coach occupants experience difficulty breathing.</td>
</tr>
<tr>
<td>22:02</td>
<td>15 French fire brigade enter service tunnel and head for one of the cross passage points</td>
</tr>
<tr>
<td>22:03</td>
<td>16 Third train instructed to back out of tunnel</td>
</tr>
<tr>
<td>22:05</td>
<td>17 Pas de Calais emergency service take charge and requests ventilation fans start</td>
</tr>
<tr>
<td>22:10</td>
<td>22 Driver of second train instructed to evacuate to cross passage</td>
</tr>
<tr>
<td>22:13</td>
<td>26 Fans started but with blades at zero pitch so not effect</td>
</tr>
<tr>
<td>22:20</td>
<td>33 Fans reconfigured to clear smoke</td>
</tr>
<tr>
<td>22:21</td>
<td>34 Control centre opens two cross passage doors, one in front of train and one near amenity coach. Airflow from passages clears smoke so amenity coach occupants can see direction arrow and the open cross passage. Staff evacuate them into the cross passage. French fire brigade open front cross passage ahead of train and see smoke but cannot find train.</td>
</tr>
<tr>
<td>22:22</td>
<td>35 Tunnel fans clear smoke. French fire brigade find train occupants in passage, check coach is clear and rescue train driver.</td>
</tr>
</tbody>
</table>

Four minutes elapsed from the time a serious fire was seen before an “unconfirmed possible fire” was reported to the train driver. In the interim the Rail Control Centre had received both the verbal 2m flames report and the activation of the tunnel smoke detectors. Despite the large fire on the train, more than 6 minutes were lost before the fire was confirmed, during which a second and third trains were allowed to enter the tunnel. The “detection” and “warning” processes took approximately 6 minutes during which individuals became aware of different information, acting in different ways. This indicates the complexity of the detection and warning sequences in the Channel tunnel system.
Behavioural response of occupants to seeing smoke and flames – pre-travel time

The behavioural response of occupants during a developing fire depends upon a range of factors related to their individual characteristics, previous experience and knowledge of the situation, and the emergency evacuation systems, but particularly on their experience of the developing emergency. Volunteer studies have measured behaviour and evacuation times to emergency exits for simulated emergencies in pedestrian, rail and road tunnels. Some of these have involved travel through theatrical smoke [13,14]. Components of travel such as times required to evacuate trains and walk along tunnels have been measured. Findings are used to optimize the design of warning systems, audio and visual signage around emergency exits in tunnels, to provide a high level of “affordance”, so that vehicle occupants in road tunnels or train carriage occupants can be motivated to leave their vehicles quickly in an emergency, locate exits and have confidence that these will lead to a safe escape. This is particularly important given the short time “window” often available for safe escape as described. Limitations of these studies are that they cannot replicate the occupant experiences and conditions occurring in actual incidents, since participants are briefed on what to expect and know they are safe. The Mont Blanc and Gottard fires provide details of occupant experiences and behaviour during the development of extreme conditions. Key aspects of the Mont Blanc fire were the different behaviours of vehicle drivers and other occupants on the French and Italian sides of the fire as summarized in Table 2. Vehicles following the burning vehicle (PL0) from France were exposed to gradually increasing smoke in the tunnel, then much more intense smoke, and flames near the vehicle after it stopped. Apart from the vehicle immediately behind that on fire, drivers of following vehicles had no indication of conditions ahead. Initially they followed through relatively low density grey smoke, but then hit a wall of dense black smoke generated by PL0 after it stopped as the fire grew large. As the leading edge of this dense smoke front was swept towards the French portal at increasing velocity, driven by the tunnel ventilation, drivers were forced to stop (apart from the first four vehicles behind PL0, who managed to overtake and continue in clear conditions toward the Italian portal). The smoke front movement was recorded by the tunnel opacimeters and the stopping times of the vehicles has been calculated from the time they were recorded as entering the tunnel and the times required for them to travel to their final locations in the tunnel (Figure 6). Figure 7 shows the final position of vehicles on the French side and the final locations of the bodies of occupants who left their vehicles and walked along the tunnel towards France, either collapsing in the tunnel or dying in refuges.

Figure 6 Location with time of second smoke front generated from PL0 when it stopped, locations and times at which vehicles stopped and witness comments on visibility (vis).
Of the 38 occupants of the 24 vehicles stopping over a distance of 500 metres behind PL0, 28 died in their vehicles (one in his lorry trailer) without attempting to leave them. Only 9 left their vehicles, three of whom entered the emergency refuges and one the trailer of another vehicle. One was a motorcyclist. The CFD analysis of the fire indicated that the drivers of PL1, PL2 and PL3 were close enough to the burning vehicle to see the large growing fire. The buoyancy of the fire plume near PL0 is predicted to have produced clear conditions below the smoke layer for around 100 metres downstream of the fire before air entrainment and mixing brought the smoke down to road level. These drivers would have been aware of the large hot fire ahead of them, and been highly motivated to leave their vehicles and attempt escape within a minute or so of stopping. The driver of PL4 also attempted to leave his vehicle but collapsed trying to do so. The first two collapsed in the tunnel 220 m from PL0, having been overcome by smoke and heat, while the driver of PL3 managed to climb into the tractor of PL8, 303 metres from the fires, before being overcome. The rapid spread of lethal conditions is demonstrated by the collapse of the driver of PL8 166 m from PL0. His vehicle stopped at 10:58:16 and he was able to travel only 52 metres before collapsing and dying in the tunnel close to the bodies from PL1 and PL2. Most other vehicle occupants remained in their vehicles, but the three occupants of a car (VL20) stopped in smoke at 11:00:34, 407 metres from PL0 and walked along the tunnel for 525 metres before collapsing from carbon monoxide intoxication.

These findings illustrate the dilemmas faced by vehicle occupants when they have limited information during the early stages of an incident, then very little time to respond as conditions rapidly deteriorate. Clearly the drivers were very reluctant to leave their vehicles, initially because conditions were benign during the early stages then because the smoke was suddenly very thick. Few attempted to reach the refuges, indicating that these were not sufficiently obvious or “attractive” to induce vehicle occupants to try to reach them. The first few drivers close to the fire were forced to attempt escape, but quickly overcome by the intense heat, as occurred during the Gotard tunnel fire. Vehicle occupants further away were able to travel far enough through dense smoke to have reached refuges so it is possible that these, and many of the other occupants who stayed in their vehicles, could have survived if emergency exits or refuges had been sufficiently well-illuminated and attractive, with appropriate warning messages. In the event there were no exits from the refuges in this single bore tunnel, so refuge occupants died during the three day fire.

For rail passengers the situation depends to some extent on whether they are close to the fire on a train, or in a remote location either on the same or a different train. For the Daegu fire, the occupants of the train on which the fire started all escaped rapidly onto the platform and through the station.
immediately after the train stopped. Occupants of a train entering the station from the opposite direction stopping next to the burning train became trapped and died as this was rapidly engulfed by the fire and the doors remained shut, partly due to electrical failure [2].

The occupants of the amenity coach behind the engine on the Channel Tunnel train were in a situation somewhat similar to the vehicle occupants in the Mont Blanc tunnel [2]. The train came to a stop in the tunnel due to an electrical failure. It was then overtaken by the smoke front from the burning part at the rear, so that the driver, guard and passengers were trapped in the coach by encountering dense smoke outside when they attempted to open the doors. They were unsure of their location and could not see the emergency exits to the nearest cross passage. Their situation was therefore extremely hazardous at this point because a very serious fire was developing in the heavy goods vehicles further back on the train. The French fire fighters then opened one of the cross passage emergency doors as they searched for the train. Fortunately this happened to be at a location almost exactly adjacent to the amenity wagon of the train. The occupants saw the light from the open doorway as fans cleared the smoke and they were motivated to escape from the wagon, a few metres in the tunnel then through the escape doorway into the cross passage. This again illustrates the need for clear and “attractive” information to motivate escape from a place of relative safety (the amenity coach), towards an exit, and shows occupant reluctance to enter smoke unless they can see a promising escape route.

**Application of CFD and FED modelling to determine effects on escaping Mont Blanc occupants**

For vehicle occupants who left their vehicles, the data for arrival of vehicles at their final locations, the locations of the bodies and the calculation of times of collapse have been used to determine their fate. The combination of CFD and FED modelling has also been used to estimate the conditions they were exposed to, how they were affected by heat and smoke and the times and locations at which they are predicted to have collapsed. Comparing the times and locations of collapse estimated by these two method also provides some validation of the CFD and FED modelling predictions [1]. Figure 8 (a) shows the predicted conditions occupants of PL1, PL2 and PL8 were exposed to as they walked along the tunnel from their vehicles between 50 and 200 metres from the fire, while (b) shows...
the FIC for smoke, the FEDs for heat and asphyxiants and their distance from PL0 with time after PL0 stopped at 10:53:00. The main hazard to PL1 and PL2 as they got out of their vehicles was radiant heat from the smoke layer above their heads, sufficient to have been painful within around 20 seconds, while the visibility at head height (below the smoke layer) was good initially. As they move away down the tunnel the radiation decreases initially, but then as the smoke layer descends and as they become immersed in hot smoke, they become exposed to poor visibility, increasing radiation and convected heat. So from 11:02:00 all three occupants in the tunnel (PL1, PL2 and PL8) have received a heat exposure capable of causing pain to unprotected skin, and third degree burns from 11:01:30 with loss of consciousness from the inhaled doses of CO and HCN. Lethal conditions are estimated at 11:03, with death from the combined effects of intoxication and burns.

For the occupants of VL20, who left their vehicle 407 metres from PL0 at around 11:01:04, there was some smoke, but visibility was initially quite good (around 5 metres) as they started to walk back down the tunnel. But after five minutes they were overtaken by the dense smoke front. Visibility decreased to around 1 metre and the temperature was uncomfortably (but not painfully) hot (around 100°C), with an increasingly hazardous CO content and some HCN. Incapacitation from the inhalation of these toxic gases is predicted at 11:11:30 with death at around 11:12-11:13.

Table 5 compares incapacitation times in the tunnel from the investigation with calculated times from the CFD and FED modelling. The two independent methods gives similar results, thereby validating the modelling. There is a better agreement for timings and location of collapse for the main estimated fire scenario on the day than for the alternative CFD scenario considered. The FED modelling results therefore resolve these uncertainties with respect to the estimated fire conditions.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>PL1</th>
<th>PL2</th>
<th>PL8</th>
<th>VL20</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Estimates from investigation reports</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starting location (m from PL0)</td>
<td>12</td>
<td>36</td>
<td>166</td>
<td>407</td>
</tr>
<tr>
<td>Final location</td>
<td>222</td>
<td>220</td>
<td>218</td>
<td>932</td>
</tr>
<tr>
<td>Arrival time of vehicle</td>
<td>10:57:00</td>
<td>10:57:32</td>
<td>10:58:23</td>
<td>11:00:34</td>
</tr>
<tr>
<td>Earliest starting time</td>
<td>10:57:10</td>
<td>10:58:12</td>
<td>10:58:33</td>
<td>11:00:44</td>
</tr>
<tr>
<td>Estimated starting time</td>
<td>10:57:30</td>
<td>10:58:32</td>
<td>10:59:03</td>
<td>11:01:04</td>
</tr>
<tr>
<td>Earliest time of collapse</td>
<td>10:59:30</td>
<td>11:00:00</td>
<td>10:59:00</td>
<td>11:07:30</td>
</tr>
<tr>
<td>Estimated time of collapse</td>
<td>11:02:00</td>
<td>11:02:30</td>
<td>11:00:30</td>
<td>11:11:30</td>
</tr>
</tbody>
</table>

| **Results of CFD and FED modelling (Scenario 0 – actual fire)** | | | | |
| Exposure to dense smoke (Visibility <2 m) | 10:59:00 | 10:59:00 | 10:59:00 | 11:06:00 |
| Time of pain from heat (initial) | 10:57:00 | 11:57:32 | 11:00:30 | no pain |
| (second time) | 11:02:00 | 11:02:00 | 11:02:00 | or burns |
| Time of 3\textsuperscript{rd} degree burns | 11:01:30 | 11:01:30 | 11:02:00 | |
| Time of unconsciousness from asphyxiants | 11:01:30 | 11:01:30 | 11:01:30 | 11:11:30 |

**CONCLUSIONS**

Examination of the impact of different individual ASET and RSET parameters during serious fire incidents in tunnels shows that several key parameters may be inadequately addressed by current assessment methods or controlled in facility design and management. Because fires in vehicles and trains may grow to large conflagrations within a few minutes, immediate action is needed for suppression, measures such as tunnel closure and evacuation warnings. Studies of major vehicle and train tunnel fires show that detection and warnings can be processes involving several stages of investigation and reporting, leading to delays resulting in life loss. Systems and procedures should facilitate detection, shut-down and evacuation warnings within 1-5 minutes of fires reaching kilowatt sizes. Reporting of response times from simulated and minor emergencies would aid design. Another issue has been the response of occupants of vehicles or trains to warnings and fire cues. The reluctance of occupants to leave their vehicles, enter smoke and travel to escape routes has been a major cause of exposure to increasing and fatal hazards. This emphasizes the need to ensure rapid evacuation.
and the value of current research on exit “affordance”, but questions still remain about occupant behaviour in actual incidents. Useful work has been carried out on walking speeds and wayfinding in theatrical smoke, but data on movement speed through irritant smoke is limited. The modelling work reported here for the Mont Blanc incident confirms that a few tunnel occupants walked some distance through dense irritant smoke at reduced walking speeds consistent with speed data used for the model. With regard to tenability in smoke, the FED calculations relating smoke and asphyxiant yield data for mixed fuels confirm that subjects can walk through smoke with optical density 0.5 (visibility reflected 2 metres) for ~20-60 minutes before collapse, depending on their susceptibility.

REFERENCES


Quantification of a Safety Target for an Underground CNG Bus Terminal in Stockholm

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ABSTRACT
There are currently no detailed regulations or guidelines for designing the safety concept for an underground terminal for buses powered by compressed natural gas (CNG). Neither are there any explicit safety targets for this type of facility in legislation or practice. A dilemma arises both in the land-use planning process and building design process when evaluating whether the safety of such a bus terminal is sufficient. However, there are internationally accepted principles in other sectors that may be useful in defining a safety target in this case. In this paper it is proposed that such a safety target can be quantified using risk acceptance criteria expressed in terms of individual and societal risk. The method developed in this study is based on comparisons with risk acceptance criteria applied in other types of facilities and activities, both nationally and internationally, and required an extensive inventory of these. The method also takes into account the fact that people’s perceptions of risks affect their acceptance. The proposed safety target is presented in terms of an upper and a lower F-N curve, and includes the ALARP principle. In addition to this a maximum average risk is specified for the facility. A plausibility check was carried out indicating that the risk level defined by the safety target is lower than, or of the same order of magnitude as, many other corresponding risks in society, e.g. in other transport systems.

KEYWORDS: Dangerous goods, risk analysis, compressed natural gas, ALARP

1 INTRODUCTION
Planning for and designing a new underground commuter bus terminal in Katarinaberget in central Stockholm (see Figure 1) required the explicit identification and assessment of the risks and safety aspects affecting human life and health. There were several reasons for this. A project prerequisite was that the terminal would enable traffic with CNG buses. No specific safety targets were available from authorities for such a facility, and common practice in this area was sparse, or had not explicitly addressed the risk of CNG bus fire. In other words, the criteria for determination of environmental impact significance concerning risk exposure to life-safety is lacking. This is not a unique situation in Sweden. Very limited support can be found in international guidelines such as NFPA 502 [1] or AS4825 [2], where the proposed design scenarios at present does not cover the potential severe fire and explosion scenarios from a CNG bus fire in an enclosed space.

In Sweden there are no general safety targets stated in regulations for other sectors or industries, such as the transport sector or the chemical industry, that could be adopted directly. Previous experience has also shown that there can be significant variation between sectors when safety targets are expressed as the level of risk. This indicates that the basis for assessing the risks associated, for example, with a bus terminal involving vehicles fuelled with CNG with the potential for serious accidents, is not well defined when evaluating whether the level of safety is adequate or not. This causes principal problems both in the planning and design processes.
1.1 Purpose and objectives

This paper describes the work carried out to establish a safety target that can be used to assess whether a specific detailed land-use plan has adequately addressed risk to human health and safety, in accordance with the Swedish Planning and Building Act (PBL) [3]. According to the Swedish Environmental Act (MB) [4] it is also stated that human life and health and the environment shall be adequately protected against accidents and other negative consequences. The safety target is necessary in the evaluation of the assessment of the environmental impact in order to evaluate the risk of accidents. The safety target, also used as criteria for impact significance, in the context of this paper, refers to severe risks associated with an underground CNG bus terminal which are not covered or managed by specific detailed regulations governing safety.

![Main passenger entrance/exit](image)

**Figure 1. Overview of the commuter underground bus terminal in Katarinaberget in Stockholm.**

The objective of this study was twofold. One objective was to develop a method of quantitatively determining the safety target for an underground bus terminal operated with CNG bussed, taking into account the scientific basic principles underlying safety targets. The second objective was to apply the method in a real case for a bus terminal in central Stockholm, in order to derive a risk acceptance criteria (i.e. criteria for impact significance) necessary in both the land-use planning and the building design process.

1.2 Limitations

The safety target considered here is based on the conditions and requirements of a new underground CNG commuter bus terminal in Katarinaberget, Stockholm, during normal operation, and deals only with life safety. The purpose of defining such a target is to enable an evaluation of whether the level of risk in the bus terminal is tolerable with regard to human life and health, and/or whether there is a need for further risk-reduction measures. No such evaluation is made in this study, but is integral to the type of risk assessment used for assessment of environmental impact in each specific project. This paper provides a necessary component to be able to carry out such an assessment, i.e. the safety target. Information about the other component that forms the base for the risk evaluation, i.e. the risk analysis, is presented in [5]. The complete risk assessment performed in the specific project when gaining permission in the planning process is publicly available [6].

The nature of the facility indirectly imposes a number of constraints, for example, the risks associated with the facility do not affect those outside the facility, the natural environment or other important societal functions. The safety target is only relevant for evaluation serious incidents within the bus terminal, that are not sufficiently addressed by other specific regulations, e.g. the building code and the workplace health and safety requirements, and their application, e.g. the fire safety design strategy [7]. The measures for fire protection defined in the concept fire and life safety strategy are intended to fulfil the regulations that apply to the kind of fire scenarios that may occur in the facility and in buses running on liquid fuels such as diesel, ethanol, etc., according to the PBL [3] and the Swedish building and construction regulations [8] [9]. As protection against serious accidents involving CNG buses
is not covered in any detail in the above-mentioned regulations, further risk-reduction measures have been included based on a detailed analysis of these risks [10]. Corresponding means of dealing with serious accidents can be found within other industries internationally, such as the chemical industry or oil and gas industry.

2 BACKGROUND

There are currently no national, regional or local safety targets in Sweden that can be applied to the kind of facility in question in this study.

An overall vision for the safety of the Swedish population has been formulated in the Government Bill, “Goals for the Safety of the Population” [11], where it is stated that society shall “protect the lives and health of the population”. It is also made clear in the “National Safety Strategy” [12] that two of the goals regarding human safety are to protect the lives and health of the population and the functionality of society. A similar general goal has been formulated in the “Safety and Security Programme” [13] of Stockholm City Council, which is both the commissioner and inspector of buildings and facilities.

The Stockholm County Public Transport Authority, which will be operating the terminal, has also formulated a general traffic safety goal [14] in which it is stated that: “No one shall suffer serious injury or death as a result of accidents involving the operations of the Authority”. It is also stated in the “Guidelines for Fire Protection in Buildings, Facilities and Vehicles” [15] that: “The safety of passengers, personnel and third parties shall be high, and shall be continuously improved when deemed reasonable and motivated. The long-term goal is that no individual shall suffer death or serious injury as a result of fire.” These general goals are formulated in different ways in terms of the consideration of safety in Figure 2.

Figure 2. Some of the general goals regarding safety relevant to the present study.

The way in which safety is related to concepts such as risk, risk assessment, individual and societal risk, is not always clear, which can lead to both the goals and the results from risk analysis being perceived as difficult to understand and apply in planning and design situations. Therefore, a short introduction is given below to the definition of each concept, and the way in which they are used in this paper. This is followed by a brief description of some of the areas that are important in the development of safety targets, such as the principles underlying safety targets, risk acceptance criteria, risk-reduction measures and the perception of risk.
2.1 The concept of risk

The concept of risk can have different meanings depending on the context. A common definition, often used in engineering, is that risk is regarded as an accident scenario, the probability of this accident in combination with its negative consequences [16].

Risk management is the name usually given to the process of identifying, analysing, evaluating and managing undesirable incidents (risks) that can prevent specific goals from being achieved. In this case, the goal is to achieve a sufficient level of safety from the perspective of society.

A risk assessment is part of the risk management process and deals with the identification, analysis and evaluation of risks to determine whether there is a need for measures to reduce the consequences or probabilities of that risk. In order to reduce the risk and complete the risk management process it is necessary for the assessment to be connected to decision making that leads to the implementation of any necessary measures, and monitoring and review of the effects of the measures.

2.2 The principles underlying safety targets

Determining whether a facility or activity is “sufficiently safe” involves determining whether a specific safety target has been achieved. In other words, it involves adopting a position and making decisions regarding the effects of risks and the need for mitigation measures, i.e., following the steps of the risk management process.

Safety targets have been developed by several countries in many sectors [17], including public transport, nuclear power, the process industry, aviation, road transport, shipping and health care, in order to fulfil, in various ways, the basic principles presented in Figure 3.

<table>
<thead>
<tr>
<th>Justification of the activity</th>
<th>Optimization of protection</th>
<th>Distribution of risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>An activity should not lead to risks that are unreasonably high in relation to the benefit to society as a whole.</td>
<td>Risks should always be minimized through reasonable protective measures, bearing in mind their benefit (in terms of reducing the risks), cost and practicability.</td>
<td>Risks should be reasonably distributed within society, in relation to the benefit of the activity. This means that individuals or groups of people should not be exposed to disproportionately high risks in relation to the benefit received.</td>
</tr>
</tbody>
</table>

Avoiding catastrophes

If risks are realized, they should be of the nature that they can be dealt with using existing resources, rather than causing catastrophes.

Proportionality

The level of detail in risk assessments should be proportional to the level of risk, and it should be possible to exclude negligible risks from detailed risk assessments.

Continuous improvement

Levels of societal risk should in general, be reduced over time.

Figure 3. The basic principles underlying the development of safety targets.

The above principles were deemed to be appropriate as a starting point for the development of the safety target in the present case. In other words, it is reasonable to expect the safety target to address all these principles, and it is suggested that these be applied to the case of the proposed underground bus terminal in Stockholm.

One way of developing a safety target that takes into account the above principles is to formulate risk acceptance criteria using quantitative measures of risk. The advantage of quantitative measures is that they are measurable, allow for comparison and consistent management of safety over time. Quantitative measures of risk allow an explicit risk acceptance level to be stated. In principle, this means that a level of risk above this level is unacceptably high (i.e., the level of safety is too low), while a risk
level under the risk acceptance level can be regarded as acceptably low (i.e. the safety is sufficiently high). This principle, or method of application, has been elaborated in many areas to define a range between acceptable and unacceptable, in which it is not possible to state directly whether the risk is acceptable or not [18]. This is sometimes called the As Low As Reasonably Practicable, or ALARP region, and means that the risks can be accepted if all reasonable practicable measures are taken (see Figure 4). What can be regarded as reasonable practicable, can be evaluated using cost-benefit analysis, for example.

The above-mentioned basic principles (Figure 3) can be accommodated in a satisfactory way by studying the two risk measures individual risk and societal risk using a model that includes the ALARP region.

The individual risk is the probability (often expressed as the frequency per year) of the fatality of a hypothetical single person, who is exposed to a specific risk. The individual risk does not take into account how many people that may be affected by the accident. The aim of this measure of risk is to ensure that individuals are not exposed to unacceptably high risks.

The societal risk is the probability (often expressed as the frequency per year) that a certain number of fatalities will result from exposure to a certain risk. The societal risk takes into account the density of population, in other words, it is a measure of the consequences in terms of the number of people affected by the accident scenario.

![Figure 4. A principle for risk assessment when using quantitative measures of risk.](image)

### 2.3 Risk acceptance criteria

The general visions regarding safety described above do not include any concrete suggestions for risk acceptance criteria for individual risk or societal risk, and do not provide any support in the application of quantitative risk measures. Some help has been provided by the Swedish Civil Contingencies Agency (MSB) [18] and the Stockholm County Administrative Board [19]. This means that responsibility for taking a stance regarding the effects of risk is borne by the person or operator involved, or those responsible for a particular project.

A lack of risk acceptance criteria also leads to difficulties in determining whether the level of risk is appropriate or not. It is thus difficult to obtain an indication of whether further safety-improving measures are necessary using risk analysis as a tool. This was pointed out by an independent expert committee in an early review of the bus terminal project [20], and by The Greater Stockholm Fire Brigade [21] during the planning process.

Stockholm City Council has not taken a stance regarding the general specification of requirements [22] drawn up together with the Greater Stockholm Fire Brigade, which stated that: “it should be clear
whether the risks are acceptable from the point of view of both the individual and society”. The question of actual levels of risk are not dealt with in strategic documents governing comprehensive urban planning [23], the accompanying assessment of the environmental impact [24], or Stockholm City Council’s Safety and Security Programme [13]. The lack of both national and local standpoints means that the way in which the risk of accidents is described and evaluated can vary from one case to another. This applies to risk management throughout the whole planning process – from the assessment of whether the risk of accidents can cause significant effects on the environment, to the evaluation of the need for additional risk-reduction measures, and the final assessment and compromises made between the risk of accidents and other interests.

No explicit risk acceptance criterion is given in the Stockholm County Public Transport Authority’s safety target, but it can be interpreted as promoting the principle of continuous improvement in a similar way to the vision of zero deaths in road traffic accidents in Sweden [25].

Despite the fact that no explicit criteria are provided in the planning process regarding the effects of risk, decisions are made continuously by, for example, the Stockholm County Administrative Board, as to whether the detailed plan should be reviewed, where the effects of risk are part of the general assessment. The County Administrative Board also approves assessments of the environmental impact of, for example, planned road and rail infrastructure, which also include the effects of risk as part of the general assessment. The basis for the Board’s assessment in such situations is not always completely transparent, and may vary from one project to another.

2.4 Risk-reduction measures

The principle of risk reduction (Figure 4) means that measures must be taken if the level of risk is in the region regarded as being unacceptably high, in order to ensure that a certain safety target is fulfilled. All reasonable measures must be taken to reduce the level of risk when risks are in the ALARP region, bearing in mind the cost-benefit perspective. The aim of these measures is to reduce the degree of risk in one way or another. Based on the definition of risk used in this context, it follows that risk-reduction measures can be directed towards reducing the probability (or frequency) of an incident, or reducing the consequences of that incident, or both, as illustrated in Figure 5.

![Figure 5. The principle of risk-reduction measures when the probability of the incident is reduced (A), the consequences are reduced (B), or when both are reduced (C).]

2.5 Risk perception

Risks and the level of risk perceived to be tolerable by society can be valued differently. The kind of factors that affect how we perceive risk, and what kind of risk is acceptable in society may be technical/mathematical, ethical, political or societal. Some of the factors that have the greatest effect on people’s perception of risk are described below. This is by no means a complete list, but according to research in the field [26] [27], these factors dominate to such a degree that they give a good representation of what governs risk assessment, and why it is that there are such large variances in the levels or targets accepted by society for different risks. This also explains indirectly why different parties are differently inclined to invest in measures to further reduce the level of different kinds of risk.

People find it easier to accept a risk when they perceive a clear benefit of being exposed to the risk associated with a certain activity [28]. Many perceive driving or travelling in a car to be a beneficial
activity. However, road traffic is associated with a level of risk that would not necessarily be acceptable in other technical systems; the benefit of such technical systems may be less clear to people, and are therefore regarded as more hazardous.

Another related aspect can be considered here, namely people’s knowledge of risks. The ability to recognise and understand the risks associated with various activities affects how we assess them, as well as our ability to actually control the risk. There may be such differences between someone working in an underground bus terminal, and a member of the public, e.g. a passenger. These two individuals have quite different knowledge regarding the nature of the activity in question, its risks, the protective measures implemented, early warnings signals, and how the extent of an accident can be limited, if this is possible.

Whether or not an activity is undertaken voluntarily is another factor that affects how risks are perceived. We find it easier to accept the risk of a voluntary activity such as rock climbing, than one we are required to carry out, for example, working in the chemical industry [28]. Similarly, people who either live close to a route along which dangerous goods are transported, or who work within a hazardous facility, do probably not want to be in the vicinity of these risks, but they accept the situation. For a household to move may be possible, but this depends on other factors, apart from the voluntary nature of the activity. Another aspect is that many in the public can be unaware of the risk exposure they are subjected to, i.e. the (un)knowledge of risk.

The degree of vulnerability may vary among those exposed to a certain risk. Differences in vulnerability can be discussed in the context of several factors, such as age and mobility. Public transport is intended for all to use, but the number of more vulnerable people may vary depending on which part of the system is being considered. The ability to escape from a dangerous situation is also related to vulnerability. In order to be able to escape from a dangerous situation one must first become aware of it, then react to it, and finally evacuate. All of these steps can be affected by age and mobility, but the individual’s knowledge concerning the source of the risk is also important.

The duration of the exposure to a risk varies depending on the type of risk and how long or how often a person is in the vicinity. There will be differences between people who use public transport regularly to commute to work, and those who use it more seldom. Similarly, the exposure to risk resulting from an industrial plant where hazardous materials are used will be quite different for someone living in the area and someone simply passing through the area.

The potential for catastrophe is another factor affecting risk acceptance that describes how people perceive the possibility that the source of the risk may lead to a major disaster, e.g. very severe consequences. Enclosed spaces are often perceived as a factor that can increase the potential for a catastrophe. Examples of this are tunnels and underground spaces, as well as large underground train or bus stations, which can also constitute totally or partially enclosed spaces, and thus have a greater potential for catastrophe than open ones.

The amount of attention directed by the media to a source of risk can vary depending on the location of the risk; e.g., whether it is an open area, or close to a school. The kind of consequences that could arise can also be assessed differently; the release of many small emissions are not given as much media coverage as a single large emission.

Finally, people’s perception of risk can depend on whether the source is manmade or natural. A tunnel is perceived as being a manmade construction, and may lead to an increased concern, despite the fact that technical equipment has been installed to detect hazardous events and reduce their consequences.

3 METHODS FOR THE QUANTIFICATION OF SAFETY TARGETS

Based on the principles for the construction of safety targets given in Figure 3, it can be deduced that risk acceptance criteria for the risk measures individual risk and societal risk should constitute a central part of the safety target for the bus terminal in question. Risk acceptance criteria can be used to determine whether the level of risk is acceptable or not, or whether further measures are required. A number of approaches for estimating a reasonable level for such risk acceptance criteria are presented.
in Section 3.1. The method chosen for application to the commuter bus terminal in Katarinaberget, Stockholm is then presented in Section 3.2.

3.1 Possible approaches to define the acceptance level
Table 1 lists a number of well-established approaches that can be used to determine the level of risk acceptance criteria in the bus terminal.

Table 1. Possible approaches to setting the level of risk acceptance criteria.

<table>
<thead>
<tr>
<th>Description of method</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Apply current best practice regarding risk acceptance criteria for underground bus terminals. The use of buses running on CNG in underground facilities is a relatively new phenomenon, both in Sweden and internationally. No standards or best practice where the novel risks are considered explicitly, nor applicable risk acceptance criteria, could be identified.</td>
</tr>
<tr>
<td>B</td>
<td>Use current data (accident statistics) for existing comparable facilities and evaluate whether the risk acceptance criteria should be the same as, higher or lower than historical outcomes. No sufficiently comprehensive accident statistics are available for similar vehicles in an underground facility. However, there are examples of accidents on the open road that show that various scenarios with potentially serious consequences can arise.</td>
</tr>
<tr>
<td>C</td>
<td>Compare with risk acceptance criteria applied to other kinds of facilities in other sectors, in Sweden or internationally. A number of acceptance criteria have been applied to other sectors in Sweden and internationally. Comparisons should take into account the different conditions, i.e. perception factors, prevailing in the evaluation of the different acceptance criteria.</td>
</tr>
<tr>
<td>D</td>
<td>Compare with the general death rate in the population (e.g. natural background risks or risks associated with transportation) and base acceptance criteria for the facility in question on this level. The application of this method as the only basis for acceptance criteria is deemed to be complicated if large uncertainties in the results are to be avoided. Comparison with natural background risks is deemed to be useful provided a plausibility check is performed, and the chosen levels are discussed.</td>
</tr>
</tbody>
</table>

3.2 Proposed method for the quantification of the safety target
The method deemed to be suitable for the current conditions is to apply method C, and then to use method D as a plausibility check. This means that a comparison is made between risk acceptance criteria applied to other kinds of facilities and activities in other sectors, in Sweden and internationally. This comparison should take into account the differences in the conditions prevailing when those criteria were established. The risk perception factors described above should also be compared to ascertain whether there is a need to increase or decrease the level of safety in the bus terminal in relation to the level or levels identified as being applicable. The plausibility check can be carried out as a comparison with both background risks and the fatality rate associated with other kinds of transport and activities.

3.2.1 Individual risk
An activity-based risk measure, i.e. the probability of death each time a passenger enters the bus terminal, is used to evaluate the individual risk. A location-specific risk measure is not deemed as relevant in a situation where the flow of people is a more dominating principle than the fact that a person is in a specific place for a certain time. An activity-based risk measure allows comparison with a number of other modes of transports where similar conditions prevail, and can be used for a plausibility check, as described in Chapter 6.
3.2.2 Societal risk

As accidents involving CNG have the potential to affect numerous people, the societal risk must be included in the safety target. In most sectors, the societal risk is usually expressed in terms of F-N curves or the average risk [18].

Depending on the sector used as the reference, it may be necessary to normalise or scale the criterion for application to the bus terminal in a proportional way. This can be done, for example, by taking into account the size of the area where the risk exposure is evaluated with the criterion or the number of people exposed to risk. For example, comparing the case of the bus terminal with the nationwide transport sector will not be as relevant as comparing with a single terminal or a set distance approximating the size of the terminal, e.g. one kilometre.

4 ANALYSIS

This chapter describes the analysis based on the method proposed above. An inventory of national and international risk acceptance criteria is made, followed by a comparison of the risk perception factors associated with an underground bus terminal and other areas of application.

4.1 Inventory of national and international risk acceptance criteria

Quantitative acceptance criteria are used to describe safety targets in a number of sectors. We have surveyed national and international acceptance criteria in order to obtain an idea of the levels used. Figure 6 shows a number of examples of the levels employed in various sectors, in a number of European countries [17][29].

![Figure 6. Examples of quantitative risk acceptance criteria in different sectors in different countries.](image)

It can be seen that there is considerable variation between different countries within the same sector. There is also significant variation between different sectors in the same country. This means that there is a broad range of acceptance criteria, making the choice of criterion appropriate for the current facility challenging.

In order to establish a suitable level, the two Swedish cases included in Figure 6 are considered, and a comparison is made between the important factors affecting the tolerated risk in society between the bus terminal and these two cases.

The first example (case) is a risk assessment for a Swedish modern road tunnel (Norra länken) included in the submission from The Swedish Transport Administration (Trafikverket) for approval to the
The Swedish Transport Agency (Transportstyrelsen). Although there is a legal demand for such a risk assessment, there are as yet no relevant guidelines on applicable levels. Information on the acceptance criteria in this case was obtained by requesting the relevant documentation from the Swedish Transport Agency [30]. The road tunnel gained approval, which makes the risk levels used for verification of the tunnels safety concept in this case relevant as precedent.

The second example concerns land-use planning and development adjacent to dangerous goods routes in Sweden. Common practice in Sweden in this case is to use the risk criteria proposed by DNV (Det Norske Veritas) [18]. Even though these criteria is not formally stated in regulations, e.g. in PBL [3], they are referenced to in guidelines issued by several County Administrative Boards, e.g. in Stockholm [19].

4.2 Comparison of the factors that affect risk perception

As there is a significant difference between the two Swedish examples, the factors affecting risk perception, discussed in Section 2.5, are considered. The table below presents a comparison between the present case of the bus terminal, and those regarding road tunnels and development adjacent to dangerous goods routes or close to hazardous facilities, i.e. chemical industry. A simplistic assessment is made of whether the risk perception factors lead to a higher or lower acceptance of risk in the present case.

Table 2. Comparison of the factors affecting risk perception in the case of the bus terminal, and the two Swedish cases described above.

<table>
<thead>
<tr>
<th>Factor affecting risk perception</th>
<th>Road tunnel (urban dual carriageway) vs. bus terminal</th>
<th>Land-use planning adjacent to dangerous goods routes vs. bus terminal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possibility of knowing about the risk</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Possibility of being able to affect the risk</td>
<td>/</td>
<td>-</td>
</tr>
<tr>
<td>Benefit of the hazardous activity</td>
<td>/</td>
<td>-</td>
</tr>
<tr>
<td>Voluntariness</td>
<td>/</td>
<td>-</td>
</tr>
<tr>
<td>Vulnerability of those exposed</td>
<td>/</td>
<td>-</td>
</tr>
<tr>
<td>Possibility to evacuate the hazardous area</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Potential for catastrophe</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Media coverage</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Natural or manmade risk</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

+ Higher risk acceptance than in the bus terminal
- Lower risk acceptance than in the bus terminal
/ Similar risk acceptance as for the bus terminal

5 SUGGESTED RISK ACCEPTANCE CRITERIA FOR THE UNDERGROUND BUS TERMINAL IN STOCKHOLM

The analysis presented in the previous chapter shows that the risk acceptance criteria used in the case of modern road tunnels in Sweden can be appropriate for the underground commuter bus terminal in Katarinanberget, in Stockholm. This conclusion was based on the levels of risk applicable to Swedish conditions, which are in line with those applied in other European countries, and an evaluation of the most important factors affecting the perception of risk. Sections 5.1 and 5.2 explain how the risk acceptance criteria for individual risk and societal risk can be expressed so as to represent the corresponding level of risk for the bus terminal.
5.1 Suggested individual risk criterion

The individual risk level is obtained by estimating the probability of fatality as a result of commuting to work through a modern road tunnel. The estimate is based on information on the risk acceptance criterion taken from the documents submitted to the Swedish Transport Agency [28] for approval in the case of the road tunnel in question:

- Total distance travelled: 170 000 000 person-km/year.
- Maximum average risk according to the criterion for the facility: 0.46 fatalities per year\(^1\).
- Distance travelled in a tunnel by a commuter travelling to work 200 days/year: 800 km/year (assuming a one-way journey of about 2 km).
- Maximum individual risk (probability of fatality) as a result of commuting in a modern road tunnel on an urban dual carriageway: \(2.2 \times 10^{-6}\)/year.

5.2 Suggested societal risk criterion

The suggested societal risk criterion for the bus terminal is presented as F-N curves in Figure 7.

![Figure 7. Suggested societal risk criterion in terms of upper and lower F-N curves for the underground bus terminal.](image)

It may be necessary to scale or adjust the risk acceptance criterion for application to the bus terminal. In the example with the road tunnel, the length of the tunnel was assumed to be about 1 km and during heavy traffic conditions this means about 600-700 people will be exposed in each tunnel tube at any one time.

The corresponding distance in the underground bus terminal, which in many key safety aspects can be regarded as being similar to a tunnel, is 800 m, and it is estimated that about 1000 people will be in or close to the areas used by the buses. It is here assumed that the areas used by the buses are separate from the areas used by passengers while waiting, i.e. people in the waiting room are not exposed to

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\(^1\) Both the F-N curve and the probability of fatality in the Swedish road network (0.0027 fatalities per million vehicle-km) are included in the acceptance criterion for the road tunnel. Assuming 170 000 000 person-km per year in the tunnel gives 0.46 fatalities per year (i.e. \(3.3 \times 10^{-5}\) per km per year). The maximum expected number of fatalities taken from the F-N curve for the upper risk level is equivalent about 10 fatalities per year in the tunnel. Both these criteria must be fulfilled, i.e. neither the average risk of 0.46 fatalities per year nor the upper F-N curve may be exceeded.
risk from the buses. This implies that the fire compartmentation and structural elements of the waiting room must be designed to withstand the overpressure in the event of a CNG explosion or a jet flame. Based on the above assumptions, the bus terminal corresponds roughly to a 1 km tunnel, and the number of people using the facilities and exposed to risks is about the same. We therefore consider it unnecessary, at this stage, to scale or adjust the societal risk criterion.

As a complement to the F-N curves, we suggest a maximum average risk of $3.3 \cdot 10^{-2}$ fataliess per year, which leads to a similar level of safety as on the Swedish open road network, as in the case of the acceptance criterion derived for the recently approved and opened for operation Swedish motorway tunnel Norra länken.

In the criterion used for the road tunnel, only an upper level is given with an F-N curve. This means that the case only specifies that the risk is unacceptably high above a certain level. Bearing in mind the basic principles for safety targets discussed in Section 2.2, we deem it appropriate to formulate criteria that allow the application of a plausibility check, and to emphasize the principle of continuous improvement.

This can be done by defining an ALARP region (see Figure 4). The principle of continuous improvement means that it is appropriate to set a relatively low lower limit in this region. We therefore suggest that this level be set at the lower level of the DNV criterion [18], which is often used in cases concerning the exploitation of land close to routes for the transportation of dangerous goods.

6 PLausibility Check

This chapter presents a plausibility check of the suggested risk acceptance criteria for the individual risk and societal risk in the underground bus terminal.

6.1 Individual risk

In order to compare the activity-based risk acceptance criterion for the individual risk, a comparison can be made with other activities in order to gain an idea of their size. It is important to bear in mind that the level of risk acceptable to the individual and society is governed by the perception factors discussed above.

Another relevant comparison is to study travelling by other modes of transport that corresponds to a probability of fatality of $2.2 \cdot 10^{-6}$.

- Riding a motorbike for 21 km [31]
- Walking 58 km [32]
- Cycling 32 km [33]
- Travelling 798 km in a car [31]
- Travelling 3460 km in a jet aircraft [33]
- Travelling 21 000 km by train [31]

In order to place this in relation to other risks, the risk of fatality as a result of various background risks and activities is given in Table 3. It can be seen that an individual risk level of fatality of $2.2 \cdot 10^{-6}$/year is below the level to which many people are normally exposed during the course of a year.
Table 3. Examples of the annual individual risk of fatality due to various background risks and modes of transport [34].

<table>
<thead>
<tr>
<th>Cause of death</th>
<th>Individual risk of fatality per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural background risks</td>
<td></td>
</tr>
<tr>
<td>Being struck by lightning</td>
<td>1.0 $10^{-5}$</td>
</tr>
<tr>
<td>Fire</td>
<td>1.4 $10^{-5}$</td>
</tr>
<tr>
<td>Workplace accident (fulltime workers)</td>
<td>1.3 $10^{-5}$</td>
</tr>
<tr>
<td>Accidents in the home and during leisure activities</td>
<td>2.2 $10^{-4}$</td>
</tr>
<tr>
<td>All causes, individuals aged 20-40 y</td>
<td>1.0 $10^{-5}$</td>
</tr>
<tr>
<td>All causes, individuals aged 60 y</td>
<td>1.0 $10^{-5}$</td>
</tr>
<tr>
<td>Other modes of transport, gender, age range</td>
<td></td>
</tr>
<tr>
<td>Car, male, 15-24 y</td>
<td>8.2 $10^{-6}$</td>
</tr>
<tr>
<td>Car, male, 65-84 y</td>
<td>7.4 $10^{-5}$</td>
</tr>
<tr>
<td>Car, male, 25-64 y</td>
<td>5.1 $10^{-5}$</td>
</tr>
<tr>
<td>Car, female, 65-84 y</td>
<td>3.2 $10^{-5}$</td>
</tr>
<tr>
<td>Car, female, 15-24 y</td>
<td>2.4 $10^{-5}$</td>
</tr>
<tr>
<td>Walking, male, 65-84 y</td>
<td>2.3 $10^{-5}$</td>
</tr>
<tr>
<td>Cycling, male, 65-84 y</td>
<td>2.1 $10^{-5}$</td>
</tr>
<tr>
<td>Car, female, 25-64 y</td>
<td>1.9 $10^{-5}$</td>
</tr>
<tr>
<td>Walking, female, 65-84 y</td>
<td>1.3 $10^{-5}$</td>
</tr>
<tr>
<td>Motorbike, male, 25-64 y</td>
<td>1.3 $10^{-5}$</td>
</tr>
<tr>
<td>Moped, male, 15-24 y</td>
<td>1.0 $10^{-5}$</td>
</tr>
</tbody>
</table>

*Only groups for whom the risk is greater than 1.0 $10^{-5}$ are included.

6.2 Societal risk

F-N curves can be difficult to interpret and compare as the scales are often logarithmic and the curves may have different gradients. To facilitate comparison between the different levels of risk identified and represented by F-N curves, the so-called average risk, i.e. the expected number of fatalities per year based on the level of risk, is presented in the table below for various cases in a number of countries, in decreasing order of risk.

Table 4. Maximum expected number of fatalities per year (average risk) based on the risk acceptance criteria (F-N curves) for various cases in different European countries.

<table>
<thead>
<tr>
<th>Country and case</th>
<th>Maximum expected number of fatalities/year (average risk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK RORO port (per vessel)</td>
<td>6.9 $10^{-4}$</td>
</tr>
<tr>
<td>Italy, tunnels (per km)</td>
<td>4.6 $10^{-1}$</td>
</tr>
<tr>
<td>Denmark, road tunnels (per km)</td>
<td>4.0 $10^{-1}$</td>
</tr>
<tr>
<td>UK, chemical industry</td>
<td>6.9 $10^{-2}$</td>
</tr>
<tr>
<td>Sweden, modern road tunnel (Norra länken) (per km)</td>
<td></td>
</tr>
<tr>
<td>- upper level F-N curve</td>
<td>9.9 $10^{-2}$</td>
</tr>
<tr>
<td>- average on Swedish open road network</td>
<td>3.3 $10^{-2}$</td>
</tr>
<tr>
<td>Netherlands, road tunnels (per km)</td>
<td>9.9 $10^{-3}$</td>
</tr>
<tr>
<td>Netherlands, chemical industry</td>
<td>9.9 $10^{-4}$</td>
</tr>
<tr>
<td>Sweden, development of land adjacent to dangerous goods routes (per km) upper level</td>
<td>6.9 $10^{-4}$</td>
</tr>
<tr>
<td>Sweden, development of land adjacent to dangerous goods routes (per km) lower level</td>
<td>6.9 $10^{-5}$</td>
</tr>
</tbody>
</table>
It can be seen that the average risk corresponding to the upper F-N curve for the societal risk acceptance criterion corresponds to $9.9 \cdot 10^{-2}$ fatalities per km per year in the road tunnel, while the corresponding value for the Swedish road network is $3.3 \cdot 10^{-3}$ fatalities per km per year in the road tunnel. If the F-N curve criterion is used in the same way as in the Netherlands, where only accidents with 10 or more fatalities are included, the value obtained is $9.9 \cdot 10^{-3}$ expected fatalities per km per year. It is thus deemed that the suggested risk acceptance criterion is of the same order of magnitude as that in tunnels in European countries such as the Netherlands, Italy and Denmark. However, the average risk is higher than those applied in the chemical industry and in the land-use planning adjacent to dangerous goods transport routes.

7 CONCLUSIONS

Although there are no explicit safety targets for the kind of facility considered in this study, we have presented a specific value for the proposed underground commuter bus terminal in Katarinaberget, in the city centre of Stockholm.

The safety target was quantified using risk acceptance criteria for measures of the individual risk and societal risk. The value obtained was based on comparisons between the risk acceptance criteria for other types of facilities and activities in various sectors, both nationally and internationally. A plausibility check was made showing that the risk level of the safety target is lower than, or similar to, that for many other kinds of risk in society, for example, other forms of transport.

The suggested risk acceptance criterion consists of an upper and a lower F-N curve. The highest tolerable risk level is equivalent to the individual and societal risk in a modern Swedish road tunnel. In order for this suggestion to live up to the basic principles discussed in Section 2.2, continuous improvements will be necessary to reduce the level of risk. The suggested criterion includes a so-called ALARP region, within which such improvements are required. Examples of the type of improvements are administrative and organisational controls, or technical measures aimed at the fleet of buses. The lower limit in the ALARP region corresponds to the risk level that is considered acceptable in the exploitation of land close to transport routes for hazardous goods in Sweden. As a complement to the F-N curve, we suggest a maximum average risk of $3.3 \cdot 10^{-2}$ fatalities per year, which is equivalent to the level of safety on the Swedish road network, and similar to the acceptance criterion applied for a modern Swedish road tunnel.

The safety target proposed in this study has been deemed appropriate by the head of administration of the Stockholm County Public Transport Authority [35] and has also formally been approved by the Stockholm Municipal Council in the detailed land-use planning of the underground bus terminal [36]. No objections regarding the safety target have been raised by either The Stockholm County Administrative Board or The Greater Stockholm Fire Brigade. The presented safety target has been a central component in both the planning and design process for the bus terminal when developing the safety concept and evaluating the acceptability of the residual risk [6].

ACKNOWLEDGEMENTS

This work was carried out in close collaboration with the Slussen Project, the Stockholm City Council and the Stockholm County Public Transport Authority. We would like to especially acknowledge those who participated in the working group for their contributions to this study coordinated and supervised by project manager Anders Norlin and Eva Johannisson. We would also like to express our deep thanks to Henrik Mistander at Structor Riskbyrån, who is the co-author of the project report on which this paper is based.
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Considerations for Design Fire Scenarios in Underground Transit Station Public Circulation Areas

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ABSTRACT

Design fire scenarios considering trash or other combustible materials in transit station public areas are becoming more frequently evaluated in the engineering analysis of Emergency Ventilation System performance of rapid transit stations. In many cases the design fires that are specified, which are intended to represent fire risk of waste receptacles or other transient combustible materials such as passenger baggage, are disproportionate to the actual fires intended. The potential risk of fire spread from small fires in public areas of modern transit stations is generally addressed with other provisions, such as non-combustible construction, limitations on interior finishes, and restriction of combustible content. This disconnect between the large design fires and the credible fire scenarios for these station public areas can result in substantial increases in life safety system requirements, station costs, and operational complexity. Recent experience has shown that addressing these large public area fires can result in the incorporation of measures such as platform- and concourse-specific emergency ventilation systems, with operational modes that could conflict with the emergency response that would be needed for a train fire.

This paper reviews the potential fire scenarios in station public areas, including a review of reported fires in transit stations, combustible content in transit stations, and a literature review of fire tests with representative combustible loading to establish credible fire characteristics. This analysis supports the assertion that evaluation of public area design fires that are not credible relative to the actual hazard in the design of emergency ventilations in modern rapid transit stations is not beneficial to the overall level of safety. Furthermore, evaluation of these design fires may even have a negative impact on life safety by introducing additional system complexity and confusing operational modes.

KEYWORD: Transit station concourse fires, Design fire size, Fire risk, Ventilation system design

INTRODUCTION

The performance of emergency ventilation systems (EVS) in rapid transit stations is evaluated using engineering analysis relative to acceptance criteria that is specified for the project. This analysis is typically conducted with Computational Fluid Dynamics (CFD) of defined design fire scenarios within the station, and ventilation equipment requirements and operational response modes that achieve the required level of performance are identified.

An important factor in this engineering analysis is the selection of design fires that will be evaluated. Design fires are selected to represent conservative, yet credible, fire scenarios with respect to the anticipated fire hazard for a given system in consideration of the station use and occupancy. The peak heat release rate, growth rate, and burning duration of the design fires can all have a direct impact on the EVS design, physical size of ventilation components, operational response modes, and overall cost of the EVS and fire protection systems required to address these fire hazards. These design fire characteristics each carry specific implications relative to the inherent risk that the engineering analysis is intended to evaluate.
The annex sections of NFPA standards are informational references provided for guidance on the application of the requirements of the standards; however, are not a mandatory or enforceable part of the standards. NFPA 130 [1] Annex Section H.2 outlines a series of fire scenarios that are recommended to be considered in the engineering analysis for the system:

“Representative design fire scenarios include the following {…} (4) A fire consumes trash, luggage, wayside electrical equipment, and so forth, in the stations or tunnels.”

Transit project experience has shown that this informational annex has been interpreted as a direct requirement for the inclusion of secondary design fires in the engineering analysis of the EVS to address potential hazards of transient combustibles in the station public areas. For this purpose, large design fires with extended durations of burning at the peak heat release rate have been observed in some transit projects. Understanding the context for the design fire assumptions is fundamental in establishing acceptable risk for the design process.

BACKGROUND

There have been few fires resulting in significant property damage or loss of life in the public areas of metro stations around the world, with the fires in the London Underground’s Oxford Circus Station in 1984 [2] and King’s Cross Station in 1987 [3] as notable exceptions. The Oxford Circus Station fire resulted from smoking materials igniting a pile of wood construction materials, while the King’s Cross fire resulted from smoking materials igniting combustible debris accumulated within a wooden escalator. Therefore, each of these fires involved the ignition of quantities of combustible materials that are disproportionate to the contents in modern rapid transit stations. Modern stations are inherently resistant to the initiation and spread of accidental fires and there have not been any comparable fires in transit stations in recent years.

Transit Station Design

The design and construction of transit stations is regulated by standards such as NFPA 130, local building codes, and system specific transit design guidelines. Modern transit stations are typically designed and constructed using noncombustible materials and finishes with low combustibility and low flame spread ratings. As well, station furniture is normally comprised of noncombustible materials with negligible combustible finishes.

In some systems, retail spaces or other occupancies may be integrated in the public areas; in which case, specific fire protection strategies are adopted to limit the propensity for fire spread to the public areas of the station. Back of house areas, including electrical rooms, elevator machine rooms, and other ancillary areas are required to be fire separated from the remainder of the station, and are frequently protected by automatic sprinklers or fire suppression systems.

The potential for fires to occur in the station public areas, specifically on the platform or concourse circulation areas, is therefore a function of the combustible materials that may be brought into the station by passengers and the likelihood of ignition. However, given the strict NFPA 130 limitations on combustible content, enclosed transit stations inherently have reduced fire risk in public areas and there is limited potential for fire spread beyond these transient combustible contents.

Occurrence of Fires in Transit Station Public Areas

Project experience with multiple rapid transit systems throughout North America provides insight on the frequency and causes of fires in transit stations. Based on the statistics from reported fires, Table 1 shows an estimate of the frequency of fires in the public circulation areas of transit station fires. In general, the vast majority of fires in transit stations are of minor consequence and either self-extinguish or are suppressed by passengers or station attendants. Larger fires that require response by the fire department are infrequent and typically comprise less than 5% of fires in stations.
Table 1  Categorization of frequency of fires in rapid transit stations.

<table>
<thead>
<tr>
<th>Fire Consequence</th>
<th>Percent of Fires</th>
<th>Fire Frequency</th>
<th>Representative Type of Fires</th>
</tr>
</thead>
</table>
| Minor            | >95%             | <1 in 2 station-years | - Debris on public area floor  
|                  |                  |               | - Smoldering fire in waste receptacle  
|                  |                  |               | - Typical acts of vandalism |
| Moderate         | <5%              | <1 in 50 station-years | - Waste bin on fire  
|                  |                  |               | - Passenger belongings on fire  
|                  |                  |               | - Rare acts of arson and extreme vandalism |
| Major            | <0.1%            | <1 in 3000 station-years | - Construction debris on fire  
|                  |                  |               | - Accident or external fire exposure |

The majority of fires in the public areas of transit stations are categorized to have occurred in waste receptacles in the public circulation areas or in accumulations of debris. In most cases, these fires had ignited from smoking materials, intentional ignition, or other unknown circumstances.

Based on reported fire events from various rapid transit systems, the following summarizes the general characteristics of North American metro station fires:

- Many higher consequence fires occur in the back of house areas, or in station areas under construction. Major fires in the platform or concourse areas are rare and have mainly occurred in combustible construction materials stored in these areas during construction projects.
- Fires originating in, or involving, passenger baggage is infrequent and have resulted in no widely reported large-scale fires in transit stations.
- Of the statistics reviewed, there were no reports of deaths resulting from fires in the public circulation areas. There were only few reports of passenger injuries resulting from fires and, in almost all cases, the passengers were intimate with the initiation of the fire.

FIRES INVOLVING TRANSIENT COMBUSTIBLES

Given the fire separation between public areas and back of house areas, limitations on combustible construction, and active fire protection of adjacent occupancies, potential fires in transit stations posing a risk to passengers would be limited by the availability of fuel within public circulation areas. This is consistent with the reviewed fire data, where most of the recorded fires in public areas occurred in trash cans, and in combustible debris in the stations.

Fuel Load in Stations

Generally, accumulation of significant transient fuel load within the public areas of transit stations would not be expected to occur if the station is regularly cleaned and maintained. Therefore, possible fuel loads could be waste receptacles in the public circulation areas, and other transient combustible materials such as passenger belongings and baggage. Figure 1 shows examples of typical trash receptacles and noncombustible furnishings in rapid transit stations.

One of the most comprehensive analyses on the fire load carried by passengers in transit stations was the Stockholm Metro carried fire load study [4]. The survey was carried out using passenger interviews along with examining, photographing, and weighing the luggage carried by passengers. In this analysis, 622 pieces of luggage were analyzed, including purses, shopping bags, backpacks, and full-sized luggage. Inclusive of all types of luggage evaluated as part of this survey, the average weight of each bag was approximately 4.2 kg/bag for the metro. It was noted that approximately 82% of passengers on the metro carried some type of bag; though this percentage represents all bags from small shopping bags to large luggage.
The Stockholm Metro study correlates well to a field analysis conducted on a commuter ferry in Boston, Massachusetts [5], where approximately 82% of all passengers carried a bag of some kind. In this analysis, 5.5% of the bags were duffel bags or large suitcases, while the remainder of bags were comprised of briefcases, backpacks, and purses. The amount of luggage carried per passenger would be expected to be affected by the mode of travel. For example, available data from a field observation study of several stations in the Vancouver SkyTrain system showed less than 0.5% of passengers carried large or wheeled luggage during peak hours [6].

NFPA 130 and other transit codes or standards require that trash receptacles be constructed of non-combustible construction and many transit systems require receptacles with self-closing lids. With noncombustible construction, the design of the waste receptacle would limit the ability for a fire to spread beyond the container. Therefore, trash fires at the platform or in the concourse would be anticipated to be limited by the size of an individual trash receptacle. In general, the volume of trash in a station would not be expected to exceed that of individual waste receptacles.

The information above indicates that there is relatively limited large luggage carried through rapid transit stations during the peak periods and that baggage would not be expected to cause, or otherwise contribute, to a fire. Other incidental combustibles, including trash, are expected to be contained in noncombustible containers and isolated from other fuel sources that could contribute to the extent of fire growth and the propensity for fire spread beyond the immediate area of ignition.

**Fire Characteristics of Transient Combustibles**

The heat release rate and burning characteristics of fires in luggage and other transient combustibles that would represent a credible fuel load in transit stations have been well studied [4,7-17]. Table 3 shows a comparison of the measured heat release rate for various transient combustibles representative of the potential fires in transit stations.

Following the field observations of the Stockholm Metro fire load study [4], a series of fire tests were conducted on luggage representative of the luggage carried by passengers. A total of 13 different types of bags were tested, with measurements, mass, and contents representative of the baggage observed. The luggage tested in this analysis ranged from small backpacks to full sized luggage, and the luggage was filled with representative contents for each type of bag. In these tests, the peak heat release rates varied between 150 kW for a small suitcase to 750 kW for a plastic pram filled with textiles. The plastic pram had the highest peak heat release rate due to thin plastic materials and configuration facilitating rapid fire development but a short duration peak burning period, with a heat release rate above 150 kW for less than 5 minutes. In all of these tests, the luggage fires attained a heat release rate greater than 100 kW for less than 10 minutes.
Other studies [7, 8] have considered the impact of ignition mechanism on heat release rate and burning characteristics of luggage fires. In tests by Transport for London (described in [7]), typical luggage pieces were observed to have an inherent resistance to ignition and starting the fires took up to ten minutes of flame exposure in some cases. For example, many of the luggage pieces had a smoldering incubation time of up to 10 minutes before sustained fire growth. Once ignited, these fires had growth period of 2 to 6 minutes to the peak heat release rate. In tests by Bulk et al. [8], a luggage piece ignited with a match equivalent flame had an approximately 20% lower peak heat release rate and lower total energy release than an identical piece of luggage ignited with a substantially more severe “paper cushion” type standardized ignition source. Therefore, the ignition source was observed to have a minor impact on the peak heat release rate and the rate of fire growth in these tests.

Table 2  
Examples of measured heat release rate characteristics for transient combustibles.

<table>
<thead>
<tr>
<th>Burning Item</th>
<th>Approximate Mass (kg)</th>
<th>Heat Released (MJ)</th>
<th>Peak HRR (kW)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Luggage and Personal Belongings</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic pram filled with textiles</td>
<td>15.1</td>
<td>179.0</td>
<td>750</td>
<td>[4]</td>
</tr>
<tr>
<td>Two carry-on bags with clothes, touching</td>
<td>-</td>
<td>47.5</td>
<td>500</td>
<td>[9]</td>
</tr>
<tr>
<td>Large backpacker’s rucksack</td>
<td>12.5</td>
<td>144.6</td>
<td>250</td>
<td>[4]</td>
</tr>
<tr>
<td>Large suitcase filled with assorted goods</td>
<td>14.7</td>
<td>123.2</td>
<td>250</td>
<td>[4]</td>
</tr>
<tr>
<td>Cabin bag suitcase filled with clothes</td>
<td>9.1</td>
<td>97.0</td>
<td>150</td>
<td>[4]</td>
</tr>
<tr>
<td>Suitcase filled with representative goods</td>
<td>-</td>
<td>234.4</td>
<td>120</td>
<td>[8]</td>
</tr>
<tr>
<td>Hard side suitcase filled with clothes</td>
<td>10.3</td>
<td>139.0</td>
<td>120</td>
<td>[10]</td>
</tr>
<tr>
<td>Soft side suitcase filled with clothes</td>
<td>3.1</td>
<td>33.4</td>
<td>25</td>
<td>[10]</td>
</tr>
<tr>
<td><strong>Trash and Wastebaskets</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amtrak trash bags from overnight trains</td>
<td>1.8 – 9.5</td>
<td>-</td>
<td>30 – 260</td>
<td>[11]</td>
</tr>
<tr>
<td>Trash bag filled with paper</td>
<td>1.17</td>
<td>20.0</td>
<td>140</td>
<td>[10]</td>
</tr>
<tr>
<td>Two 40 gal. (151 L) trash bags with assorted waste materials</td>
<td>30.9</td>
<td>-</td>
<td>119</td>
<td>[12]</td>
</tr>
<tr>
<td>Two plastic trash bags with crumpled paper</td>
<td>9.1</td>
<td>-</td>
<td>109</td>
<td>[12]</td>
</tr>
<tr>
<td>50 gal. (190 L) plastic trash can filled with crumpled paper</td>
<td>13.6</td>
<td>-</td>
<td>109</td>
<td>[12]</td>
</tr>
<tr>
<td>Two trash bags with paper</td>
<td>36.4</td>
<td>-</td>
<td>40</td>
<td>[12]</td>
</tr>
<tr>
<td>Polyethylene wastebasket filled with shredded paper</td>
<td>0.8</td>
<td>110.2</td>
<td>15</td>
<td>[13]</td>
</tr>
<tr>
<td>Empirical calculation for trash bags</td>
<td>5</td>
<td>3.8</td>
<td>435</td>
<td>[14]</td>
</tr>
<tr>
<td><strong>Liquid Fueled Fires</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5 L gasoline, spill on concrete</td>
<td>1.12</td>
<td>31.0</td>
<td>1,500</td>
<td>[15]</td>
</tr>
<tr>
<td>1.0 L gasoline, spill on smooth concrete</td>
<td>0.78</td>
<td>18.2</td>
<td>932</td>
<td>[16]</td>
</tr>
<tr>
<td>1.0 L gasoline, spill on brushed concrete</td>
<td>0.78</td>
<td>23.1</td>
<td>742</td>
<td>[16]</td>
</tr>
</tbody>
</table>

*1.14 kg rags, 7.7 kg paper towels, 5.9 kg plastic gloves and tape, 5.9 kg methyl alcohol
*50 gal. (189 L) plastic trash can with 13.6 kg crumpled paper
*4.6 kg crumpled paper and 31.8 folded computer paper
*0.6 kg plastic basket and 0.2 kg paper
*Empirical calculation is based on waste bag total surface area
While accidental luggage fires are often included in the specification for platform and concourse public area fires in transit stations, it is noted that there were no recorded instances of fires initiated in, or involving passenger luggage in the historical fire records described previously. The low incidence of reported luggage fires is consistent with an analysis by Bowman and Tooley [7], who reviewed battery fire statistics from the Federal Aviation Association (FAA) to estimate the probability of luggage fires. Assuming that an electrical failure in a portable device would be the primary cause of an accidental luggage fire, the probability of an accidental fire involving electrical failure in passenger luggage was estimated to be approximately 1 in 9.8 million.

Multiple studies have been conducted on the heat release rate of trash receptacles and bags packed with typical refuse materials. The rate of fire growth and peak heat release rate are largely impacted by the containment and packing of the waste bags [11]. A study of waste bags consistent with the type of waste that could be located in transit stations was conducted on a number of waste bags collected from Amtrak overnight trains [11]. The unconfined trash bags had a typical heat release rate ranging from 60 to 260 kW maximum. Based on measurements of multiple trash bags, the researchers established an “average” trash bag intended to be representative of the range of bags collected from the trains to be used in repeat tests. The average trash bag was filled to 2.7 kg with sheets of paper, and had a peak heat release rate of approximately 203 kW.

The intentional introduction of fuel into transit stations could result in a higher peak heat release rate and faster rate of fire growth than typical fuels found in transit stations. Based on the historical metro system fire statistics, the probability of intentional and vandalism fires in North American metro stations is expected to be between 1 in 25 to 1 in 3 station-years for modern systems. Most times, these intentional fires are comprised of small fires in debris on the floor or in waste bins, and are overwhelmingly minor fires that do not necessitate response by the fire department.

Based on a review of the fire behavior of a number of known arson fires, the conclusions of Nilsson et al. [17] indicate that intentional ignition of baggage or waste receptacles could result in a faster growing fire; however, the peak heat release rate and total burning duration would not be expected to be materially different than those ignited by smoking materials or other accidental causes [8]. As such, possible intentional fires that could result in fires substantially different than those of accidental fires would mostly include liquid fuelled fires, including liquid pour fires and accelerant aided fires. Liquid fuels poured on a combustible material (for example gasoline poured on a waste receptacle) would be expected to result in an initial flash fire, with continued burning largely consistent with that of the original waste receptacle.

The heat release rate of liquid fires is largely dependent on the free burning surface area of the liquid pool, while the burning duration is a function of the pool depth [16, 18]. On non-absorbent floors such as tile, liquid fuels quickly spread resulting in large spill area with shallow liquid depth [16]. Therefore, a pool fire in a transit station would be expected to have a high peak heat release rate with a short total burning duration. This is demonstrated in testing of Molotov cocktail scenarios conducted by Richards et al. [15], where measurements of heat release rate were recorded for various liquid spill fires. A 1.5 L spill of gasoline was measured to generate a short peak heat release rate of 1.5 MW, with burning duration of less than 60 seconds. Similarly, liquid spill fires of 1.0 L of gasoline and denatured alcohol on concrete resulted in peak heat release rates of 932 kW and 323 kW, respectively, and total burning duration of less than 60 seconds in both fuels [16].

**Context of Secondary Design Fires**

From the experimental data across a diverse range of materials, credible fire sizes established in transient materials in a transit station would generally be on the order of 100-300 kW. The SFPE Handbook [10] provides a similar range of credible design fires, concluding that:

“For design purposes, the range of 50-300 kW appears to cover the bulk of the expected fires from normal residential, office, airplane, or similar occupancy trash bags and trash baskets.”
Similarly, Bulk et al. [8] propose a severe design fire for the ignition of train carriage fires considering the peak burning behavior of large passenger luggage pieces. This design fire has a medium $t^2$ fire growth curve with peak heat release rate of 120 kW and steady fire decay following 15 minutes of burning at peak heat release rate. Therefore, based on the reviewed literature, credible fires in transit station public areas could include trash receptacle and passenger luggage fires, and heat release rates for these types of fires would be expected to range from approximately 15 to 400 kW.

Concourse design fires with “medium” $t^2$ fire growth to a peak heat release rate of between 1000 and 2000 kW (2.0 MW) with sustained burning at peak heat release rate have been adopted for many rapid transit projects. Figure 2 shows a comparison of typical design fire curves with the heat release rates of some of the items described in Table 2. The magnitude of heat release rate from the reference tests is much lower than the 1.0 and 2.0 MW design fires, and a 20-minute burning duration of these design fires far exceeds the periods of burning at or near the peak heat release from the test results.

![Figure 2](image-url)  
*Heat release rate profile from test results compared with typical design fires.*

Figure 3 and Figure 4 shows representative images of various burning items from the tests shown in Figure 2 above with range of fire sizes from 120 to 742 kW peak heat release rate.

![Figure 3](image-url)  
*Selection of images from range of transient combustible fire tests: Amtrak trash bag: 203 kW peak heat release rate [9], Suitcase: 120 kW peak heat release rate [8], and 1.0 L gasoline spill on concrete: 742 kW peak heat release rate [16].*
Figure 4  Selection of images showing fire progression in 136 L (30 gal) plastic waste bin filled with 10 kg of combustible construction debris (240 kW peak heat release rate) [19].

Figure 5 shows a comparison of the total energy released from the design fires and burning items referenced in Figure 2. In this plot, the total heat released for the 1.0 and 2.0 MW design fires, assuming a medium and a fast t^2 growth rate and a 20-minute burning duration, are considered. The total heat released from these design fires is extreme in comparison to the test data for representative consumed items.

On this basis, the peak heat release rate, total energy released, and total smoke generation from these design fires are substantially disproportionate to the characteristics that would be expected in the station and concourse public areas of a modern rapid transit station. Based on overall fire load, these
design fires exceed credible values for the associated fire risk when compared with what is expected to be present in a circulation space of a modern rapid transit station that is compliant with NFPA 130 or equivalent transit standard.

Table 3 provides an estimate of the amount of various representative trash contents and other goods that would be required to be consumed in a fire to release the total amount of energy released in the design fires described previously. This table compares design fires with 1.0 and 2.0 MW peak heat release rate and a 20-minute burning duration for both a medium and fast t² fire growth rate. As well, the number of items is calculated using heat of combustion data from [20] and assumes 100% combustion efficiency. As demonstrated in this analysis, the amount of representative fuels that would have to be consumed in a fire to result in the energy output of these design fires far exceeds the volume of a typical waste receptacle provided in transit stations, or of typical passenger luggage.

Table 3 Estimated number of various items required to be consumed in a fire for comparable energy release for typical 20-minute burning duration design fires.

<table>
<thead>
<tr>
<th>Total Energy Released (MJ)</th>
<th>1 MW Medium</th>
<th>1 MW Fast</th>
<th>2 MW Medium</th>
<th>2 MW Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of PE-lined paper coffee cups</td>
<td>5,038</td>
<td>5,529</td>
<td>9,268</td>
<td>10,652</td>
</tr>
<tr>
<td>Number of large format newspapers</td>
<td>367</td>
<td>403</td>
<td>676</td>
<td>777</td>
</tr>
<tr>
<td>Number of average Stockholm Study bags [4]</td>
<td>11</td>
<td>13</td>
<td>21</td>
<td>24</td>
</tr>
<tr>
<td>Liters of gasoline</td>
<td>27.6</td>
<td>30.3</td>
<td>50.8</td>
<td>58.3</td>
</tr>
</tbody>
</table>

DISCUSSION

The design fire considered in the engineering analysis of EVS performance in rapid transit stations has significant implications on the required emergency ventilation system equipment and operational modes. As observed from historical fires and project experience, significant fires in the public circulation areas of transit stations are rare and there have been few of these fires that have resulted in life-safety risk to passengers.

As discussed in the previous sections of this paper, credible fuel loads in platform and concourse public areas would be expected to include garbage in non-combustible waste receptacles, or other transient materials such as combustible passenger belongings. With consideration of rapid transit station fire statistics and evaluation of a wide range of fire tests presented in the literature for representative fire tests, credible fires in rapid transit station public areas would likely be on the order of 50 to 300 kW with peak burning period of less than 5 minutes.

The SFPE Handbook [21] provides a risk-based approach to identify and evaluate design fire scenarios in a rapid transit system. This process uses a generic cost-benefit approach to identify the credibility of the scenario that represents the greatest overall cost/benefit risk. The approach conceptually illustrates that design fires with a high frequency - low consequence fall within the band that do not warrant consideration as a design basis as this can be addressed through other measures. As further supported in the selection criteria for design fires in performance analysis described in the International Fire Engineering Guidelines [22]:

“Usually, a number of severe scenarios which have a reasonable probability of occurrence and significant potential for loss (life, property, etc.) are selected for analysis.”

Small, isolated fires – such as the trash or passenger belongings fires presented in this paper – do not exhibit a consequence that is intended to be analysed in the design process. This category of fires (frequent - low consequence) are reasonably anticipated by the provisions of the reference building codes and standards and are addressed through building design.
The requirements of transit standards, such as noncombustible construction, limits on combustible contents, and regulation of interior finish, inherently mitigate the risk of fire spread beyond the area of ignition for fires in the station public areas. The risk of small, incidental fires in the public circulation areas is intended to be addressed through prevention of fires (i.e., vandalism deterrence by station attendants and video surveillance), as well as fire protection measures such as fire extinguishers and timely fire department response. Accordingly, evaluating the EVS design requirements to address platform and concourse ‘trash’ fires, as described in this paper, lacks basis to be considered as a credible design scenario.

CONCLUSION

The original – and current – design basis for evaluation of the EVS in NFPA 130 is a train fire at the platform, since the train is the primary substantial fuel load in the station. Based on the reported fire statistics and historical fire events, the incidence of non-train fires in the public areas of transit stations is low, and are predominately minor fires in trash bins and other transient combustibles. Fire test results presented in literature for transient combustibles expected in transit stations indicate that peak heat release rates would be on the order of 50 to 300 kW for trash fires and up to 300 kW for typical passenger luggage. This range of fires is reasonably expected to be addressed by the building design and construction, as required by the reference building codes and standards.

An important part of establishing an appropriate design basis for the station EVS performance is understanding the inherent risk in each of the specific fire parameters. Experience has shown that: 1) fire sizes have been conservatively overestimated, 2) the credibility of the scenario should be appropriately evaluated, and 3) implication of conflicting system responses requires consideration. Requiring fire scenarios that are disproportionate to their credibility could introduce design implications and costs that are beyond what is intended by the objectives and intent of the applicable codes and standards.

REFERENCES

ABSTRACT

This paper presents the design of a passive fire protection system for the joints in the Conwy immersed tube tunnel in Wales. The design presented a number of challenges, including seasonal movements of the elements with respect to each other, and significant misalignments between the element edges. The final design was developed following a series of fire tests and simulations carried out using CFD models of the passive fire protection system. The CFD models generally showed a good correspondence with measured data, with deviations being on the conservative side. A final set of CFD simulations were then carried out to predict the performance of the protection systems proposed for the six primary joint types within the tunnel. The designed solution has subsequently been successfully installed in the Conwy Tunnel.

KEYWORD: tunnel passive fire protection, joint protection, CFD, immersed tube

INTRODUCTION

Conwy Tunnel is a twin-bore immersed tube tunnel that forms part of the A55 under the estuary of the River Conwy near the town of Conwy on the north coast of Wales. The A55 Chester to Holyhead Trunk Road forms part of the Trans-European Road Network (TERN) route E22. Conwy Tunnel is part of this TERN and as such is subject to the Road Tunnel Safety Regulations 2007. The tunnel is also subject to the requirements of the Regulatory Reform (Fire Safety) Order 2005.

The tunnel is 1090m long, with cut and cover sections of the east and west of 260m and 120m lengths respectively with six immersed tube tunnel sections forming the central 710m section beneath the estuary. Figure 1 shows a typical as-built tunnel cross-section.

![Figure 1 Typical As-Built Tunnel Cross-Section](image)

When opened in 1991, the Conwy Tunnel had no passive fire protection installed to protect its
structure. Subsequent studies identified that the element and dilation joints in Conwy Tunnel were vulnerable to fire, with a potential risk of inundation in case of fire-induced damage of the joints. Fire protection to the joints was therefore recommended as a high priority, and the design and installation of a fire protection system to the joints was subsequently commissioned.

CONWY TUNNEL JOINT TYPES

The locations of the tunnel joints are shown in Figure 1. The joints between the immersed elements and the interface between the cut and cover and immersed elements are known as the element joints and are numbered from TEJ1 to TEJ6. The joints between cut and cover sections are known as dilation joints and are numbered from EDJ2 to EDJ5 on the east side and WDJ1 to WDJ3 on the west side.

![Figure 2: Locations of Tunnel Joints](image)

For both types of joint the areas requiring passive fire protection (walls and soffit) are divided into three discrete regions; external walls, soffit (including the haunches) and internal walls that separate the two bores. Figure 3 shows a typical original element soffit joint, and Figure 4 shows a typical original element internal wall joint.

![Figure 3: Original Element Soffit Joint](image)
Figure 3 and Figure 4 suggests that the two sides of the element joints are completely aligned with one another. In practice this is not the case. Joints can be misaligned vertically (up to 65mm) or rotationally. The passive fire protection must accommodate these misalignments in addition to the seasonal variations in the joint width as the tunnel elements expand and contract. The measured seasonal variations indicated a total range of movement of 9.5mm. For conservatism, a total seasonal movement of 15mm was allowed for.

PASSIVE FIRE PROTECTION CRITERIA
The concrete joints were to be protected against exposure to a 2-hour RWS fire curve. The protection system was deemed satisfactory if all requirements noted below are satisfied.

1. For the primary protection of the joint (up to 335mm from the joint) a maximum average concrete interface temperature of 350ºC after 2 hours’ fire exposure and an average temperature of 120ºC or less at the gasket material (Omega seal). The 335mm length was selected on the basis of experience and the widths of commercially available fire protection boards.
2. The fixing system should not fail during 2 hours of fire exposure. Failure is defined as either partial dislodgement or complete collapse of the fire protection board.
3. No spalling of the concrete in the primary protected area of the joint (up to 335mm from the joint) should occur during 2 hours of fire exposure under the conditions defined above.

The dilation joints were filled with Korkpak. This is a bitumen impregnated cork board material used to prevent the ingress of moisture through a construction joint. If the Korkpak were to be ignited then the fire could potentially propagate through the joint sufficiently to damage the Omega seals. To prevent this occurring it is necessary to limit the temperature of the Korkpak to less than spontaneous ignition temperature. Further it is possible that when warmed, the bituminous element of the Korkpak may flow under gravity to warmer locations where it may spontaneously ignite or come in direct contact with flames. To better determine if bitumen will flow from the Korkpak under fire conditions, physical tests on material removed from the dilation joints were carried out. The results of these tests showed that bitumen did not melt or leak from samples of Korkpak removed from the tunnel at temperatures of up to 120ºC. This was adopted as the fire protection criterion for the dilation joints.

PASSIVE FIRE PROTECTION SCHEME
The selected passive fire protection scheme comprises passive fire protection calcium silicate fibre boards (trade name “Promatect-T”) spanning across the face of the joint to a sufficient distance beyond the joint to prevent the temperature at the Omega seal reaching its limiting value and to ensure that concrete spalling will not occur within 335mm of the joint. The boards were coated with a special paint (trade name “Ceramiccoat C”) to protect them from water ingress and to ensure sufficient reflectivity in the tunnel.

Longitudinal movement is allowed for at the connections between the boards and the walls through slotted holes. Misalignments between the tunnel elements were addressed through usage of packing.
boards and the boards’ inherent flexibility.

Composite steel/cement impact protection sheets (trade name ‘Durasteel’) was applied immediately across the face of the joints in order to minimise damage to the joints should any impact occur with vehicles or equipment. Allowance for movement was the connections of these sheets to the boards and walls. Stainless steel edge protection strips was applied in potential impact zones below a nominal level of 3.75m above verge level. All stainless steel used for the edge protection strips was grade 316L.

Individual layers of insulation inserted into the element voids were bagged in aluminium bags which act as vapour barriers against the movement of superheated steam generated from the boards in case of a fire. Figure 5 depicts the protected element soffit joint.

Figure 5: Protected Element Soffit Joint

FIRE TESTING

The following full-scale fire tests were conducted at CSTB in France to verify that the fire protection designs for the element joints would comply with the fire protection requirements:

1. Vertical (wall) element joint (Figure 6)
2. Horizontal (soffit) element joint (Figure 8)
3. Vertical (wall) dilation joint (Figure 10)
Figure 6: Sectional View of Vertical (Wall) Element Fire Test

Figure 7: Vertical (Wall) Element Fire Test: Preparation of the insulation material and thermocouples positioned on the joint ('cold' side)

Figure 8: Sectional View of Horizontal (Soffit) Element Joint Fire Test
Figure 9: Horizontal (Soffit) Element Joint Fire Test: Promatect-T (25mm) protection boards positioned on the exposed surface before the test ('hot' side)

Figure 10: Sectional View of Vertical (Wall) Dilation Joint Fire Test

Figure 9: Horizontal (Soffit) Element Joint Fire Test: Promatect-T (25mm) protection boards positioned on the exposed surface before the test ('hot' side)

Figure 10: Sectional View of Vertical (Wall) Dilation Joint Fire Test
The fire tests were undertaken using cured concrete blocks with the same material specification as the tunnel (cube strength of 37.5 N/mm² and 20mm aggregates). The measured water content of the test blocks was around 5%, which was consistent with core samples taken from the tunnel.

The unprotected slabs in the first and third tests were to be subjected to a compressive stress of 12.5N/mm², which was the maximum design compressive stress of the tunnel concrete. The extent of concrete spalling is linked to the compressive stress in the concrete, so the concrete in the test slab would then be representative of the maximum compressive stress likely to occur in the tunnel.

An axial load of 2343kN (239 tonnes) would be required to produce a stress of 12.5N/mm². The loading frame at CSTB was limited to 1765kN (180 Tonnes). A load of 1750kN applied centrally to the slab provided a uniform compressive stress of 9.3N/mm2 across the section. The load was displaced to give an eccentricity of 14mm, which gave a combined (axial + bending) compressive stress of 12.5N/mm² on the front face of the unprotected test slabs.

A 10mm steel plate was used to connect the protected and unprotected slabs on the back (cool side), in order to minimise the relative displacement at the front face, and to minimise the appearance of any joint gap between the slabs during fire tests 1 and 3.

The three fire tests confirmed that all the passive fire protection criteria had been satisfied. The measured temperatures are presented in the section below.
CFD MODELLING OF JOINT HEAT TRANSFER

Since there were differences between the test geometries and the actual tunnel construction, it was decided to use 3D CFD modelling to predict the conditions in the vicinity of the joints in the presence of an RWS fire located in the traffic space. Comparisons were also undertaken between the measured test temperatures and 3D CFD predictions of the experimental rigs.

It was recognised early on in the modelling process that the water content of the fire protection boards had to be accounted for. This was due to two reasons: firstly, it became clear that the boards were “held” at around 100°C for a substantial length of time during the tests due to the conversion of water into vapour, implying that reliance upon conduction as the only heat exchange mechanism through the boards would not be appropriate. Secondly, there were concerns that any super-heated steam could penetrate into the insulation and damage the Omega seals.

The three-dimensional (3D) simulations have been undertaken using the three-dimensional finite volume CFD code ANSYS-CFX version 16.1. This mature software is designed for the solution of fluid flow and heat transfer problems and includes options relating to the modelling of radiative heat transfer and multi-phase physics modules.

The solid elements of the joint (fire protection boards, concrete, insulation) are represented as conducting solids through which the computer software can calculate thermal conduction. However, in addition, the software allows the solid to be treated as porous and separate fluid transport equations are solved across the volume representing the flow of water and vapour. The two sets of equations for the solid (conduction only) and fluid (fluid flow and heat transfer) are then interconnected by heat transfer equations to allow for appropriate heat exchange between the solid and the fluids within.

Water embedded in the fire protection board and other porous materials has a significant impact on the rate of temperature rise and the transfer of heat through the materials. As the board (or other material) heats up, liquid water embedded in the material evaporates and forms vapour within the pores of the material, which slightly cools the solid. As the evaporation continues the pressure in the pores will increase and start to drive water vapour and air through the material into cooler regions. At this point, vapour will condense back into water and release heat into the solid.

As fire protection boards and concrete have very small pores and very high resistances to flow, the pressures generated by the water vapour will be high and as a result the local boiling temperature of water will be significantly higher than at atmospheric pressure. If vapour exits the material into a lower pressure environment then it will condense very rapidly back into water until an equilibrium condition is reached. This will tend to occur in the gaps between boards and between boards and adjacent surfaces (concrete and insulation).

Within the CFD code, liquid water is represented using a scalar representing the mass of water per unit volume. Source terms are used to add and subtract water in each computational cell as evaporation and condensation occur. It is assumed that the liquid water is at the same temperature as the solid it is contained within.

In this representation the water itself has no thermal properties; instead the heat capacity of the water and the transfer of thermal energy associated with evaporation and condensation are associated with the solid. This is valid as water and solid are assumed to be at the same temperature.

Water vapour is represented as a mass fraction of a mixture of water vapour and air that exists within the porous medium of the board. The CFD software automatically calculates the thermodynamic and transport properties of the mixture based on this mass fraction.

Source terms are used to add and subtract vapour and thermal energy to the vapour/air mixture in each computational cell as evaporation and condensation occur. Unlike the liquid water, the vapour/air
mixture has thermal properties and a transport equation for the mixture temperature is solved so the mixture and solid can be at differing temperatures. However, in practice there is little or no difference in the dry bulb temperatures of the vapour/air mixture and the solid, due to the very small dimensions of the pores.

At conditions other than boiling (described below), the rate of evaporation or condensation of water is calculated on the basis of:

\[ q = uA[m_{surf} - m_v] \]  

(Equation 1)

where:
- \( q \) – rate of vapour transfer (kg/s)
- \( u \) – mass transfer coefficient (kg/(m\(^2\) s))
- \( A \) – mass transfer area (m\(^2\))
- \( m_{surf} \) – saturation vapour mass fraction at water ‘surface’
- \( m_v \) – vapour mass fraction

And mass fractions \( m_{surf} \) and \( m_v \) are defined so that

\[ m = \frac{M_v}{M_v + M_a} \]  

(Equation 2)

where:
- \( M_v \) – specific mass of vapour (kg/m\(^3\))
- \( M_a \) – specific mass of air (kg/m\(^3\))

The mass fraction of vapour and air is calculated by the CFD code. The saturation mass fraction at the water surface is calculated on the following basis:

It is assumed that the liquid water is at the temperature of the adjacent solid. The saturation vapour pressure at the solid temperature (\( P_{vs} \)) is made by reference to steam tables. The concentration of water vapour at the surface (\( m_{surf} \)) can then be calculated from the saturation pressure using:

\[ m_{surf} = \frac{\omega}{1+\omega} \]  

(Equation 3)

\[ \omega = \frac{0.622P_{as}}{P_{as}} \]  

(Equation 4)

\[ P_{as} = P_{tot} - P_{vs} \]  

(Equation 5)

where:
- \( P_{tot} \) – absolute local pressure (Pa)
- \( P_{as} \) – partial pressure of air (Pa)

The equations above have been implemented in the computer model and used to calculate the mass transfer between the liquid water equation and the water vapour mass fraction. The heat transfer between the phases is then calculated from the latent heat of vaporisation for water and energy source terms set appropriately.

Experimental or other empirical data for the rates of condensation and evaporation of water within fire protection boards have not been located at the time of writing. Instead the base transfer rate term (\( uA \)) has been determined by tuning the model to obtain the best fit possible for the ‘Test 2’ results. The results discussed here assume a base transfer rate (\( uA \)) of 0.005 kg/m\(^3\).

When the saturation pressure at the solid temperature is greater than the total pressure in the pores within the material then boiling heat transfer will occur.
Heat transfer rates in the boiling regime are dependent upon the difference between the temperature of the surface driving the boiling (for instance the element of a kettle or in this case the temperature of the solid) and the saturation temperature of the air/vapour mixture. This varies as shown in Figure 12.

![Boiling Heat Transfer Rates](image)

This basic boiling behaviour has been implemented in the computer model. It is assumed that with a temperature difference of 1°C that boiling occurs at a rate of 1.23kg/m³s. The rate varies at rates proportional to those shown in Figure 12.

Although the fire protection board is a solid, it is porous and is filled with many extremely small pores. These pores allow both liquid water and water vapour to pass through the solid albeit at a low rate. There are two mechanisms for the transport of fluid through the solids: diffusion and pressure driven convection. Diffusive transport is calculated by the CFD code using fluid properties and local concentration gradients. The pressure driven transport is calculated by the CFD code from local pressure gradients and pressure loss coefficients for the material.

The velocity of vapour through the material can be calculated from Darcy’s law [Ref. 2].

\[ v_G = \frac{K_{G}K_{G}}{\mu_G} \nabla P_G \]  

(Equation 6)

where

- \( v_G \) – velocity of vapour/air mixture (m/s)
- \( P_G \) – pressure difference (Pa/m)
- \( \mu_G \) – dynamic viscosity of vapour/air mixture (m²/s)
- \( K \) – intrinsic permeability of board (m²)
- \( K_{G} \) – relative permeability of vapour/air mixture

The intrinsic permeability of the board has been measured as 0.0246mdarcy or 2.42x10⁻¹⁷m². The relative permeability of the air/vapour mixture was assumed to be 0.5.

Where possible specific manufacturer’s data are used to define material properties backed up by measured data. Where this is not possible generic material data have been used. Concrete properties are taken from BS EN 1992-1-2:2004.
The properties of the passive fire protection boards and the ceramic insulation were based on the manufacturer’s literature. The moisture content of the boards at room temperature was measured as 5.3%. The porosity of the boards was measured as 57.9%, and the mean pore diameter was measured as 0.1421µm.

A contact resistance equivalent to a heat transfer coefficient of 25W/(m²K) was used at all the interfaces.

Figure 13 depicts the calculated and measured board interface temperatures for one of the tests. The CFD calculations were in reasonable agreement with the measured results, and that provided confidence with for the designed arrangement.

The CFD calculations were subsequently repeated for all tunnel joint types for the proposed construction, to confirm that the passive fire protection requirements were met.

**PASSIVE FIRE PROTECTION INSTALLATION**

Figure 14: Installation of fire protection boards on tunnel wall
CONCLUSIONS

A passive fire protection system for the joints in the Conwy immersed tube tunnel has been designed, tested and installed. The design was arrived at following a series of physical tests and simulations carried out using CFD models of the passive fire protection system. Following the completion of the physical tests, the predictions of the computer models were tested and compared with measured data. A final set of simulations were then carried out to predict the performance of the protection systems proposed for the six primary joint types within the tunnel. The design has received technical approval and has been successfully installed in the Conwy tunnel.

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REFERENCES


Public Investigation of Fire in Tank Trailer in the Skatestraum Tunnel in Sogn og Fjordane County on 15\textsuperscript{th} of July 2015

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ABSTRACT
After a truck with a tank trailer entered the Skatestraum tunnel in Norway in Sogn og Fjordane county on 15\textsuperscript{th} of July 2015 the tank trailer broke loose from the truck and ran into the tunnel wall. The tank got perforated in the crash and the fuel leaked out and spread downwards on the roadway surface and inside the tunnel's drainage system. 16,500 liters of petrol caught fire inside the tunnel and the fire escalated very quickly. The incident resulted in the largest tunnel fire in Norway to date. The Accident Investigation Board Norway (AIBN) has completed a public investigation of the fire [1]. The investigation identified several learning points, and the findings of the investigation should be of interest to many stakeholders.

AIBN's investigation shows that the trailer drawbar broke due to internal corrosion in the drawbar rods. The investigation also revealed weaknesses in the tunnel's ability to resist the spread of fire, which spread over nearly 500 meters and escalated very quickly. It was only a very short window of time available for evacuation, but luckily, no road users got seriously injured in the fire. This paper describes the facts, analyses and conclusions/results of the investigation of the fire

KEYWORD: Road tunnel, tunnel fire, accident investigation, fire in tank trailer

INTRODUCTION

Accident Investigation Board Norway (AIBN)
The AIBN is a permanent, public and independent body of inquiry for accidents in all transport modes in Norway. The purpose of AIBN investigations is to clarify the sequence of events and factors which are assumed to be of importance for the prevention of transport accidents.

The AIBN shall not apportion blame or liability. The AIBN itself decides the scale of the investigations to be conducted, including an assessment of the investigation's expected safety benefits with regard to necessary resources.

Since 2011 there have been five large tunnel fires in Norway. The Accident Investigation Board Norway (AIBN) has investigated four of these fires and issued public reports. This paper is based on the investigation of the fire in the Skatestraum tunnel, which to date is the largest tunnel fire that has occurred in Norway.

Fire in the Skatestraum tunnel
On 15\textsuperscript{th} of July 2015 a tank trailer loaded with 16,500 litres of petrol broke loose from a truck inside the Skatestraum tunnel, a subsea tunnel in Sogn og Fjordane county. The incident took place approximately 475 metres after the truck started the ascent from the bottom of the tunnel, and resulted in the front right-hand corner of the tank trailer hitting the tunnel wall. The impact with the tunnel
wall created a hole in the front tank compartment of the tank trailer containing 4500 liters of petrol, from which the petrol leaked out and subsequently ignited.

As the fire developed, the top of the other aluminium tank compartments on the trailer melted. Subsequently large quantities of petrol leaked out of the tank compartments onto the road surface and quickly spread downhill to the bottom of the tunnel due to the steep gradient of the tunnel. The petrol originating from the front tank compartments leaked both alongside the roadway and through the tunnel’s drainage system. The petrol then subsequently ignited and also the fire spread downhill from the trailer to the bottom of the tunnel. The fire later spread throughout the entire drainage system of the tunnel, over a total distance of 900 metres.

The driver of the tank truck managed to drive the truck out of the tunnel unharmed. Behind the tank trailer an evacuated passenger car was destroyed by fire. When the incident occurred, there were 17 people inside the tunnel in total. They all managed to evacuate without sustaining any serious injuries. The results of the investigation show that the trailer drawbar broke due to an advanced state of internal corrosion in the drawbar rods [2]. From the time that the repairs were carried out until the trailer drawbar broke, the trailer had undergone eight official inspections without the defective repairs having been detected.

The SP Technical Research Institute of Sweden contributed to the fire investigation [3,4] by studying possible sources of ignition and the spread of the fire in the tunnel. According to SP’s calculations, the maximum heat release rate exceeded 400 MW during the period when both the running petrol and the tank trailer were on fire, and the temperature above the burning trailer was approximately 1,350 °C.

The investigation uncovered that the tunnel’s surface water system was not designed to handle the amount of petrol that ran out from the tank trailer. Furthermore, the report concludes that any individuals caught in the smoke downstream or upstream of the fire would have found it very difficult to evacuate and would most likely died due to high thermal radiation.

The investigation also uncovered that risk analyses of the tunnel had been conducted that, among other things, described a fire/explosion in a heavy goods vehicle and accidents involving dangerous goods, but that no descriptions had been provided for how such scenarios were to be handled when it came to extinguishing the fire, evacuation, self-rescue and assisted rescue.

FACTUAL INFORMATION FROM THE FIRE IN SKATESTRAUM JULY 2015

The tunnel design
The Skatestraum tunnel is a subsea single bore tunnel on the Fv 616 road between Hamnen on Rugsundoya Island and Klubben at Bremangerlandet in Bremanger municipality. The tunnel is 1,902 metres long and has an annual average daily traffic (AADT) of approximately 300 vehicles. It was designed in accordance with the NPRA’s Manual 021 – Road tunnels. According to the NPRA, heavy goods vehicles represent approximately 10% of the traffic in the tunnel which has a 6-metre wide roadway with a 1-metre wide concrete shoulder on either side. It has an overhead clearance of 4.5 metres. The speed limit in the tunnel is 80 km/h. The tunnel rises at a gradient of 10% on either side of the lowest point, which is approximately 80 metres below sea level. It was opened for traffic on 12th of July 2002.

The chain of events
On the morning of Wednesday 15th of July 2015, a heavy goods vehicle set out from Måløy Havneservice AS’s facility in Måløy. The road tanker consisted of a tank truck and a tank trailer, loaded with 19,000 and 16,500 litres of petrol, respectively, for delivery in Florø. See map in figure 2.

1 Annual average daily traffic (AADT) = average daily traffic through the year, total for both directions.
2 Data from the NPRA’s National Road Database (NVDB).
When the driver had driven the road tanker ashore at Oldeide, he stopped to allow the cars that came off the ferry behind him, to pass. He intended to avoid having a tail of cars behind him along the road to Florø, which was narrow and winding. Nor did he want to have cars behind him through the Skatestraum tunnel, which reaches its lowest point 80 metres below the sea surface and falls/rises at a gradient of 10%; see figure 5.

Approximately 10 minutes after leaving Oldeide ferry landing and heading towards Florø, the road tanker entered the Skatestraum tunnel on the Fv 616 county road; see figure 2. To prevent the brakes from overheating while driving to the lowest point of the tunnel, the driver only used the truck’s retarder and engine brake.

About 450 metres after starting the drive uphill from the bottom of the tunnel, the driver heard a bang and noted that the truck was going faster although he had not stepped on the accelerator. When he checked the mirror, he saw that the trailer had broken loose from the truck and that it was standing with its front right-hand corner up against the tunnel wall some way behind the truck. He stopped the truck and went out, and observed that some parts of the trailer drawbar were still attached to the truck. The trailer drawbar had broken just in front of where it was attached to the trailer; see figure 4.

When he looked towards the trailer, he observed that petrol was leaking out of the trailer’s front tank chamber, see figure 3. The driver immediately notified the Traffic Control Centre (VTS) of the incident using the tunnel’s emergency telephone, enabling them to close the tunnel. At the same time, he warned an oncoming passenger car so that it was able to turn around and evacuate the tunnel.

Figure 2: The scene of the accident and the direction in which the road tanker was heading. Map: Road map, NPRA.
Just over two minutes after discovering that the trailer had broken loose from the truck, the driver heard another loud noise and observed that fire had broken out at the rear end of the tank trailer. The tunnel ventilation system was sending the smoke from the fire in the direction of the tank truck, and the driver therefore chose to drive the truck out of the tunnel. The build-up of smoke from the fire increased, and the tank truck was surrounded by dense smoke through the final section of the tunnel before reaching the exit. The driver parked the truck a good distance away from the tunnel portal, but subsequently had to move it further away because of the intense smoke and heat generation.
Figure 5: The tunnel’s vertical and horizontal curvatures and overview of the fire incident.
Illustration: AIBN/NPRA.

Four passenger cars and one camper van had followed the road tanker into the tunnel. Three of the passenger cars and the camper van were able to turn around and leave the tunnel, while one passenger car was evacuated and left standing 150 metres behind the tank trailer. The driver and passenger in this passenger car were eventually evacuated in the camper van, which was one of the last two vehicles to leave the tunnel. A detailed description of the road users’ experience of the incident is given below.

Figure 6: The remains of the tank trailer as left behind when it had broken loose from the truck.
Photo: AIBN.
The fire developed quickly, and much of the petrol in the trailer’s front tank chamber leaked out and ran towards the bottom of the tunnel. All the petrol was eventually ignited and the fire spread from the bottom of the tunnel through the drainage system up to the eastern tunnel portal, over a distance of approximately 900 metres. The tank trailer and the evacuated passenger car were completely consumed by fire, and the damage to the tunnel and tunnel infrastructure was extensive. Figure 5 shows damage to the tank trailer and the tunnel.

The road users’ description of the incident
When the trailer broke loose from the tanker truck, there were four passenger cars and one camper van inside the tunnel. The first vehicle (a passenger car) caught up with the road tanker just after it passed the bottom of the tunnel and was driving behind until the trailer broke loose from the truck. The driver of the passenger car observed that the trailer had started to sway violently over a distance of 50–100 metres before it broke loose and hit the tunnel wall. When the driver of the passenger car saw that liquid was leaking out of the tank trailer, he chose to reverse his car and turned around at the bottom of the tunnel. He exited the tunnel from where he had entered it. While driving back through the tunnel, he was able to warn the first oncoming car, but three other vehicles continued driving towards the leaking tank trailer.

Just after starting the ascent out of the tunnel, the driver and passenger of the camper van noticed that liquid was running down the side of their lane. Continuing uphill, they passed a passenger car at a standstill in their lane just before arriving at the trailer that had run into the tunnel wall.

When they were 5–10 metres from the tank trailer, the people in the camper van heard a bang and a fire broke out around the trailer. The pressure wave from the fire pushed the bonnet of the camper van upwards and dislodged the headlights. The driver of the van immediately started reversing towards the bottom of the tunnel. The two people in the van stated that the fire spread rapidly in the petrol that was running down the roadway. As they reversed downhill, the flames from the petrol stream were leaping up along the side of the camper van.

As the van approached the bottom of the tunnel it caught up with two people who were running downhill. The two people were eventually able to get into the camper van, and they proved to be the driver and passenger of the passenger car that the van had overtaken on the way uphill towards the road tanker. The two people that had driven the passenger car said that they had stopped because of a puncture, and that they had left the car and run downhill when they heard the bang and saw that the trailer was on fire. As they left their car, they had stepped right into the petrol that was running down the roadway.

The camper van continued reversing to the bottom of the tunnel and some way up towards the Bremanger side. When it felt safe, the driver turned the camper van around and drove out of the tunnel.

FINDINGS AND ANALYSES:

Drawbar breakdown:
The investigation has uncovered the event chain and the causes for the drawbar breakdown. In order to document the damage, corrosive action and strength of the remaining parts of the trailer drawbar, the “Norwegian Defence Laboratories” (NDLO/ADK) was commissioned to carry out metallurgical examinations of these parts [2].

The result of the investigation shows that the trailer drawbar broke due to an advanced state of internal corrosion in the drawbar rods. AIBN completed a metallurgical examination of the coupler structure, and the examination concluded that the structure had lost its mechanical strength due to
major internal corrosion. The remaining material strength was less than required and the structure failed during towing.

The investigation revealed that this corrosion was first detected during an inspection in 2011. The rust damage was repaired by welding sheets of metal onto the rusted parts of the trailer drawbar. The metal sheet was welded onto the outside of the corroded areas, without removal of any rust in that connection and without any further assessment of the scope of the internal corrosion damage to the drawbar rods. The repairs were not in accordance with the trailer manufacturer’s specifications, which state that welding is not permitted and that damaged drawbars must be replaced.

From the time that the repairs were carried out until the trailer drawbar broke, the trailer had undergone eight official inspections without the defective repairs having been detected.

The fire cause and development
The results of this research is a main topic in this paper, and was a central part of the investigation. The “SP Technical Research Institute of Sweden” has on behalf of AIBN studied possible sources of ignition and the spread of fire in the tunnel. SP issued two central reports in this connection [3,4]:

Part 1: Investigation into the origin of the fire in the Skatestraum Tunnel on July 15th, 2015

Based on available information, SP considered the following hypotheses on how the petrol was ignited in table 1:

Table 1: Assessment of possible ignition sources. Source: Investigation into the origin of the fire in the Skatestraum tunnel on July 15th, 2015 – Part 1, SP Technical Research Institute of Sweden [3].

<table>
<thead>
<tr>
<th>Possible cause of ignition</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sparks from collision</td>
<td>Improbable</td>
</tr>
<tr>
<td>Electricity in tank trailer</td>
<td>Improbable</td>
</tr>
<tr>
<td>Electrical installations in the tunnel</td>
<td>Improbable</td>
</tr>
<tr>
<td>Spark formation as a consequence of the tank trailer moving and scraping against the wall</td>
<td>Improbable</td>
</tr>
<tr>
<td>Spark formation as a consequence of static electricity when the petrol ran out of the tank and onto the roadway</td>
<td>Improbable</td>
</tr>
<tr>
<td>Hot surfaces on the tank trailer such as hot brake discs or other hot surfaces</td>
<td>Low</td>
</tr>
<tr>
<td>The driver of vehicle B observed ‘smoke’ between the tank trailer and the tunnel wall</td>
<td>Improbable</td>
</tr>
<tr>
<td>A vehicle (behind the tank trailer) initiated the fire</td>
<td>High</td>
</tr>
</tbody>
</table>
Conclusion:
The study of possible ignition sources concluded that it was highly probable that the fire was initiated by one of the vehicles that was following the road tanker, particularly the camper van (vehicle E), as that vehicle had sustained pressure damage indicating that there may have been an explosion in the engine compartment.

This conclusion is supported by observations made by the people inside the camper van. They observed that the petrol ignited and that there were flames around the van before it started to reverse down the slope. The fact that the van’s bonnet had been forced up, indicates that the fire started as a consequence of a pressure change in the engine compartment.

Part 2: Investigation into the development of the fire in the Skatestraum Tunnel on July 15th, 2015.

The study was carried out based on documentation about the tunnel’s design, material damage, the amount of petrol involved and the leakage, witness statements and the AIBN’s own photos and description of the scene of the accident. SP has developed a timeline based on the information that is shown in table 3 below [4].

Table 1: Timeline of the incident before and after the fire broke out. Source: Investigation into the development of the fire in the Skatestraum tunnel on July 15th, 2015 – Part 2, SP Technical Research Institute of Sweden [4].

<table>
<thead>
<tr>
<th>Logged time</th>
<th>Time in min:sec from the start of the fire</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2:40</td>
<td></td>
<td>The accident occurs, the tank trailer breaks loose and collides with the tunnel wall – vehicle A</td>
</tr>
<tr>
<td>-2:40</td>
<td></td>
<td>Vehicle B has stopped 10 metres further down and witnesses the accident</td>
</tr>
<tr>
<td>10:24:51</td>
<td>-01:41</td>
<td>The door to BS03 is opened by the driver</td>
</tr>
<tr>
<td></td>
<td>-01:30</td>
<td>Petrol front 150 metres downhill from the tank trailer</td>
</tr>
<tr>
<td>10:25:36</td>
<td>-00:54</td>
<td>The tunnel is closed</td>
</tr>
<tr>
<td>10:25:38</td>
<td>-00:52</td>
<td>Tunnel closure is confirmed</td>
</tr>
<tr>
<td></td>
<td>-00:30</td>
<td>Vehicles B and C meet vehicles E (the camper van) and D at F2 (see figure 5), 367 metres downhill from the tank trailer</td>
</tr>
<tr>
<td></td>
<td>-00:20</td>
<td>Petrol front at F2</td>
</tr>
<tr>
<td>00:00</td>
<td></td>
<td>Vehicle B has reached the lowest point of the tunnel</td>
</tr>
<tr>
<td>00:00</td>
<td></td>
<td>The fire starts. At this point in time, the camper van is located 10–20 metres from the tank trailer</td>
</tr>
<tr>
<td>00:00</td>
<td></td>
<td>Vehicle D stops (the road users step out into the petrol that is...</td>
</tr>
</tbody>
</table>
Logged time | Time in min:sec from the start of the fire | Event
--- | --- | ---
 |  | flowing past)
00:05 | Vehicle A drives towards Hamnen (immediately after the fire started)
00:25 | Vehicle E is by sand trap 5 (103 metres from the tank trailer)
00:25 | The petrol reaches the pumping station (463 metres from the tank trailer)
00:25 | The flames have reached sand trap 5 (103 metres from the tank trailer)
10:27:50 | 01:20 | Short-circuit in the night light cable between the tank trailer and the portal at Hamnen
10:28:01 | 01:30 | Vehicle A drives out of the tunnel at Hamnen in dense smoke
10:28:01 | 01:31 | The first of fans V01-V08 starts up
10:28:16 | 01:46 | All fans V01-V08 in operation
10:28:20 | 01:50 | Critically high CO level at F1
 | 01:50 | Vehicle E has reached the pumping station and picks up two road users from vehicle C. Talking is difficult due to noise from the fans
02:00 | The flame front reaches the pumping station

Conclusions from SP [4]:

- The tunnel’s falling/rising gradient of 10 % played a decisive role in the spread and development of the fire.

- The rates at which the initial smoke and heat spread to the areas above and below the scene of the fire are determined by the gradient of the tunnel.

- The drainage system that should have drained away the liquid from the roadway surface was not effective enough to avoid a surface fire with an effect exceeding 200 MW within two minutes of ignition.

- Because of the air streams generated by the fire, the ventilation system had no effect on the sequence of events or the environment in the tunnel.

- Fatalities were prevented by rapid and correct action on the part of those involved.
- In the area below the fire, radiation heat would have caused certain death had it not been possible to evacuate before being enveloped in smoke.

- Any individuals caught in the smoke downstream or upstream of the fire would have found it very difficult to evacuate and would most probably have lost consciousness and subsequently died.

- The powerful thermal current generated by the fire gave rise to an air flow rate of 27 m/s (100 km/h) downstream of the fire (hot) and 9 m/s (30 km/h) upstream of the fire (cold).

- The initial fire caused by the petrol leakage had an effect of 212 MW. The fire peaked at 440 MW for a brief period when both the petrol in the roadway and the remaining petrol in the tank were on fire at the same time.

- The estimated maximum temperature was 1350 °C under the roof 10–20 metres uphill from the tank trailer.

- Going uphill from the fire, the temperature dropped from around 600 °C about 150–200 metres from the tank trailer to just under 200 °C at the tunnel portal (460 metres from the tank trailer).

- The smoke quickly exceeded the critical values and was followed by high temperatures and finally radiation heat.

These reports also concluded that the falling/rising gradient of the tunnel had a significant bearing on the spread of the fire, and that this was exacerbated by the inadequate capacity of and a fault in the tunnel’s wastewater and drainage system.

The fire effect and temperature in the tunnel
According to SP’s calculations, the maximum heat release rate exceeded 400 MW during the period when both the running petrol and the tank trailer were on fire, and the temperature above the burning trailer was approximately 1,350 °C. The greatest air flow rate generated by the fire inside the tunnel was around 100 km/h. Furthermore, the report concludes that any individuals caught in the smoke downstream or upstream of the fire would have found it very difficult to evacuate and would most likely have died due to high thermal radiation.

Risk analyses and safety management of the tunnel
The investigation also found that risk analyses had been conducted that, among other things, described a fire/explosion in a heavy goods vehicle and accidents involving dangerous goods, but that no descriptions had been provided for how such scenarios were to be handled when it came to extinguishing the fire, evacuation, self-rescue and assisted rescue.

After the fire, Sogn og Fjordane county administration has not implemented or considered implementing compensatory measures to limit the consequences of any similar incidents.

ANALYSES
The triggering event
The investigation has shown that the tank trailer broke loose from the tank truck because the trailer drawbar was overloaded. The material strength of the drawbar rods was significantly reduced due to an advanced state of internal corrosion. In the AIBN’s opinion, the reason why the trailer drawbar broke was because the strength of the drawbar rods had been reduced due a very advanced state of corrosion.
The spread of fire
When the tank trailer broke loose, it hit the tunnel wall approximately 475 metres from where the road tanker started the ascent from the bottom of the tunnel. One of the tanks on the tank trailer ruptured, and the petrol that ran out was ignited. This caused the fire to spread to the bottom of the tunnel, both along the roadway and through the tunnel’s drainage system. As the fire developed, it burnt holes on the top of the remaining tank compartments on the tank trailer. The petrol that ran out was most likely ignited by heat/sparks from a van that had stopped behind the tank trailer.

The investigation found that the tunnel’s surface water system was not designed to handle the amount of petrol that ran out. Furthermore, a leakage in the surface water pipes caused some of the petrol to run into the ground. This meant that both the petrol running on top of the roadway and the petrol that ran into the surface water system was on fire. The AIBN believes that the rapid spread of fire to the bottom of the tunnel was due to the steeply falling/rising gradient of the tunnel (10 %) combined with weakness in the drainage system.

The road users’ actions
In the AIBN’s opinion, the driver acted in accordance with what should be expected of drivers of vehicles carrying dangerous goods. He acted extremely responsibly, both during the journey prior to the incident and in the situation after the tank trailer had broken loose from the truck. He stopped to let other cars pass before he left the ferry landing at Oldeide, and he mindfully engaged the truck’s retarder and engine brake to curtail the speed as he drove towards the bottom of the tunnel. When the tank trailer broke loose, he immediately notified the VTS centre, stopped oncoming vehicles and evacuated the tunnel in a responsible manner. Through his actions the timeline of the incident turned out very positively, despite the extremely dangerous situation.

The people in the five vehicles that entered the tunnel behind the road tanker acted quickly when they saw that the tank trailer had hit the tunnel wall. Four of these vehicles reversed and turned around immediately, while the driver and passenger in the fifth car evacuated on foot as they believed their car could not be driven. They were subsequently picked up and evacuated out of the tunnel by the camper van that had turned around.

The AIBN believes that the situation would have been critical for the road users in the road tanker and the five vehicles, had they not reacted as quickly as they did.

The VTS centre’s response
No radio alert was issued in connection with the incident and the road users did not receive any warning. According to the NPRA, the VTS operator was concentrating on warning the road users and notifying other parties of the possibility of issuing a radio alert without receiving any response. The VTS operator was not aware that the radio alert system was not working in the Skatestraum tunnel at the time of the incident, however, although the VTS centre had previously been notified of this. The AIBN does not know why this information had not been received by the VTS operator.

The response of the fire and rescue services
The fire in the Skatestraum tunnel was very intense and produced a large amount of smoke. On being notified of the incident, the VTS centre notified the emergency communication centre in Sogn og Fjordane county, which immediately proceeded to issue a triple alert. The fire and rescue services responded and arrived at the tunnel within a relatively short period/time, considering the distance. The fire crew focused on searching for and rescuing any road users that might still be inside the tunnel. They then withdrew until the fire died out by itself.

The AIBN considers the response of the fire and rescue services to have been satisfactory, in relation to the intensity of the fire and the limited possibility of searching the tunnel once the fire had escalated.
Lessons learned from earlier investigations
In previous reports, the AIBN has highlighted the need to immediately instruct road users located in a tunnel to evacuate during a fire. This issue was addressed in Safety recommendation ROAD No 2013/08T after the Oslofjord tunnel fire in 2011, and Safety recommendation ROAD No 2015/03T after the Gudvanga tunnel fire in 2013. In the AIBN's opinion, fast and informative notification is a key element to improving road users' chances of self-rescue before a tunnel is filled with smoke. The NPRA's own evaluation of the fire in the Skatestraum tunnel mentioned the inoperative radio alert system, and defined this as one of several learning points after the fire.

The AIBN takes a positive view of the fact that the NPRA has identified the problem and recommended measures to ensure that radio alerts are issued in consultation with the local fire service.

SUMMARY AND IMPORTANT RESULTS OF THE INVESTIGATION

Drawbar brake down
The rust damage that was detected in an ADR inspection of the tank trailer in 2011 was repaired in contravention of the manufacturer's instructions, by welding sheet steel on top of the rust holes. Rather than increasing the strength of the structure, the repairs contributed to increasing the risk of corrosion fatigue. The corrosion was therefore allowed to develop, until the trailer drawbar finally broke in 2015.

Tunnel design
The gradient of 10 % inside the tunnel, combined with the fact that the drainage system was unable to drain away the liquid from the roadway surface, caused the petrol that leaked out to quickly spread over a wide surface area, which in turn generated a lot of smoke and heat, and explains the intensity of the fire.

Restriction for ADR transport
The risk analyses for the Skatestraum tunnel from 2013 and from 2016 after the fire, are both inadequate in terms of assessing scenarios and measures. The damage/injury potential associated with the carriage of dangerous goods and fires has not been adequately assessed in relation to the tunnel’s special characteristics. There is no restriction on the transport of dangerous goods through the tunnel.

Safety management
Sogn og Fjordane county Administration follow-up of the safety in the Skatestraum tunnel has not been satisfactory. Neither has the capacity of the tunnel’s surface water system been increased after the fire, nor have any measures been implemented to reduce the consequences of similar future incidents.

Recommendations from AIBN
In addition to the issued safety recommendations, this investigation report provides a detailed description of what caused the trailer’s drawbar to break as a result of an advanced stage of internal corrosion in the drawbar rods.

After the accident, the Directorate of Public Roads on behalf of the Norwegian Public Roads Administration (NPRA) has sent out information/guidelines on following up repairs and damage to trailer drawbars. The AIBN is of the opinion that the written information provides good guidelines on how to follow up repairs and will therefore not submit any further safety recommendations on this topic. However, the AIBN expects the NPRA to follow up that this information is incorporated into the training and procedures of garages, inspection bodies and the NPRA’s Driver and Vehicle Licensing Offices.
The AIBN issued four safety recommendations as a result of the investigation of the fire in the Skatestraum tunnel;

**Safety recommendation ROAD No 2016/13T**

Like most other tunnels in Norway, the Skatestraum tunnel has a drainage system designed in accordance with the NPRA’s manual on road tunnels. The gradient of 10% inside the tunnel combined with the fact that the drainage system was unable to drain away the liquid from the roadway surface, caused the petrol that leaked out to quickly cover a wide area, which in turn generated strong heat and a lot of smoke and explains the intensity of the fire on 15th of July 2015. In order to prevent the spread of dangerous spills from vehicles and limit the size of the accident site, the tunnels’ wastewater drainage systems should be designed with a greater capacity for draining away large spills of dangerous liquids and prevent them from spreading at an early stage.

The AIBN recommends that the NPRA revise its requirements for tunnel drainage systems, so that they are designed to handle large spills of dangerous liquids carried by vehicles.

**Safety recommendation ROAD No 2016/14T**

The risk analyses for the Skatestraum tunnel carried out both before and after the fire on 15th of July 2015 were not in accordance with the recommended guidelines in Manual V721 – Risk analyses related to road traffic, which require consideration or implementation of measures related to the most serious scenarios/incidents, regardless of the probability that they will occur. The AIBN is of the opinion that the risk analyses were inadequate with respect to the consideration of scenarios and risk-reducing measures. Inadequate risk analyses can entail that the damage potential and the unique features of each tunnel are inadequately assessed and addressed.

The AIBN recommends that Sogn og Fjordane county administration and the NPRA, when conducting risk analyses, describe and follow up measures related to the described scenarios/incidents.

**Safety recommendation ROAD No 2016/15T**

The investigation of the fire in the Skatestraum tunnel on 15th of July 2015 showed that road users had a very short time window for evacuating the tunnel when the tank trailer broke loose from the truck. The road users responded rapidly and correctly when the incident occurred, but a minor change in circumstances could have had dramatic consequences. Because of the short time window and the extensive effect of a fire, the AIBN is of the opinion that consideration must be given to restricting the transportation of dangerous goods through the Skatestraum tunnel and similar tunnels.

The AIBN recommends that the relevant road authority together with the Directorate for Civil Protection and Emergency Planning introduce restrictions on the transportation of dangerous goods through tunnels, based on a risk assessment of each individual tunnel.

**Safety recommendation ROAD No 2016/16T**

The investigation of the fire in the Skatestraum tunnel on 15th of July 2015 shows that the safety of this tunnel has not been adequately followed up by Sogn og Fjordane county administration. The risk analyses of the Skatestraum tunnel carried out both before and after the fire did not adequately address scenarios and measures. When the tunnel was restored after the fire, the capacity of the drainage system was not increased to prevent the spread of liquid over large areas. Nor have measures been considered or implemented to reduce potential consequences or restrict the transportation of dangerous goods.

The AIBN recommends that Sogn og Fjordane county administration review and strengthen its follow-up of safety in the Skatestraum tunnel and other similar tunnels on the county roads.
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A new approach to road tunnel fire safety design

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ABSTRACT

There is evidence for that the current fire safety design process is limited by a mathematical rigor to get the analysis rather than the solution right. The approach satisfies with an acceptable solution which often means that only one alternative is evaluated. This work can be described as a journey of safety. Along the way questions such as what fire safety is, how it can be measured, whether we at all are posing the right questions or engineer the best solutions have surfaced. The journey naturally started out with the traditional view with fire safety engineering based on deterministic design. Then arbitrarily safety levels with a reference to worst-case scenarios or risk curves are defined as absolute measures of safety regardless of other objectives. This contradicts the basic rationale of decision-making where the best trade-off is sought between all objectives. This naturally led to the second stop of the safety journey called probabilistic design where risk is exchanged as a cost factor in a cost and benefit analysis, in accordance with the basic rationale of decision-making. Then safety is allowed to be a relative concept depending also on a few other objectives. The journey next went on to also include social structures and the ethical and democratic component of risk. The proposal is based on a general decision making process aimed at finding the best solution to the design problem. Only engagement of the design group and stakeholders into the hole decision process including #1 framing, #2 objectives, #3 alternatives, #4 consequence and uncertainty analysis and #5 risk evaluation and trade-off can guarantee that the best solution is found. Solutions should initially exhibit Vision Zero strategies such as inherent safety or fail safe design. A decision-oriented fire safety approach fits naturally into the Swedish road design process.

KEYWORD: road tunnel, fire safety, Vision Zero, deterministic design, probabilistic design, decision-making

INTRODUCTION

With the introduction of performance-based fire regulation, new questions about safety can be posed, e.g. how safe is actually safe enough? How safe something should be is a normative question and if we should believe the Scottish philosopher David Hume, we cannot derive an ought from an is. There will never be a definite answer, but we can argue for better or worse ones. How safe road tunnels should be turned out to be a very challenging and intriguing question. In literature it emerges in different framings and consequently different logical answers. Largely this journey has gone from a deterministic view, i.e. safety limits specifying how safe the tunnel should be?, to a probabilistic, i.e. enough safety if the overall utility is maximized to a decision oriented framing, i.e. which tunnel design is the best solution to the problem? These three different problem framings highlight different aspects and give rise to different design processes and solutions. The deterministic framing focuses on measurable safety objectives where each objective is treated in isolation. The probabilistic dimension is only implicitly considered, e.g. through subjective reference to a “worst-case” scenario. This approach transforms the decision problem into a mathematical problem of verification. In the probabilistic approach the probabilistic dimension is quantitatively included. Usually this approach relies on a cost-benefit analysis that investigates the optimal trade-off between protection and cost. Then it can be argued that the globally optimal solution from an economic stand-point is derived. A decision-oriented framing could also include qualitative aspects such as fairness or the quality solutions should have.
This paper starts out with a background of fire safety design, the road tunnel design process, deterministic design and probabilistic design. Based on identified shortcomings, a new approach to road tunnel fire safety is proposed based on a general decision-making framework and the Vision Zero design philosophy. How the new approach works is visualized with two examples. The paper finishes with a discussion and conclusions.

BACKGROUND

The Swedish road (tunnel) design process

Johansson [1] has described the Swedish road design process. Gehandler et al. [2] has in particular described the Swedish road tunnel design process. The construction of a road or a tunnel is often preceded by a lengthy process affected by many different policies, rules or regulations, local, regional or national politics and the opinions of various stakeholders. Swedish tunnels and roads have a similar planning and design process since the road administration often is responsible for both. This process contains four stages: pre-study (förstudie), road-study (vägutredning), work-plan (arbetsplan) and technical specification (bygghandling), see Figure 1.

![Figure 1  The four road design stages.](image)

In the pre-study the main question is whether a road connection should be made between A and B. Aspects such as mobility, safety, accessibility and the environment are evaluated. If it is decided that a new construction is necessary, a suggestion of a geographical area and a description of is made. Information concerning road tunnels can be sought if that is an option. In negotiation with affected stakeholders the road administration decides whether the project should continue or not.

In the road-study stage different possible corridors for the road are evaluated. Advantages and disadvantages with different alternatives are compared with the alternative to do nothing and the alternative to improve existing infrastructure. The aim is to solve the identified problem with the least environmental impact. For this purpose an environmental consequence description according to The Swedish Environmental Code is required. It is mainly the road administration and concerned municipalities that decide which alternative that is best. The winning alternative is sent to the government for approval. It is by now decided if a tunnel is needed or not. If the government approves the plans, the project enters the work-plan stage.

In the work-plan stage the tunnel or road is planned in greater detail. In this stage the chosen corridor is evaluated against existing regulation (in particular the Environmental Code). For tunnels this is where the main fire safety design is made, which means that road tunnel fire safety regulation also is included at this stage. An identified problem at this stage is that there are many different objectives that can be in conflict. It is for example unclear today how natural protection should be weighed against safety. It is also not clear how the fire safety engineering (FSE) process relates to the overall design process. Risk analysis is often required but the purpose of the analysis or what to do with the
result is unclear in regulation and in practice [2]. At the end of the work-plan stage a preliminary (fire safety) design exist.

In the technical specification stage it is specified in detail how the tunnel should be built so that entrepreneurs can bid to win the construction contract of the tunnel. The technical specification stage is not mentioned in any regulation and cannot be appealed. This stage can be done by another group of contractors than in the work-plan stage. By experience the interest for fire safety is reduced here and there are no routines that ensures that the preliminary design of the work-plan, in the end, becomes specified [2].

At the end of each stage, and sometimes during a stage, consultation meetings are arranged by the Road Administration where stakeholders such as the public, rescue service, contractors, Road Administration experts and third party reviewers are invited. The purpose is to have an open discussion on relevant issues but the meetings are often experienced as a lecture by the Road Administration. The idea is though that the Road Administration could get help with risk evaluation and tough trade-offs from these meetings. But instead it is the Road Administration that decides without any consultation [2].

Fire safety design
Historically, prescriptive requirements based on historical fire incident investigations have been the dominant approach to building safety. However, as the field of FSE has evolved, regulation has allowed a performance-based option to prescriptive provisions, allowing the fire safety design to be engineered by fire safety engineers. In this work FSE draws much upon risk management [3]. Lundin [4] investigated several FSE projects in Sweden and identified some fundamental problems concerning society's ability to control fire safety by performance-based building regulations, which leads to arbitrary design decisions.

The basis for deciding a performance-based acceptable level of life safety risk is that the available safe escape time (ASET) is larger than the required safe escape time (RSET) by a margin of safety for some selected scenarios [5]. Bjelland and Njå [6] find that current practice of ASET/RSET analyses in the Norwegian building industry are done to confirm that chosen solutions are sufficient while the analyses themselves have limited constructive value for engineering design. Out of 75 examined projects, none contained evaluations of more than one design alternative. Generally, there is no legislative or regulatory objective to maximize fire safety. In a typical performance-based building project, many alternatives will often be worked through in a qualitative design sense, e.g. timber, steel or concrete structure; or natural versus mechanical ventilation for smoke control in an atrium. Many different attributes can be considered, including fire safety, before a tentative design decision is taken, which must then be checked for acceptance by modelling and analysis. Bjelland [7] argues for that the problem-framing in FSE projects is too narrowly focused on mathematics. The mathematical problem-framing excludes or at least discredits other types of knowledges such as moral and tacit knowledge and past experinece. According to Babrauskas et al. [8], the ASET/RSET concept is limited precisely because it is used, as the example above illustrate, to verify fire safety to an “acceptable level”, rather than to maximise fire safety. Further, the concept commonly ignores the wide variation in fire scenarios, human capability and behaviour in fire. Roughly half of all deaths and 2/3 of the injuries from home fires could be prevented if more time was available for escape. In order to save these people another method or concept seems to be necessary. The two dominating approaches within safety design are deterministic and probabilistic design [7, 9].

Deterministic design
In the deterministic design approach safety is managed by limits, e.g. ‘plausible worst case’ or ‘worst case’ scenario [10]. An example could be a specification of a design fire that the ventilation system should handle. A critical issue in deterministic design is the selection of limits or a reference scenario since the consideration of likelihood of occurrence, or any other objectives, are only implicitly considered. Should it be more of a ‘worst case’ or a ‘worst plausible case’? The deterministic approach ignores questions such as how large a sacrifice, e.g. cost of protection, should be directed
toward incredible “worst case” scenarios [10]. With a worst case or worst plausible case fire, deterministic design discredits or ignores any preventive work that might lead to less or smaller fires. Deterministic limits are often prescribed in regulations or design guides, e.g. minimum number of exits, door and exit widths, but they can also be derived in performance-based design work. Deterministic safety levels are, perhaps correctly, accused of being magic numbers, although we may still need a few of them [11]. Although deterministic design appears to be at odds with the basic rationale of decision-making, deterministic approaches are common in fire safety, e.g. the use of design fires or quantitative design criteria for fire safety objectives in performance-based design.

**Probabilistic design**

In the probabilistic design approach the likelihood of occurrence is explicitly included in the analysis and it is argued that enough safety is achieved if the utility is maximised [9]. Most decision theories are based on the idea that the choice depends on the probabilities of various consequences and their utility, or value, to the decision-maker [12]. The logic is to choose the option that promises most of what you want. In the fire safety context, utilities are for example property, cost and life, and utilitarian evaluations are most often done by cost-benefit analysis (CBA). From a moral perspective an unjust societal arrangement could produce more utility as measured by the CBA than a just one. Therefore other relevant factors, e.g. justice and fairness need to be acknowledged in the decision. Minorities with special needs, e.g. disabilities, are not visible in statistical estimates and are therefore ‘sacrificed’ for the needs of the majority [13, 14].

**A NEW APPROACH TO ROAD TUNNEL FIRE SAFETY DESIGN**

**A general decision-making process**

According to Fischhoff and Kadvany, the foundations of risk lie in decision theory, which articulates concepts whose emergence must have begun with the first human thought about uncertain choices [15]. Hermansson [16] argues that the focus in risk management should shift from the outcome to the procedure for decision-making. Those affected by a risk decision should have the opportunity to be involved in a fair decision-making process. Public participation is a goal for democracy and a requirement for rational decision-making [17, 18]. It is thus argued that decision-making should not be separated from design and evaluation as they are strongly dependent and iterative processes. Decision-making is fundamental to fire safety design. Therefore we should acknowledge that we are dealing with a decision problem. The logic of decision-making is to choose the option that promises most of what you want. Most decision theories are based on Bernoulli’s concept that choice depends on the likelihood of various outcomes and on the utility of those outcomes to the decision-maker [12].

Accordingly this paper reframes the question of how safe a road tunnel should be from the deterministic framing mentioned above to a more open decision-oriented framing. A general decision-making process is proposed where the problem and its solutions can be reframed and negotiated along an iterative process based on the following five main phases [12, 19]: #1 problem framing, #2 objectives, #3 development of alternatives, #4 consequence & uncertainty analysis, and #5 risk evaluation & trade-off. The fire safety problem is reframed into: “finding the best solution to stakeholders’ decision objectives”. In light of new understanding along the iterative process the problem and potential solutions are reframed. The tools from decision-making can be used to structure the problem, to remove constraints and biases, to identify the key objectives and improved solutions, to evaluate solutions and to strike trade-offs. Public participation can be ensured through the political parties that are included in road design process and the consultation-meetings that are arranged along the way. Then the keywork for the consultation meetings should be ‘dialog’ or ‘consultation’ rather than ‘information’.
Figure 2  A general decision-making process.

Note that in the current FSE approach the first three stages in Figure 2 are only implicitly considered. As was argued by Babrauskas and Bjelland the problem framing is limited to a mathematical analysis to verify fire safety or to show acceptable risk, as opposed to for example finding the best solution. Final objectives are typically limited to those identified in law, e.g. life safety, that are captured by the quantitative methods. And finally, as was identified by Bjelland, at worst and perhaps most commonly, only one alternative is included in the analysis, which is next verified to be “acceptable”.

The Vision Zero design philosophy

If safety is seen as a decision problem it becomes important to discuss what goal or aim we should aim at. At a first glance it may seem that Vision Zero on the road network is little less than an unrealistic goal. However, Vision Zero is much more than the distant goal of zero. Vision Zero calls for necessary innovations so that no people are killed or seriously injured on the road network. Zero is not a target to be achieved by a certain date. It highlights how the optimum state of the road system is [20]. Vision Zero assumes human error and mistakes will continue to occur. During such conditions, it is the responsibility of the system designers to ensure that the road system (roads, vehicles and users) is inherently safe, i.e. eliminate errors, or at least fail safe, i.e. forgiving to errors such that the exerted violence on the human body is tolerable [20-22]. Inherent safety followed by fail safe design are identified as the two most efficient safety concepts within safety engineering by Möller and Hansson [23]. In the Vision Zero design philosophy, safety should be an inherent property and engineered into the system from the start rather than reactive measures taken to correct inferior solutions. Incremental fixes or safety systems added to imperfect solutions is not good enough. This sets higher or at least different requirements than what is typically analysed and engineered in deterministic or probabilistic design. It is not good enough to engineer an acceptable or a safe enough solution but instead the aim is to achieve a close to absolutely safe system that is forgiving to human errors and mistakes (excluding e.g. violations) engineered by the principles of inherently safer and fail safe design [22].

Compared to traditional safety approaches, Vision Zero can create innovations and improved solutions [24]. Despite this potential, Vision Zero has not been very successful in reducing road fatalities and serious injuries yet. Further, some of its measures such as lowered speed limits have been unpopular, suggesting that the public do want to trade mobility for safety. Andersson and Pettersson [25] argue that the strong visionary and idealistic political goals in Vision Zero suppress critical objections and can create lock-in effects and actually prevent effective policies from being implemented [25]. Elvik [26] estimates that the cost of reaching Vision Zero would be many more lives lost in other areas of society. A strict focus on reaching Vision Zero can therefore be unethical since it implies that other values, including safety in other areas, are disregarded without any
justification [27, 28]. Elvik [26] argues for a more pragmatic and probabilistic interpretation of Vision Zero. If we are ever to get as close as possible to the goal, Vision Zero calls for an efficient use of resources, which means resources should be allocated to the lowest net cost to save lives. This contradicts the principles and ideas behind Vision Zero, where economy is regarded as a means towards safety. Only if two measures offer the same level of safety CBA can be used to choose between them [22]. A strict focus on probabilistic design may create lock-in effects towards current solutions and technology since they often will be the cheapest option. Deterministic design is even more auspicious for creating lock-in effects towards inferior solutions, since it is enough to find one acceptable design that fulfils a pre-defined criteria [6, 8]. Although mobility and cost are downplayed in Vision Zero, inherently safer or fail safe solutions are not necessarily worse than other solutions; in the long run they may very well pay off [24, 29]. Given that society actually wants improved safety, then Vision Zero emerges as the best starting point. Other aims such as cost and feasibility can also be included in the decision process.

Only the whole decision process can ensure the best decision has been made

The whole decision process rather than some risk analysis performed at the end should ensure the outcome of the decision. Thus fire regulation need to cover the whole decision process, e.g. specify the roles and knowledge of different stakeholders and the objectives that might be relevant including also moral factors to ensure fairness and a balance between conflicting objectives. A balance is struck when the design team and stakeholders agrees that the best solution is found or agrees on a compromise between conflicting values or objectives.

Summary

Current challenges of fire safety design in a performance-based regime are summarized below.

- The view of safety as something absolute that is either acceptable or not acceptable and the practice of defining safety levels for each objective in isolation (deterministic design).
- To only evaluate one alternative that is verified as “acceptable” in a deterministic approach.
- That neither deterministic, nor probabilistic design encourages creative or innovative solutions; instead they can both satisfy with mediocre solutions.
- That the fire safety problem is turned into a narrow mathematical problem where mainly quantitative factors matters.

To address these, a new framework is proposed based on:

- An awareness of the limitations of deterministic and probabilistic design.
- A decision-making framing to find the best possible solution that acknowledges stakeholder objectives and priorities (including both quantitative and qualitative factors, both technical and ethical or democratic aspects).
- A general iterative decision-making process.
- A view of safety as something relative; relative to all decision objectives and values of stakeholders. The design team and stakeholders know the values and priorities for making the best decision or trade-off in each particular decision.
- Decision-making theory should drive the process and highlight where analysis matters and when objectives are in conflict and thus ensure high quality solutions.
- High ambitions through a Vision Zero design philosophy (in particular to derive solutions that have the quality of being inherently safer or fail-safe).

Application

The developed framework with its explicit emphasis on the decision-making process fits well into the road design process with its implicit decision-making process outlined by Johansson [1]. Inherently safer solutions are most likely derived during the early stages. Therefore road safety knowledge should be part of the pre-study and in particular road tunnel fire safety knowledge as soon as road
tunnels start to be discussed in the road-study stage. However, most obviously the developed framework enters into the third stage, the work-plan stage, see Figure 3. As can be seen from the described process above, many objectives apart from fire safety will already have been identified by various regulations and stakeholders. It would be preferable if the Road Administration was an active part through all four stages of the road design since they, unlike contractors that come and go, can maintain knowledge between all stages. Information including identified decision objectives from the earlier stages gives a good start for the fire safety design in the work-plan stage. In the two proceeding stages there will be one decision group headed by the Road Administration.

For the work-plan stage one can imagine many different decision structures. Whatever the structure, the proposed framework will contribute with an explicit decision-making process that clearly shows how the FSE process connects to the overall decision-making process. It should ensure that analysis is made where it matters with a clear purpose. It excludes a deterministic design approach. Instead it offers an iterative decision-making process where the solution is shaped. Since it is important that information is not lost between design stages the road administration needs to take an active role. A performance-based fire safety regulation without deterministic safety limits will be assumed. This paper will assume that a design group in negotiation with the owner (i.e. the Road Administration) are in charge of the fire safety decision process. Input from other stakeholders comes from the preceding more political stages and through the consultation meetings.

The Road Administration should also verify and validate that the specification-stage design is congruent with the work-plan design. In Figure 3 the stages over time and detail are visualised. It is important that the thinking and knowledge is transferred and validated between the stages (visualized with red in Figure 3). Each design group iterates through the five decision phases (see Figure 2), starting with overall strategies and concepts working towards increasing detail for each new road tunnel design stage.

![Figure 3: Application of the new framework in the road design process.](image)

Note that the safety work does not finish with the technical specification. During realisation and operation, the required safety functions needs to be verified and tailored to the actual tunnel, traffic situation and organisation [2]. At ISTSS 2016 [30] 12 general decision objectives where identified (hereafter referred to as Objective 1,…,12) as follows.

1. Limit the occurrence, generation and spread of fire and smoke.
(3) Means and safety for rescue operations.
(4) Load-bearing capacity of the construction.
(5) Organisational and administrative measures.
(6) Economic efficiency.
(7) Tunnel availability.
(8) The environment and long term sustainability.
(9) Fair risk and benefit distribution.
(10) Catastrophic fires.
(11) Perceived safety.
(12) Vision Zero.

Other objectives may be identified by the design team or any stakeholder. The weight put on each objective should reflect a balanced view of all stakeholders and ultimately society at large. Along the process, key objectives as well as irrelevant objectives will emerge. Projects for tunnels that are under design do not start from zero. Previous projects, existing tunnels and legislations including EC minimum requirements for road tunnel safety [31], set a standard that can be regarded as the first ‘status quo’ alternative. For existing tunnels or tunnels under refurbishment the current tunnel solution becomes the natural status quo alternative. In decision-making it is important that a status quo alternative is defined since it offers a sound reference for all other alternatives [19]. The status quo alternative evolves along the design process as more and more decisions are being made. The 12 objective above were analysed in [30] for a general case. It was found that a unidirectional road tunnel with longitudinal ventilation along the traffic flow fails safely in the event of fire, i.e. can achieve Vision Zero. Two fictitious examples are given below to visualize how the framework is applied in more detail. The examples below include the general aspects of the previous paper [30], e.g. the identified objectives and the general analysis of them.

Example 1: A 2 km city tunnel in Stockholm

In this example busy city tunnel on a three-lane highway is to be constructed. At the road-study stage the project group realise that a unidirectional two-bore road tunnel is the only logical option (in accordance with EC requirements). A two-bore solution is economically and practically feasible. With such a large amount of traffic much ventilation is required to reach clean air requirements (although a smaller need can be foreseen in the future with electric vehicles). From the analysis above it becomes clear that a longitudinal ventilation system with sufficient capacity (perhaps 8 m/s, well above any critical threshold for backlayering) offers a fail-safe solution. This means that the preferred problem framing from the section above, to achieve the principles of Vision Zero is within reach! Two possible corridors for the road tunnel are evaluated; one with 4 % inclination and a tough curvature and one with 2 % inclination and almost no curves. The design group argues in favour of the later corridor since it will be inherently safer and have fewer accidents.

The project now enters the work-plan stage. A fire safety design group is formed. The knowledge, problem framing and objectives are transferred from the previous design stages. At this stage some more detail concerning the construction of the tunnel is known. The tunnel is a cut-and-cover tunnel which means that the load-bearing capacity during fire must be considered. The tunnel will be constructed in a concrete that is resistant to fire-spalling. In Sweden current prescriptive regulation prescribes that the load-bearing construction should handle the hydrocarbon fire curve (HC) for 180 min. Since worst-plausible vehicle fires last for less than one hour this is a very conservative deterministic requirement. Lower temperatures than the ones prescribed in the HC curve can be expected for most vehicle fires for a concrete construction (could be higher if the tunnel is insulated) [32]. Further, the large width of a three lane tunnel also lowers the temperatures. One member of the design group thinks that the reason for having the 180 min requirement has to do with uncertainties regarding the cooling phase as this is not included in the standardised testing methods. It is decided to include an evaluation of the strength after cooling. In a performance-based approach a reasonable solution between the costly and risky can be derived. Probabilities for fires are uncertain but very close to zero for fires that last above 1 hour. Consequences from a tunnel collapse can be considerable, but has never materialized yet. Among the other objectives, a safe rescue operation...
requires that the tunnel does not collapse. Evacuation will be completed or have failed well before the HC temperatures are reached. Cost, environment and fairness speak against a conservative solution. The project group feels confident to start with a status-quo solution that achieves the HC 60 min curve and an added requirement to avoid a collapse also after cooling. For other reasons it is later found that the construction will have a corresponding HC 90 min property. This means that this objective is met.

In a later iteration, safety functions such as traffic and incident management and perceived safety, with such high traffic flows, become obvious cost-effective systems that adhere to and further strengthen the Vision Zero quality of an inherently safer and fail-safe system. A virtual reality study is launched to evaluate how the perceived safety from driving in the tunnel can be optimized. All objectives that are set up now appear to be reached.

\textbf{Table 1} Consequences on all objectives for the derived solution judged to be fulfilled without the need for compromises.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Consequence</th>
<th>Achieved?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 limit fires</td>
<td>Traffic and incident management limit the number of fires. For most fire scenarios the fire is limited to the vehicle of origin since there are no vehicles downstream that the fire can spread to.</td>
<td>☺</td>
</tr>
<tr>
<td>2 evacuation</td>
<td>For most scenarios the tunnel fails in a safe state with regards to life safety, there is no need for evacuation in smoke and thus life safety is not compromised.</td>
<td>☺</td>
</tr>
<tr>
<td>3 rescue service</td>
<td>Fire service can safely reach the fire and assist evacuees from the unexposed tube, or from the upstream portal.</td>
<td>☺</td>
</tr>
<tr>
<td>4 load bearing</td>
<td>Load bearing capacity is ensured for 90 min which comprise all worst-case scenarios.</td>
<td>☺</td>
</tr>
<tr>
<td>5 organisation</td>
<td>Required organisation for efficient operation, maintenance, and traffic and incident management.</td>
<td>☺</td>
</tr>
<tr>
<td>6 cost</td>
<td>Well within budget.</td>
<td>☺</td>
</tr>
<tr>
<td>7 availability</td>
<td>Tunnel availability not affected negatively by fire safety measures. Longitudinal ventilation is required for clean air and fire safety requirement.</td>
<td>☺</td>
</tr>
<tr>
<td>8 environment</td>
<td>Not negatively affected.</td>
<td>☺</td>
</tr>
<tr>
<td>9 fairness</td>
<td>No conflict identified.</td>
<td>☺</td>
</tr>
<tr>
<td>10 catastrophic fires</td>
<td>Catastrophic risk judged to be de minimis, so low that it is accepted.</td>
<td>☺</td>
</tr>
<tr>
<td>11 perceived safety</td>
<td>Good according to virtual reality studies. Should later be verified once the tunnel is drivable.</td>
<td>☺</td>
</tr>
<tr>
<td>12 Vision Zero</td>
<td>The solution complies with the strategies of inherently safer and fail-safe design.</td>
<td>☺</td>
</tr>
</tbody>
</table>

A deterministic designer might argue that the highly implausible scenario of a fire and stopped traffic on the downstream side should become a design scenario. This challenge the problem framing to one focused exclusively on conservative safety measures. However, the design group refrains from a deterministic problem-framing. As was shown in [30], to design for such unlikely events does not make sense from a probabilistic and decision-oriented perspective. The likelihood is extremely small and the consequences cannot be called catastrophic in comparison with other dangers our society face, e.g. from large industries. According to the Swedish Civil Contingencies Agency [33] incidents should be prevented within reasonable cost. For other events, society should minimize the consequences. The design teams argues for that this event falls in the second group. The cost of prevention is greater than the relatively small risk of dealing with the consequences [33]. It can further be argued that more costly systems such as a transversal ventilation system (required in EC regulation for this tunnel) or a sprinkler system (not required in current law) have a low support from most
objectives since it could violate the fail-safe quality, increase cost, could decrease tunnel availability when the systems are maintained and constructed, negatively affect the environment and long-term sustainability. Finally, from a fairness perspective extra safety measures should benefit pedestrians or cyclists who rarely benefit from safety systems inside the tunnel.

After several iterations, the design group, together with the stakeholders, feel that a very good solution (unidirectional road tunnel with longitudinal ventilation along the traffic flow with good organisational measures and perceived safety) has emerged that fulfils all 12 objectives set up above, see Table 1. The road tunnel project moves on into the specification stage where more detailed system specifications are defined congruent with the general ideas of the earlier phases. No tough trade-offs were really required in this example, however, that will be the case in the next example.

**Example 2: An existing rural 3 km road tunnel**

In this example a 3 km rural existing road tunnel is to be evaluated and possibly upgraded. Since this is an existing tunnel there will only be one design group and one design stage. Initially the design group starts with the general problem framing from the section above, to find a solution that comply with the principles of Vision Zero. It is not considered feasible to construct a second tube to turn it into a two-bore unidirectional tunnel. Some critical factors are early recognised by the design team: a high tunnel inclination, a bi-directional road tunnel, no separate emergency pathway, a fairly low ceiling height and small cross-section area. However, the traffic load and share of HGVs is fairly low. The load-bearing capacity (Objective 4) is not an issue since this is a rock tunnel. Perceived safety is identified to be an obvious objective to improve due to the limited sensory impressions from the long and static experience from driving in the tunnel. Availability is not a critical objective since there are alternative routes and low traffic volumes. On the other hand Objective 1, 2 and 3 appear to be difficult to reach.

The design team invest large efforts into generating creative alternatives that adhere to a Vision Zero safety concept with regards to objective 1, 2 and 3, i.e. #3 and #4 in the decision process. Soon it is realised that at the minimum a new evacuation system is required to really provide the means and safety for evacuation. Drivers need to be alerted that there is a fire and instructed to do one of the following: drive out/make a U-turn or evacuate by foot depending on where they are relative to the fire and tunnel portals. The tunnel needs to automatically close to stop more vehicles from entering. The benefit of these systems appears to be worth the relatively small cost. No other objectives are significantly affected negatively by an evacuation system, as long as the systems are designed taking various human disabilities into account (fairness). Despite that tunnel experts are hired to give expert advice, no inherently safer or fail-safe alternative could be derived.

The project group have struggled to come up with a Vision Zero concept but must, in negotiation with the stakeholders, satisfy with inferior solutions. The problem is re-framed to find the best solution in light of the identified key objectives. Then a set of alternative design can be proposed.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Status-quo)</td>
<td>The tunnel as it is with an upgraded evacuation system and perceived safety</td>
</tr>
<tr>
<td>1</td>
<td>Alternative 0 + transversal ventilation</td>
</tr>
<tr>
<td>2</td>
<td>Alternative 0 + sprinkler</td>
</tr>
<tr>
<td>3</td>
<td>Alternative 1 + 2</td>
</tr>
</tbody>
</table>

Currently there is no ventilation system in the tunnel and the design team ponders whether a longitudinal or transversal ventilation system should be installed. It seems the tunnel does not need any ventilation for clean air purposes. A longitudinal ventilation system would not fail safely in the event of fire and it is not clear how to control it in the event of fire considering that there probably are road users downstream and upstream any vehicle fire. After some iterations the option of no ventilation emerge to be a better option compared to longitudinal ventilation since it fails in a better
state of minimal ventilation which limits the initial fire growth and smoke spread. A transversal ventilation system is costly to install but could improve the difficult situation. Later in the process the rescue service starts to demand some kind of ventilation to ensure tenable conditions for their personnel. Another solution that starts to be discussed with the rescue service is to install a sprinkler system. From a probabilistic perspective a large fire is very unlikely. Still, smaller fires cannot be disregarded even from a probabilistic perspective and can still have significant consequences with a difficult and long evacuation. At this stage the following objectives are identified by the project group as being most critical: Means for safe self-evacuation (2), Means and safety for rescue operations (3), and cost (6). Table 2 lists the 4 alternatives at this stage.

Table 3  Consequence table.

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Sub objectives</th>
<th>Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Smoke free outside the extraction zone which means very good conditions for tunnel users there once the system is started.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slower fires and no fire spread but possibly same or even more smoke which also will be cooled and approach the floor faster</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For sure the fire will be limited to the first vehicle and the smoke to the extraction zone once the systems are in operation</td>
</tr>
<tr>
<td></td>
<td>b) Saved lives/y</td>
<td>0 (reference)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>(3) Rescue op.</td>
<td>a) Means for safe rescue operation (qualitatively)</td>
<td>Probably need to attack fire in smoke. Better to let it burn and try to assist evacuees if possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Can approach the fire and attack the fire safely, possibly in smoke the last bit. Less need to assist evacuees</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Probably need to attack the fire in smoke, but less need to attack the fire since it is limited by the sprinkler system. After a while or with a portable fan it can safely be extinguished</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Safe and easy access to the fire which can be approached when conditions are favourable (no hurry since the fire is kept under control)</td>
</tr>
<tr>
<td></td>
<td>b) Saved lives (rescue personnel) /y</td>
<td>0 (reference)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.015</td>
</tr>
<tr>
<td>(6) Cost [mSEK]</td>
<td>a) Asking price (20 year life time) /y</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>b) Maintenance /y</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

All alternatives are considered to be more or less equal with regards to Vision Zero since neither can be said to achieve the strategies of inherently safer or fail-safe design. The project group orders a CBA that compares the four alternatives, although it is soon recognized that there are large uncertainties considering the benefit of these systems. The project group therefore decides to also rate the alternatives qualitatively in discussion with experts and stakeholders. Table 3 lists the result that is reached (in a real case the sub objectives for Objective 2 and 3 should be decomposed in more specific sub objectives). Based on discussions concerning:
uncertainty (systems might not work or be used wrongly and the probability of fire is uncertain),

fairness (these systems do not benefit the more vulnerable road users; cyclists or pedestrians since they are not allowed in the tunnel), and

environmental effects (the environmental impact from these systems is found to be higher than the effect from a possible reduction in vehicle fires),

it is decided that the cost is larger than the benefit for alternative 1-3. The design group thinks these resources can be better used elsewhere which is also confirmed by the Road Administration.

Resulting from the learning along the decision process and in discussion with the rescue service a new possible solution emerge: that the rescue service should have a system to see evacuees inside the tunnel so that they can assist evacuees and navigate and drive in smoke without driving into something or someone. With the help of a fixed IR cameras and a large screen inside the fire truck the fire service from each portal can drive inside the tunnel and assist evacuees as long as the temperature is within survivable limits. This improves the means and safety of the rescue service to save lives and favours Objective 2, evacuation. The cost of such a system is judged to be worth the benefit considering that it could also be used in other situations.

At this stage, the project group and the stakeholders agrees that the best decision has been made, no better alternatives can be thought of, despite that not all objectives could be fully reached. They were forced to satisfy with the best trade-off, which is usually the case for most decisions.

**DISCUSSION**

The deterministic designer as well as the probabilistic designer would have some objections to the proposed design approach. The deterministic designer would not like that safety was seen as something relative at all. A good example is Malmtorp et al. who argues for that safety should be equal in all Swedish tunnels be them road, rail or metro [34]. However, unfortunately, safety will never be the same for all people at all times and spaces. This does not seem to be something that we in general would even like. Economic and risk perception studies reveal that we are paying much more to save a life depending on the situation, e.g. depending on whether it is children or extreme athletes who are exposed. We do not want risks to be the same in all situations. I would argue that it is highly natural to find such variations in society and it should not be our objective to make it equal, instead this highlight the relative side of how we prioritize between risk decisions. Naturally we can do this within fire safety as well as in society at large. This does not mean that we should not consider ethical aspects such as fairness. On the contrary such aspects can easily be included in a general decision making approach. I think this highlights the core controversy between two different views of safety and problem framings; Is safety some absolute right with natural levels that must not be violated, or should it be a decision objective among others (i.e. relative)? I think there is much evidence for the latter, that safety is one of several decision objectives and therefore must be allowed to vary with these. The Swedish Environmental Code, which is the most fundamental law for road design, does not regard safety to be more important than other aspects that are concerned. Further, the Swedish Civil Contingencies Agency (MSB) states that, although accident prevention is the preferred option, it must come at a reasonable cost. When prevention is not possible, e.g. because the event is too unlikely, society deals with the consequences once they happen [33].

At a first glance it may seem that the proposed design process would require more resources since more objectives are included in the analysis. However, a central aspect in iterative decision making is to analyze the parameters that matters in the detail required for the best decision to emerge. As an example, Bjelland & Aven [35] describes how a lot of resources where directed into finding a reference tunnel that was never to be built. One reason is the deterministic idea that the tunnel should be equally safe as a reference tunnel. In the proposed framework the focus would be on the actual tunnel design and the decision problem that needs to be solved and engineered.
In this way it could be argued that resources are spent where they matters, to find the best solution given our objectives and resources, and that we could get better decision.

Bjelland [7] and Babrauskas et al. [8] identified that the FSE process only evaluates one alternative which is then verified to be acceptable safe. In this sense there is little encouragement to further improve safety when you do not need to. In the proposed theoretical framework a more ambitious goal is set and a more creative process is proposed that partially could remedy this problem. However, what really may be missing is incentives towards safer designs, i.e. why should the design team care? Here one probably needs to look at the whole value chain for different structures. For road tunnels it is often the state that is the tunnel builder/owner. They then need to set up ambitious goals that are followed up throughout the process. One way to ensure a creative process is to ensure a good mixture of skills and experience in the design team such that all objectives are covered. Another way to work with innovation would be to require a certain fund for research in larger projects aimed at developing and reaching the strategies of Vision Zero or to organize design competitions.

The proposed framework primarily challenges the road administration and the fire safety engineer to stop thinking about safety in deterministic terms. Fire safety objectives should still be defined but they should be careful about setting deterministic limits on “acceptable” safety. Instead they should focus on finding creative solutions that best fulfill the objectives set up and aim for Vision Zero, e.g. inherently safer or fail-safe solutions. In the end the decision-making process should find the right balance and trade-off between all objectives (and the level of safety could be calculated although it is not very interesting, what matters is that the decision was the best one and can be justified by the objectives and priorities of the stakeholders and design team).

The design team should include knowledge not only about engineering and road tunnel fire safety but also design science, decision-making and ethics. The working method (see previous chapter) could be enforced by the road administration. Stakeholder views and objectives should be set up under the supervision of the traffic administration that has the final word on their priorities for the national transportation system. An example were the working method was changed by a road administration is the Dutch Road Administration that made all consultants use systems engineering as the working method for all their projects.

CONCLUSIONS

Fire safety engineering in performance-based regulation, education and practice is heavily focused on verification of an acceptable solution congruent with deterministic thinking and prescriptive regulation. Then safety is managed by limits that refer to arbitrary worst-case scenarios or risk curves. Safety is considered as something absolute without specific consideration of any other decision objectives. This can lead to extremely conservative solutions. In probabilistic design risk is transformed into a cost factor that can be traded with other objectives such as cost and availability. Then safety becomes a relative concept.

Both deterministic and probabilistic design can become limited by an exclusive focus on quantitative aspects. Case studies suggest that the fire safety design process today is limited by a too large focus on mathematical rigor. Other aspects such as fairness or perceived safety could be included in a general decision making process. The aim in general decision-making is to find the best solution i.e. that best fulfils the decision objectives set up. Solutions can be limited by the wrong or unclear problem-framing or objectives. For example, we could set higher aims and principles of safety, e.g. to derive inherently safety or fail safe solutions.

This paper proposes a new theoretical framework for fire safety design. The framework acknowledges the scientific or technical aspects of risk and social structures, the ethical and democratic aspects of risk. It is based on a general decision-making process where the problem and its solutions can be reframed and negotiated with stakeholders along an iterative and creative process.
It is further argued that better solutions can be derived with a Vision Zero design philosophy with its emphasis on inherently safer or fail-safe systems in practice, rather than a deterministic approach with its emphasis on mathematical verification of an acceptable solution. The decision process (rather than mathematical rigour) should ensure that the best solution is found. In the proposed framework safety is considered to be relative, i.e. a decision objective among others congruent with general decision making ideas that already are well established in the road design process.

I hope this paper, together with other critical work [e.g. 4, 7], will be a wake-up call to get more out of fire safety engineering in a performance-based regime; that we will get solutions tailored to the problem and not to the narrow logics of current verification methods based on the logic of a prescriptive regime. For road tunnel fire safety design, we should make a conscious choice among possible alternatives such that the best fire safety decisions are made for society at large.

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ABSTRACT

Due to the growing amount of citizens in urban areas, multiple space use becomes more common, but there still is a lack of safety regulations for the over-all life safety of these types of complex buildings. The extension of the Amsterdam Central Station area is an example of a multiple space area consisting of a metro tunnel, road tunnel, shopping area and bus station on different levels of the building. This paper presents the analyses to determine the necessary safety measures. Both a quantitative and a qualitative risk analysis have been made to clarify the risk for the road tunnel on the one hand and the shopping area and bus platforms on the other hand. The quantitative analysis is focused on the life safety of the tunnel users, the qualitative analysis on the scenarios with interaction between the tunnel and the life safety in other areas. It became clear that besides the risk assessment of the tunnel itself the interaction between different functions were dominant for the commissioning permit of the tunnel. The outcome of the analysis shows that there is a serious threat in the shopping area in case of a fire and, in a lesser extend but still serious, on the bus platform. The main recommendation therefore is when using multiple space solutions, it is wise to investigate interaction of incidents in a preliminary design stage so one can optimize architectural design and safety installations at an early stage.

KEYWORDS: Safety concept, multiple space use, fire safety engineering

INTRODUCTION

On a global scale the number of people living and commuting in urban areas increases. This gives rise to the need for flexible infrastructure in these urban areas. To realize complex infrastructure crossings in existing (historic) urban areas, multiple space use can be a solution. To provide over-all safety in the entire system, the safety of each individual system, interactions between the separate parts of the system and functions should be checked [1]. A good example is the Amsterdam Central Station area consisting of a railway station, metro crossing, bus terminal on top of the station, shopping area and a road tunnel. When tunnels are part of the multiple space solution, it is clear that the effects of incidents in tunnels can have major impact on the safety of other parts of the system. An example is presented in this paper about the safety concept for the commissioning of a new road tunnel crossing Amsterdam Central Station in the Netherlands.

UPGRADING AMSTERDAM CENTRAL STATION

The Amsterdam Central Station is the main railway station of Amsterdam. It is the real heart of the city: central not only by the name, but also as the biggest public transport transfer spot. Every day 250,000 people use the Amsterdam Central Station. The Central Station impressive Neo-Renaissance building has been opened to the public in 1889. As the city grew, the station had to change. Refurbishment works and station renewal have been a constant factor throughout the last decennia. At present, the station area is extended with the construction of the new North-South metro line, which will be completed in 2018. A new bus terminal, shopping area and road tunnel was recently added at the IJ lake side of the station. Final
stops of several lines of city trams and buses are here, as well as waterfront stations of city ferry lines to Amsterdam North.

Based on Dutch legislation which is derived from the European directive 2004/54/EC [2] a special permit was necessary for commissioning the new road tunnel. As a legal basis an appropriate safety analysis was necessary to gain this permit. This analysis included the safety for the tunnel and scenarios in which the interaction between incident scenarios in the tunnel and the other areas was taken into account.

Figure 1 Multiple space use at Amsterdam Central Station.

Figure 1 shows a cross section of the Central Station of Amsterdam. On the deepest level (-2) the station for the North/South metro line is situated. One can enter and leave the metro station with stairs, escalators and elevators to ground level (0). Moving up from the metro station one passes the road tunnel tubes (-1). On the route from the metro station to ground level there is no connection to the road tunnel. On the ground level there’s a transfer and shopping area and on the first floor the bus platforms are located. The bus platforms are situated in an semi-open area: front, rear and lake-side façade are open. On top the roof is transparent. On the south side of the bus platform and shopping transfer area, the main train station of Amsterdam is situated, on the north side the pedestrian ferry’s are mooring.

Figure 2 Cross section extension of Amsterdam Central Station
A lot of parties are involved, for example parties for the administration of all these assets and parties responsible for reliable transportion. Not only different departments of the municipality of Amsterdam are involved, also the national railroad company and regional transport management for buses.

The system discribed is complex in geometry, functions and organisation. For a proper operation there are a lot of interfaces that should be managed. In case of an emergency a single line of command is needed for detection of the incident, alarming and activation of threatened people.

SAFETY SYSTEMS IN A SHORT ROAD TUNNEL

The European directive 2004/54/EC [2] holds for road tunnels in the road network with a length over 500 m. To implement the European directive in the Netherlands a Dutch tunnel law was derived. Because of the relative high tunnel safety levels in the Netherlands at the moment of introduction of the European directive, the national government decided the Dutch law to be stricter to keep the actual safety level. This is expressed for instance by the fact that the Dutch tunnel safety law is applicable for all road tunnels in the Netherlands with a length over 250 m. The required safety measures prescribed by the law are dependent on the length of the tunnel. For the tunnels longer than 500 m mechanical tunnel ventilation must be present. For tunnels with a length in between 250 m and 500 m an engineering analysis should be done to decide about the application of mechanical ventilation.

Tunnel safety legislation gives direction to determine the required tunnel safety measures and how to check the prescribed safety level. In case of the Michiel de Ruijertunnel the bus platform, shopping area and the other transport systems are also threatened in case of a tunnel accident. The Netherlands lacks safety regulations for the life safety in the surroundings of the Michiel de Ruijertunnel: the busplatform on top, and the public space near and adjacent to the road tunnel. Based on model calculations it became clear that tunnel fires could be a serious threat for people in the shopping area and on the bus platforms, depending on the fire size, wind speed and direction and the accident locations. Initially, an early warning system for people in the adjacent facilities was missing, because of the geometry. This posed a serious risk for the people not able to see the incident and being overwhelmed by the smoke coming out of the tunnel. For all involved it became clear that additional measures had to be taken to ensure a quick and adequate response in case of such an emergency.

Based on a quantitative risk analysis [3] and qualitative scenario analysis [4] the necessity of additional measures was checked. The process to meet the legal safety levels (societal risk) and the decision-making on the safety measures is illustrated in this paper.

MICHIEL DE RUIJERTUNNEL

The length of the Michiel de Ruijter road tunnel is 301 m and consists two separated tubes for one-directional traffic. Figure 3 shows a cross section of the Michiel de Ruijertunnel. A dedicated escape route is available for each tube and fire fighters can enter via the adjacent tube using three separate links between the tubes. Because of the limited length of the tunnel there was a large discussion on the need of safety measures such as tunnel ventilation, overpressure systems to secure the escape route and provide a safe entrance for fire fighters, traffic signalling for guidance and prevention of traffic jams in the tunnel.
The level of tunnel safety is defined by:

- The type of traffic in the tunnel.
- The tunnel organisation.
- The geometry and technical safety installations.

The tunnel situated in the city centre of Amsterdam is used for passenger cars, busses and cargo trucks. Not admitted are trucks with dangerous goods like fuel transports, pedestrians, bicycles and slow traffic (like tractors).

As the tunnel is part of an essential road network for the city centre, the tunnel is controlled 24/7 by the central tunnel control centre of Amsterdam.

The city of Amsterdam decided this city tunnel to have a similar ‘look and feel’ as larger tunnels in the city for a better understanding of self-rescue and emergency response. For this reason the escape and self rescue facilities have a comparable layout. The geometry of the escape routes and passageways for fire fighters is shown in Figure 4.

The tunnel is fitted out with a large number of technical safety installation including CCTV, a public address system, detection of slow traffic speed and an automatic traffic jam protection system.
Because of the length of the tunnel it was decided that tunnel ventilation and fire detection in the tunnel tubes was not necessary.

**FIRE SAFETY ENGINEERING**

Both a quantitative and a qualitative risk analysis have been made to clarify the risk for the tunnel on one hand and the shopping area and bus platforms on the other hand. The quantitative analysis focused on the life safety in the tunnel, the qualitative analysis on the scenarios with interaction between the tunnel and the life safety in other areas.

*Quantitative Risk Analysis (QRA)*

In accordance with the Dutch legislation a QRA has been made to calculate the risk level for people who use the Michiel de Ruijter tunnel. The analysis has been carried out using the calculation model QRA-tunnels, which has been developed by the Dutch Ministry of Infrastructure. The model uses a prescribed calculation method which was needed for the special permit for commissioning the tunnel. Using this model, the cumulative annual probability that at least 10 people will die in the tunnel as a direct consequence of an accident in the tunnel has been determined. This calculated societal risk (per year per tunnel tube) for the tunnel tubes should not exceed the limit of $0.1/N^2$ (for $N > 10$) described by Dutch law, where $N$ is the number of fatalities.

The risk of people dying or getting injured in the areas surrounding the tunnel can not be considered in these calculations with QRA-tunnels. In the risk assessment methodology, a different measure should be used for these people because for them this is an involuntary risk.

![Societal risk (km/year)](image)

*Figure 5  Societal risk (Y-axis) versus fatalities N (X-axis) for the northern and southern tunnel tube Michiel de Ruijter tunnel with the test line $0.1/N^2$*

*Where VW = the estimated mean and PR = personal risk*
Input for the calculations with QRA-tunnels are the geometry of the tunnel and technical installations and the use of the tunnel (vehicle types, traffic volume, transportation of hazardous substances, congestion frequencies and incident probabilities) like described in the previous paragraph. Based on these parameters (sub)calculations for different scenarios are made to determine the over-all societal risk. The societal risk is heavily determined by the vehicle fire scenarios, especially large truck fires. The result of the calculation of the societal risk for both tunnel tubes of the Michiel de Ruijter tunnel are shown in Figure 2.

The figure shows a societal risk curve of each tunnel tube, each of them below the test line $0,1/N^2$. The (small) difference between the societal risk curves can be explained by the following:

- The expected traffic in the northern tube is about 40% more than in the southern tube. This causes a larger probability of an incident to occur in the northern tube.
- The expected fraction of busses in the southern tube is about 40% more than in the northern tube. More busses means more passengers and potentially more fatalities in case of a fire incident.

In addition to the societal risk in Figure 5 a sensitivity analysis has been carried out for the following traffic parameters:

- Traffic volume: also by an increase in traffic volume by 30% the societal risk does not exceed the test line.
- Probability of congestion: increasing the congestion frequencies from once a month to five times a month causes an increase of the societal risk, especially at 95 fatalities and more.
- Fraction of busses and the amount of occupants: duplication of the fraction of busses in combination with an increase of the average amount of occupants from 55 to 90 causes a large increase of the societal risk. The societal risk remains just below the test line.

As part of the design process also calculations have been made for a tunnel system without a ‘calamity button’ for traffic control or a system for low speed detection in the tubes. The system for low speed detection contributes to a quick detection of potential accidents. The ‘calamity button’ contributes to a fast start of warning and evacuating of tunnel users because after detection a group command activates several systems. So both installations have a large, positive impact on the societal risk of the Michiel de Ruijter tunnel.

Analysis of specific incident scenarios, checking interaction

As described in the previous paragraph the QRA does not give a complete picture of all the people carrying risk because of the exploitation of the Michiel de Ruijter tunnel. The scope of this analysis is limited to the life safety in the tunnel. To gain insight in the consequences for life safety in the surrounding shopping area and bus platform a scenario analysis for some specific incident scenarios has been made. This scenario analysis contains two parts:

1. A pure qualitative analysis of the incident scenarios with a low impact on the surroundings like a vehicle break down and a multiple-vehicle collision (without fire).
2. A qualitative analysis extended with a quantitative analysis of the (potential) effects of a vehicle fire in the tunnel on the shopping hall and the bus platform.

The qualitative analysis of the scenarios contains:

1. A description of the course of the scenarios including detection of the incident, warning and evacuating of tunnel users and the assistance of the emergency services.
2. An evaluation of the four safety processes for traffic handling, the incident management, self rescue and the intervention of the emergency services.
3. A list of necessary, complementing and ALARP-measures.

To get more insight in the consequences of a delivery van fire and a truck fire, Computational Fluid Dynamic (CFD) calculations have been made focused on the surrounding shopping area and the bus platform. Here, Fire Dynamics Simulator (FDS) version 6 was used, which was developed by the
National Institute of Standards and Technology (NIST). FDS is applicable for low-speed, thermally-driven flows, with an emphasis on smoke and heat transport from fires.

Figure 5 presents the geometrical model that has been made for the CFD calculations including the road tunnel (-1), shopping area (0), bus platforms (+1) and the roof.

Figure 6 Geometrical model for the CFD calculations.

CFD calculations have been made for:
- A delivery van fire (20 MW, grow 10 MW/min):
  Scenario 1, 2 and 3 are delivery van fires on three locations: 1. In a tunnel tube, near the entrance; 2. Outside the tunnel, near the entrance; 3. In the middle of a tunnel tube.
- A truck fire (100 MW, fire growth 20 MW/min):
  Scenario 4, 5 and 6 are truck fires on three locations: 4. In a tunnel tube, near the entrance; 5. Outside the tunnel, near the entrance; 6. In the middle of a tunnel tube.

Figure 7 Incident locations of the vehicle fires (1-3 delivery van, 4-6 truck)

The fast growing 100 MW truck fire is considered as a worst-case scenario, viz. the most extreme vehicle fire for the Michiel de Ruijter tunnel. CFD calculations for a smaller (20 MW) delivery van were also made. This is representative for a situation where trucks and busses would be prohibited in the tunnel.

Design goals and criteria
The CFD calculations were made to assess the life safety of people in the escape routes (corridors), shopping area and on the bus platform. To effectively secure life safety by the system the following questions need to be answered:

a. Are the conditions in the tunnel tube good enough to survive and reach the escape routes?
b. Are the escape routes (corridors) free of smoke and hot gasses?
c. Is the area near the end of the escape routes free of smoke and hot gasses?
d. Are the conditions in the shopping area good enough to stay there for a longer period (safe stay)?
e. Are the conditions on the bus platforms good enough to stay there for a longer period?
f. Are the conditions in the tunnel good enough to make intervention of the emergency services possible?

In Table 1 three scenarios (vertical) and tested conditions (horizontal) have been defined for a delivery van fire and a truck fire (see also Figure 7 for the incident locations). The crosses in the table indicate the tested conditions for each fire scenario.

**Table 1 Scenarios delivery van fire and truck fire**

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 3 delivery van (20 MW, 10 MW/min) and 4 – 6 truck fire (100 MW, 20 MW/min)</td>
<td></td>
<td>tunnel tube</td>
<td>escape routes (corridors)</td>
<td>area near the end of the escape routes</td>
<td>shopping area</td>
<td>bus platforms</td>
<td>emergency services</td>
</tr>
<tr>
<td>1 and 4: In tunnel, near entrance</td>
<td>5 m/s in the direction of the traffic</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 and 5: Outside tunnel, near tunnel entrance</td>
<td>5 m/s in the direction of the traffic</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 and 6: In the middle of the tunnel</td>
<td>0 m/s</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The CFD calculations have been made for a period 900 s (15 min) after the start of the fire. This will be the critical period for self rescue. A summary of the most important results for these 6 fire scenarios has been described in the next paragraphs.

**Results CFD calculations delivery van fire**

The possibility to leave the tunnel before conditions might lead to incapacitation or become lethal depends on the wind direction and speed. A head wind of 5 m/s causes smoke and hot gasses till 150 m upstream within 60 s, which would make an escape impossible and causes fatalities (Figure 8).

![Figure 8 Result CFD calculations delivery van fire – scenario 2 after 60 s and scenario 1 after 150 s – Visibility](image_url)

The expectation is that in less than 150 s the overpressure system in the escape routes is switched off at one or both sides of the tunnel, so the escape route is no longer safe (scenario 1 and 2, Figure 8). In specific situations the area near the end of the escape routes is not free of smoke and hot gasses within 150 s.
According to Figure 6 the conditions at the shopping area and the bus platform during a fire in the tunnel with wind (scenario 1) are good enough for a safe escape during more than 15 min (900 s).

At scenario 1 and 2 (scenarios with wind) self rescue in the shopping area and on the bus platforms is possible. At scenario 3 (no wind) self rescue at the shopping area is only possible if the shopping area facades are closed within 3 min after the start of the fire (Figure 10).

In a situation without wind, within 6 and a half minutes the smoke will divide the bus platform area into two sections while the stairs to the shopping hall can still be used (Figure 11). At 10 – 20 % of the platform surface, smoke reduces the visibility to a level where a safe escape is no longer possible from these areas. During the first 6 - 7 min after the start of the fire a safe escape is possible. Whether the conditions on the platform would cause fatalities, would depend on the time for detection, alarming and activation of the travelers, and the number of travelers on the platform at the moment of the incident.

Intervention of the emergency services at a 20 MW fire at the central zone of the tunnel is not possible because of the lack of tunnel ventilation.
A summary of the results is presented in Table 2.

**Table 2 Summary CFD analysis delivery van fire**

<table>
<thead>
<tr>
<th>Location</th>
<th>Tube</th>
<th>Wind direction</th>
<th>Wind speed</th>
<th>Escape tunnel</th>
<th>Area end escape route</th>
<th>Shopping hall</th>
<th>Bus platform services</th>
<th>Interventions emergency services</th>
</tr>
</thead>
<tbody>
<tr>
<td>In tunnel entrance</td>
<td>South</td>
<td>NW/SE</td>
<td>&lt; 1.5 m/s</td>
<td>ok</td>
<td>ok</td>
<td>Not always possible</td>
<td>Not possible</td>
<td></td>
</tr>
<tr>
<td>Just outside the tunnel</td>
<td>South</td>
<td>NW</td>
<td>&gt; 1.5 m/s</td>
<td>ok if there’s no traffic jam</td>
<td>1 side switched off after 10-150s</td>
<td>Failure 1 side after 10-150s</td>
<td>ok</td>
<td>ok</td>
</tr>
<tr>
<td>In the middle of the tunnel</td>
<td>North</td>
<td>SE</td>
<td>&gt; 1.5 m/s</td>
<td>Failure within 60 s over 150 m</td>
<td>1 side switched off after 10-150s</td>
<td>Failure 1 side after 10-150s</td>
<td>ok</td>
<td>ok</td>
</tr>
</tbody>
</table>

Legend:  
- green : ok  
- red : failed  
- orange: not according to design criteria, effectiveness over-pressure installation unknown.  
- white: to be checked in a quantitative risk analysis (QRA)  

Based on the analysis, it is concluded that a ‘delivery van fire’ of 20 MW could not be handled in all situations given the infrastructure, installations and organization of the Michiel de Ruijter tunnel.

**Results CFD calculation truck fire**

The possibility to leave the tunnel before conditions become untenable depends on the wind direction and speed. A headwind of 5 m/s causes smoke and hot gases till 200 m upstream within 60 s (truck fire, makes an escape impossible and causes fatalities (Figure 12).

![Figure 12 Result CFD calculations truck fire – scenario 5 after 60 s and 150 s – Visibility](image)

The expectation is that in less than 150 s the overpressure system in the escape routes is switched off at one or both sides of the tunnel, so the escape route is no longer safe (scenario 4 and 5 Figure 8). In specific situations the area near the end of the escape routes is not free of smoke and hot gases within 150 s. The amount of smoke rising to the shopping area and bus station is considerably larger at a 100 MW truck fire than at the smaller (20 MW) delivery van fire as presented in Figure 4.
According to Figure 13 the conditions at the shopping area at a fire in the tunnel and wind (scenario 5, truck fire just outside the tunnel) are tenable for a safe escape during more than 15 min. At the bus platforms the visibility reduces during the first 15 mins, but self rescue is still possible.

At scenario 6 (fire in / near the middle of the tunnel tube, no wind) self rescue at the shopping area is only possible if the shopping area facades are closed within 3 min after the start of the fire (Figure 14).

In a situation without wind after 360 seconds smoke divides the bus platform into two sections while the stairs to the shopping hall can still be used (Figure 15). At a substantial part of the platform smoke reduces the visibility in such a way that a safe escape is no longer possible in these areas. In the first 6 min after the start of the fire a safe escape is possible. Whether the conditions on the platform because fatalities depend on the time for detection, alarming and activation of the travelers and the number of travelers on the platform at the moment of the incident.
Intervention of the emergency services at a 100 MW fire is not possible because of the lack of tunnel ventilation.

A summary of the results is presented in Table 2.

### Table 3 Summary CFD analysis delivery van fire

<table>
<thead>
<tr>
<th>Location</th>
<th>Tube</th>
<th>Wind</th>
<th>Escape tunnel</th>
<th>Escape surrounding areas</th>
<th>Intervent emergency services</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In tunnel entrance</td>
<td>South NW/SE</td>
<td>&lt; 1.5 m/s</td>
<td>ok</td>
<td>ok</td>
<td>Not always possible. Ok if everybody can leave the platform within 6-7 min.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not possible</td>
</tr>
<tr>
<td>Just outside the tunnel</td>
<td>South NW</td>
<td>&gt; 1.5 m/s</td>
<td>Ok if there is no traffic jam</td>
<td>1 side switched off after 10-150s</td>
<td>Ok</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Failure 1 side after 10-150s</td>
<td>ok</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on the wind</td>
</tr>
<tr>
<td>In the middle of the tunnel</td>
<td>North SE</td>
<td>&gt; 1.5 m/s</td>
<td>Failure within 60 s over 150 m</td>
<td>1 side switched off after 10-150s</td>
<td>Ok</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Failure 1 side after 10-150s</td>
<td>ok</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not possible</td>
</tr>
</tbody>
</table>

Legend:
- green : ok
- red : failed
- orange : not according to design criteria, effectiveness over-pressure installation unknown.
- white : to be checked in a quantitative risk analysis (QRA)

Based on the analysis, it is concluded that a ‘truck fire’ could not be handled in all situations given the infrastructure, installations and organizational measurements of the Michiel de Ruijtertunnel. Therefore, the tunnel manager had to realize a couple of adjustments. To define and categorize these adjustments a subdivision has been made between normative scenarios (chance larger than 10⁻⁶ per year) and worst-case scenarios (chance smaller than 10⁻⁶ per year).

![Figure 16 Probability per year for vehicle fires in the Michiel de Ruijter tunnel](image)

Necessary adjustments have been defined for normative scenarios, supplementary adjustments for worst-case scenarios.

Most important necessary adjustments based on the results of the scenario analysis are:
- Change the location the overpressure installation gets its fresh air from.
- Extend the escape routes as far as needed for smoke free exits.
- Make sure the shopping area façades can be closed within 3 min. For this reason, the closure of the façade was automated based on smoke detection near this façade.
• Enlarge the capacity of the escape routes from the bus station by turning all escalators downwards in case of an emergency.

The realization of a system of mechanical tunnel ventilation in both tunnel tubes to improve the possibilities for self rescue and intervention of the emergency services has been defined an important supplementary adjustment.

CHECKING INTERACTION

It was acknowledged from the risk analysis that a car or truck fire is a major threat for those present in the shopping mall and on the bus platform. Because of the open connection between these two areas on top of the tunnel, smoke can be a threat there. Due to lack of early detection - the incident will be out of sight - there’s a risk for too late evacuation.

A fire safety analysis [5] was made to analyse the effects of smoke in the shopping area and on the bus platform. Therefore time-history calculations were executed using CFD calculations (see Figure 17). With these calculations the available egress time was calculated and safety measures were defined.

Figure 17 Model of tunnel and calculated visibility in crosssection over busplatform after 720 seconds

Based on the CFD and risk analysis a minimum of necessary measures were determined to fulfil the compulsory set of requirements. Besides that the results were basis for an objective evaluation with the fire brigade, the safety officer and tunnel administrator to discuss what additional measures were implemented.

DISCUSSION

In this paper the risk evaluation for the multi space use of the extension of the Amsterdam Central station is presented. It became clear that besides the risk assessment of the tunnel itself the interaction between different functions was dominant for the commissioning permit of the tunnel. Lack of regulations for these boundary conditions made it necessary to discuss effects of an incident in the tunnel in the shopping area and on the bus platforms.

The outcome of the analysis shows that there is a serious threat in the shopping area in case of a fire and, in a lesser extend but still serious, on the bus platform. Because different parties are involved in the asset management there is not enough time to alarm all stakeholders in time. Therefore detection, alarm and action was automated to prevent spread of smoke in to the shopping area.

When using multiple space solutions it is wise to investigate interaction of incidents in a preliminary design stage so one can optimize architectural design and safety installations at an early stage. This prevents the need for difficult and expensive solutions.
REFERENCES

Common Life Safety Targets in Traffic Tunnels

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¹Brandskyddslaget AB, ²WSP Sverige AB
³RiskTec Projektledning AB

ABSTRACT
This paper focuses on quantifying a common safety target level that can be used to verify safety levels in road tunnels, railway tunnels, and subway systems with regards to life safety. This safety target should provide a risk acceptance level, according to which tunnel projects can be compared to one another while factoring in the benefit of the tunnel in terms of the value of transporting people and goods. In order to ascertain a reasonable safety target, risk acceptance levels of regulations and recent tunnel projects were studied. The estimated risk levels of recent road and railway tunnel projects were also identified, and converted into the same entity of risk. These risk levels were also compared to estimated risk levels of several fictional road and railway tunnels that comply with current standards, with and without the transportation of dangerous goods.

There are large differences in how risk is expressed in road and railway tunnel projects, and none of the projects or regulations studied fully factor in the societal benefit of traffic when formulating safety target as a societal risk profile. Risk-benefit assessment, however, is quite common in the projects studied. The railway tunnel risk acceptance levels used by the Swedish Transport Administration (Trafikverket) are close to incorporate these benefits, as they state risk on the basis of train-km, whereas other bodies and projects only consider the tunnel as a whole or state it in terms of tunnel-km. The analysis of calculated risk levels shows that they can be stated on the basis of risk per person-km, which provides comparable data for the different transport systems and are directly proportional to transport benefits. Risk acceptance criteria for all three transport systems can preferably be measured in deaths per person-km for societal risk profiles. This unit does not state the total risk of each facility; rather, it allows an ALARP zone to be created, which allows a risk-benefit comparison to be performed. In this paper, it is suggested that risk acceptance levels should be set just above those of tunnel projects that have recently been approved by the Swedish Transport Agency (Transportstyrelsen), and that the establishing of ALARP zones should be a requirement in these processes, as this promotes risk assessment and the design of cost-effective tunnel systems.

INTRODUCTION
Background
The building of road and railway tunnels in Sweden began in earnest in the 1990s, although no rules and regulations specific to this type of project came into existence straight away. For the first few years of this period, requirements were posed within each project; later, Swedish national regulations were introduced, and today there are European-wide regulations stated by the EU enforced in Sweden. The level of safety achieved as a result of these regulations depends on the specifics of individual tunnels, and it is common for risk assessments to be legal requirements for some tunnels in order to ascertain whether further safety measures are required. In Sweden, this has led to a debate regarding which further requirements are reasonable to pose in order to achieve a level of safety that is cost-effective in relation to society. The level of safety required is generally considered to be unclear and discussions regarding it difficult to conduct, during both the planning and approval processes of a tunnel project. Thus, the Swedish Transport Agency (STA) commissioned a research project in order
to facilitate and simplify this process. This article is based on that research project, which was presented in [1]. In the project specification, the STA concluded that:

“If there is no safety target, there is a risk that the measures decided upon during safety work will lack a clear connection to what is desired – protecting people’s lives and health, weighed against the financial cost to society. In order to be able to ascertain whether the desired level of safety has been achieved, methods for verifying whether a safety target has been fulfilled are required. The basic requirements on such methods should be the same, regardless of the transport system.

The transportation-political goals are intended to be guidelines rather than hard and fast rules. Safety cannot be handled separately from other targets in the transportation system, and financial considerations must always be taken into account and considered when formulating a safety target. Existing safety targets have no clear connection to societal benefit. Society should strive to identify and establish a safety level that for operations that are similar to one another which is clearly connected to a suitable verification method.”

At the outset of the project, a workshop was held to which representatives of the STA, the Swedish Transport Administration, the members of the research project, and interested parties relating to roads, railways, and subways were invited. It was concluded that current European regulations for road and railway tunnels form a basis for the project. Based on the discussions held, the following directions were formulated:

- Identify a basic standard for design and functional requirements in order to fulfil the minimum level of safety.
- Suggest risk measures that are suitable for quantifying and assessing the safety of individuals in tunnels.
- Suggest methods for assessing societal benefit when introducing safety measures that are in addition to the basic standard.

The basis on which common safety targets are formulated

Risk acceptance in society is founded on a number of basic principles, formulated in the literature [2] and generally resting on the following concepts:

- Justification of the activity,
- Optimisation of protection,
- Allocation of risk
- Avoidance of disasters,
- Assessment threshold, and
- Continuous improvement (not discussed in the reference above).

One way of creating a safety target that meets these principles is to formulate risk acceptance criteria using quantitative risk measures, which are quantifiable, comparable, communicable, and enable a consistent handling of safety over time. The use of quantitative risk measures results in a risk acceptance level that can be stated or selected, which is one of the main objectives of this work. Risk acceptance levels should be used to identify unacceptable risk levels and facilitate the performing of cost-benefit analyses in cases where it is impossible to tell immediately whether a risk is acceptable or not. Setting an assessment threshold by stating the level below which risks can be considered to be acceptable (without performing a cost-benefit analysis) has the advantage of reducing the number of cases in which analyses must be performed, e.g. with regard to less complex tunnel projects. Risk levels between the acceptance level and assessment threshold are termed ‘ALARP’ (As Low As Reasonably Practicable). This ALARP concept is used in many industry sectors.
In order to be able to accommodate the principles listed above, it is important to standardise the acceptance levels for accident rates in a suitable way. This is important and valuable experience, gained as a result of previous infrastructural projects. It is deemed to be advisable to formulate safety targets and criteria that are nuanced in relation to the benefits that a facility may provide, as not doing so may result in an overly conservative and costly safety standard for some types of facility, and have the opposite effect for others. In the traffic safety work that is carried out for the surface road network in Sweden, this approach is well-established and already applied. It is thus obvious that the predicted number of accidents for a short, lightly trafficked road is not the same as for a long, heavily trafficked one. One way of standardising risk exposure in the context of road traffic is to focus on traffic volume.

Considering only Expected Value/Potential Loss of Life (PPL value) as a figure generally provides insufficient support for handling accident risks involving the likelihood of many casualties. The total contribution to the PPL value of these accidents is often so small that the difference is negligible, and may be significantly lower than the entire uncertainty range of the probability of smaller accidents occurring.

**RESEARCH METHODS**

The research project was commenced by performing a review of the rules and regulations governing the various transport systems, along with accident statistics, previously applied safety targets, and methods for assessing the societal benefit of safety measures.

An analysis was then conducted of the calculated risk profiles of both previous tunnel projects in Sweden and hypothetical tunnels, based on the minimum requirements laid down in law, mandatory provisions and requirements for representative tunnel types.

Based on risk profiles for existing tunnels, hypothetical tunnels, and previously used risk acceptance criteria, it has been possible to suggest a suitable risk acceptance level and assessment threshold.

**THE VARYING SETS OF PARAMETERS FOR EACH OF THE TRANSPORT SYSTEMS**

**Review of accident statistics**

Statistics are available primarily for accidents that involve a small number of people and traffic on surface roads/railways. Larger accidents are very rare. Accident statistics show that, in road traffic accidents, it is primarily the road users themselves that are exposed, whereas the fatalities in railway traffic and subways are primarily non-passengers who are on or near to tracks. The number of fatalities in railway accidents is (per person-km) on par with the number of deaths among road users in road traffic. In total, however, the number of deaths per person-km is significantly higher as the number of suicides is large in comparison to actual traffic volume. These conditions are illustrated in Figure 1 below.
The review of existing safety targets and criteria shows that the targets are stated in different units of measurement, and that in several cases they are connected to societal benefit (PPL values for road tunnels and risk contours for railways). In order to be comparable, they must be stated in a unit that is suitable for all transport systems. There are no international references that can be applied, without modification, to any of the transport systems analysed in this article and still take societal benefit into account.

**Overview of existing safety targets**

According to PIARC’s [3] review, the risk acceptance levels for road tunnels vary strongly both domestically and internationally. Risk acceptance levels are in some instances stated per tunnel and in others per tunnel-/tunnel pipe-km, and the risk sources are in some cases limited to only dangerous goods; regardless of how they are stated, however, the spread is significant (see Figure 2). Risk acceptance criteria can also be related to specific models for risk assessment.

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**Figure 1: Fatality statistics for each transport system.**

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**Figure 2: Applied safety targets and risk acceptance levels, taken from international references described by PIARC.**
No studies of international risk acceptance criteria for railway tunnels have been conducted. However, the construction requirements of the Swedish Transport Administration (as the commissioner of construction works), as laid out in the document TDOK [4], produces criteria that are to be fulfilled according to figure 3. This risk acceptance level was recently changed from the requirements previously set down in BVH 585.30 [5].

![Figure 3: Risk acceptance in Swedish railway tunnels, produced by the Swedish Transport Administration. A further ALARP zone, not discussed here, is also specified.](image)

No quantitative risk acceptance profiles have been identified for subway systems.

**A study of risk levels in tunnel projects**

The risk profiles of completed tunnel projects were compiled and compared in various ways in order to assess their differences and similarities. The study included the recently opened Northern Link tunnel, consisting of 14 km of tunnel pipes, and the ongoing Stockholm Bypass road tunnel project, consisting of 47 km of tunnel pipes. The railway tunnels that are included in the study are the Hallandsås Tunnel, the West Link in Gothenburg, the Stockholm City Line, the Krokberg Tunnel, and the Strängnäs Tunnel. With the exceptions of the West Link and Stockholm City Line, which are passenger train-only tunnels, all of the tunnels in the study are used by both passenger trains and goods traffic, without restrictions on dangerous goods. In Sweden, the only subway that exists is in Stockholm, but no risk profiles have been calculated for this system. Similar passenger train tunnels have been studied in order to assess the risk level of the currently planned additions to the subway system. The tunnel type that most closely resembles the subway is the Stockholm City Line, which is only trafficked by commuter trains and has a similar safety standard. The existing subway system has a significantly lower safety standard, and is thus not comparable.

The risk profile of road tunnels is normally presented as risk per year and tunnel, whereas railway tunnels are compared to the existing criteria in BVH 585.30 [5], which is stated as risk per train-km. Figure 4 presents the total risk per risk object.
As was expected, the spread is large – in the order of several powers of ten – between the various facilities, as length and traffic flow vary widely. In addition, there are differences in design that may impact safety, e.g. whether a tunnel is single or double pipe. The risk acceptance level (i.e. the probability of an accident occurring, combined with the consequences of said accident) is strongly connected to the size and geographical delimitations of the system, particularly if there exist great differences in terms of the benefit provided by the facility or activity in comparison to its size. For example, a greater number of accidents are accepted on a national level than within a smaller geographical area, e.g. a municipality or single facility. It is thus reasonable to assume that a safety target must be in some way scaled down to suit a system’s size or geographical extent.

An important issue in the project has been investigating the possibility of standardising risk measures so that they reflect the benefit of the facility, as well as formulating a common or equivalent risk acceptance criterion for the various transport systems. A number of approaches to standardisation have been tried for different facilities, but the inevitable conclusion is that, for a standardisation relating to traffic volume that takes both length and road user flow into consideration, a significant reduction in spread between the facilities studied takes place. Traffic volume provides a good metric for the benefit that a facility produces. The conclusion is that risk impact is relatively similar, regardless of facility and transport system. Thus, it appears to be possible to formulate a risk acceptance criterion that spans all transport systems. For the studied facilities, the risk profiles (F/N curves) are similar when risk is standardised against traffic volume, even for differing transport systems. This indicates that the risk level that is the result of current construction approaches and design concept is in fair agreement for the various transport systems, and that risk aversion for large accidents is in the same order of magnitude in relation to the number of people that use the facility.

In Figure 5, the risk for different facilities is standardised per person-km. It can be seen that the range between the highest and lowest risk levels has decreased to roughly two powers of ten. Given an interval of 300-500 fatalities, a risk acceptance level of $10^{-7}/N$ per million person-km would be above but relatively close to existing projects for all transport systems.

![Figure 4. Risk per facility and year for the studied road and railway tunnels.](image_url)
Individual fatalities have been found to largely depend on smaller accidents such as collisions, traffic accidents, and, to some extent, fires. These accidents are assumed to have been taken into consideration by the basic standard laid down in the rules and regulations for each type of tunnel, which are generally not designed based on analysis.

**Hypothetical tunnels that follow a basic standard**

An additional analysis has been performed on two hypothetical road tunnels to show how the varying parameters of transport systems affect the risk profiles of different tunnels. One of these is a < 1000 m long, two-way tunnel with a maximum permitted traffic volume, which is the longest possible without requiring a fire detection system and emergency alarm. The other is a heavily trafficked two-way tunnel, the risk level of which was calculated by factoring in all of the safety measures that are required by the rules and regulations. An additional calculation was performed for this tunnel, assuming that 5% of the traffic takes the form of queuing conditions, requiring that the risk be verified through risk assessment. Additional risk profiles were also calculated for these same tunnels, assuming that dangerous goods corresponding to the national average for Sweden are transported through them. Figure 6 shows a selection of these calculated risk profiles.
A selection of risk profiles (presented in Figure 6) lead to the conclusion that the accepted risk in a simple tunnel can be high in the interval of 1-3 fatalities, but that the risk profile rapidly falls to low levels. Figure 6 also shows that tunnels in which dangerous goods are moved can result in a relatively high risk profile, particularly if they are two-way. In comparison to the Northern Link tunnel, which allows the transportation of dangerous goods with some limitations and is calculated to experience queuing conditions relatively rarely each week, it is evident that a corresponding hypothetical tunnel that lacks a fire suppression system and has a slightly larger share of dangerous goods for which no time restrictions has been posed will have a much higher risk profile. It is doubtful whether such a tunnel design could be considered to be acceptable.

A hypothetical railway tunnel that strictly adheres to the requirements of the TSI [6] has been investigated. Complete calculations have not been performed; instead, comparisons have been conducted with the Strängnäs Tunnel, which has a 1.2 m-wide footpath and 800 m between emergency exits, largely corresponding to the requirements of the TSI. The conclusion of the comparison is that a hypothetical tunnel that is constructed in adherence to the requirements of the TSI would attain the ‘tolerable’ rating of the Swedish Transport Administration’s ambition level. The ‘tolerable’ rating means that measures to increase safety shall be assessed in relation to their cost-efficiency. It should be noted that the comparison is general in character; more complex tunnels with a greater number of passengers and red lights may fail to reach this ambition level. Precisely where the line is drawn has not been investigated.

**Delimitations for very small and large accidents**

Frequently occurring accidents involving few fatalities differ markedly between transport systems regarding both frequency and the safety measures used to lessen their impact. Accident types involving few fatalities are not considered to be typical ‘tunnel accidents’. Here, there should be a basis for posing specific requirements and targets for each individual transport system. The best safety
measure is not necessarily related to tunnel construction; rather, more general measures specific to transport systems, e.g. seat belts, should be considered. In order to allow a quantitative target to also encompass smaller accidents, one possibility would be to establish a complementary risk target based on PPL values. Such a method would be equal between transport systems and encompass all types of accidents, but the objective would be specific to the transport system. This has been extensively discussed, but no further investigation has been conducted.

Accidents involving several hundred or thousands of fatalities are very rare, and the cause or combination of causes may be difficult to theoretically define; in the field of nuclear power, for example, incredibly extensive analyses have not yielded thorough explanations of all causes. In addition, the material produced by analyses does not provide a coherent picture of accidents involving several hundred or more fatalities. Our suggestion is thus to not state a safety target as a risk measure on the F/N curve for accidents involving fatalities exceeding the 500. For these accidents, which have a very low probability and extremely severe consequences, it is likely that a different type of handling is required, wherein extremely improbable accidents are weighed together and handled separately. Such analyses are generally not cost-effective for individual projects, as the uncertainties involved are very large. Here, earthquakes, structural material failure, and designing errors, for example, become relevant.

RECOMMENDATIONS AND CONCLUSIONS The research project resulted in the following safety target for all three types of transport systems:
“The risk profile for societal risk during road, railway, and subway tunnel transportation shall be equal, and stated as risk per person-km.”

The risk graphs for various completed tunnel projects regarding the investigated transport systems show a general trend of movement towards this target. A comparison with hypothetical tunnels constructed according to the minimum standards set down in the rules and regulations is, for those parts that are comparable, in line with this. A quantitative, verifiable target has been developed, wherein the probability of fatality per person-km and risk acceptance criteria are evidenced using an F/N curve.

The selection of the risk measure “number of fatalities per person-km” takes transportation benefit into account by considering differences between transport systems and factoring in the high passenger flow that often occurs in new facilities, while at the same time ensuring that the measure is applicable to simpler facilities. The connection to societal benefit also takes place based on the ALARP principle, wherein cost-benefit analyses are to be performed in order to assess whether further safety measures are good investments. The same analyses can also be used to choose the most effective safety measure if the risk level is above that of the maximum acceptable risk.

The methodology and process suggested use the existing rules and regulations as a basic standard which, according to the studies, is deemed to provide a risk level that falls within the ALARP zone. For these tunnels, a qualitative cost-benefit analysis may be sufficient, meaning that less complex tunnels do not need to be further investigated. For those tunnels where the basic standard is insufficient, a risk assessment shall be performed. The methodology for risk assessments exists, is currently actively used in tunnel projects, is deemed to function satisfactorily, and can be used to present risk level measurements. To perform ALARP cost-benefit assessment, less advanced qualitative methods should be used along with more advanced calculation models based on societal cost evaluations that use relevant figures and assessment parameters according to the ASEK report [7].

A delimitation of the proposed measure for safety targets is suggested with regard to frequently occurring accidents involving few fatalities, as well as extremely improbable accidents involving...
many fatalities. Frequently occurring accidents involving few fatalities differ markedly between transport systems as regards both frequency and the safety measures used to lessen their impact. Accident types involving few fatalities are not considered to be typical ‘tunnel accidents’. Here, there should be a basis for posing specific requirements and targets for each individual transport system. The best safety measure is not necessarily related to tunnel construction; rather, more general measures specific to transport systems, e.g. seat belts, should be considered. For extremely improbable accidents for which fatalities exceed the 300-500 range, the assessment does not provide a sufficient basis for determining the risk level. In order to allow a quantitative target to also encompass smaller accidents, one possibility would be to establish a complementary risk target based on PPL values. Such a method would be equal between transport systems and encompass all types of accidents, but the target would be specific to the transport system. This has been extensively discussed, but no further investigation has been conducted.

We deem that our suggestion would result in:

- safety being optimised, regardless of transport system, against transportation benefit through the selection of risk measures,
- the introduction of safety measures being optimised against cost benefit (ALARP), and
- the use of existing rules and regulations, methodologies, and processes, helps minimise the cost of its introduction.

Finally, and in summary, we are of the opinion that this suggestion promotes risk assessment as a means of supporting the continued development of the tunnel safety field through an understanding of the ways in which risks arise and how they can be handled. In addition, the suggestion forms a foundation for the assessment and optimisation of the cost efficiency of safety measures. The work on quantitative targets that have a clear connection to societal economy provides a basis for consultation with authorities and decisions based on rational factors.

The project formulates a suggestion based on a review of rules and regulations, general principles and bases for risk assessment, experience from various projects, and analysis of different ways of measuring risk. The suggestion is based on a common safety target that is not specific to any transport system, stated in an F/N diagram for road tunnels, railway tunnels, and subways and with a clear connection to societal benefit. In summary, the suggestion can be formulated as follows:

“The risk during transportation in a road, railway, and subway tunnel shall be equal, and be stated as risk per person-km.”

**ACKNOWLEDGEMENTS**

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Specification of Fire and Life Safety Requirements for Pipeline Utility Tunnels

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ABSTRACT
Pipeline utility tunnels occur infrequently and are typically required only by energy shipping companies when the pipeline alignment allows no alternative. Consequently, shippers and industry regulators have little experience with tunnel environments. Existing energy industry legislation, regulations and standards do not generally cover tunnel environments and so may not provide a sufficient set of safety requirements to ensure the safety of pipeline operations within a tunnel. It is therefore currently necessary for each project to responsibly develop a specialised set of safety requirements when an accessible tunnel is to be included within a pipeline project. This set of requirements will incorporate industry legislation, regulations and standards, applicable occupational health and safety (OHS) requirements, and will include, as appropriate, best practice guidance for tunnel safety from applicable tunnel safety standards.

KEYWORDS: Pipelines, industrial tunnels, utilities, fire safety requirements, operational health and safety, regulatory framework, standards for utility tunnel, pipeline tunnel

INTRODUCTION
Utility tunnels differ significantly from transportation infrastructure tunnels. Pipeline utility tunnels in particular are comparatively rare. Pipeline tunnels that are accessible, i.e. not fully backfilled or flooded, are rarer still. The environment and hazards are very different from transportation tunnels, and in the case of pipeline tunnels, potentially extreme. Individuals accessing the tunnel are different, being in general authorised and trained staff only. The regulatory framework that governs the utility typically does not consider tunnels and the specific hazards and risks therein. Additionally, the specific utility industry and the individual businesses that operate the tunnels often do not have standards of their own to govern safety within the tunnels, due to their scarcity. The utility operators may not have experience of operating a tunnel. The question thus arises of how best to specify fire safety requirements for such tunnels. This paper describes a best practice process for identifying and specifying the fire safety requirements for one class of such tunnels, namely accessible pipeline utility tunnels.

FIRE SAFETY OBJECTIVES
The fire safety objectives are to:

- Achieve compliance with legislation and other mandatory requirements
- Ensure life safety of tunnel occupants and emergency services
- Ensure service continuity and asset protection for the pipelines and the tunnel
- Prevent the spread of fire
- Provide suitable means of access for the emergency services

PIPELINE UTILITY TUNNELS
Pipeline owners and operators are increasingly looking to construct pipelines within mountainous areas. Due to the nature of the product being transported, usually oil or gas, it is often not feasible to
route the pipelines over higher elevations as (i) for liquid product, pumping requirements become excessively onerous, (ii) construction costs are considerably higher, and (iii) extreme weather conditions can put the pipeline at risk and make access very difficult over lengthy seasonal periods. Consequently, the ability to run a pipeline through a tunnel becomes attractive. However, the incidence of accessible pipeline tunnels is currently rare, and there are few such tunnels globally. Those that do exist are either old or are in jurisdictions that do not share information. Consequently, details of their existence, construction and design criteria processes are not shared.

**PRINCIPAL CHARACTERISTICS**

Pipeline utility tunnels are private sector infrastructure and form part of a pipeline corridor which transports either (i) liquid energy product, such as oil or liquefied petroleum gas (LPG) or liquefied natural gas (LNG), or (ii) gaseous natural gas. Due to the issues (e.g. pressure, temperature) with maintaining LNG in a liquid form within a pipeline, most natural gas pipelines transport the product as a gas, with it only being liquefied at the receiving terminus. The pipeline is owned by the private company providing the shipping service, but the product remains owned by the producer, usually a private energy company.

The pipeline itself is formed by welding together sections of steel pipe. At intervals there are isolation valves, known as ‘block valves’, or ‘remote sectionalising valves’ (RSV). There are also locations for insertion and extraction of specialised inspection devices known as ‘pigs’ (due to early pigs’ habit of making a pig-like noise during their passage through the pipe) in a process known as pigging. This is commonly executed for reasons such as cleaning and inspection of the inside of the pipeline. The pig is a cylindrical device inserted into the pipeline via an angled connection and is carried along by the flow to a similar angled connection at the extraction point.

A pipeline is normally buried in a shallow trench, or, less commonly, elevated above the ground on low trestles, depending on the nature of the terrain. Tunnels are used only when (i) required either by regulatory and/or environmental issues, or (ii) when the terrain makes the standard approach impractical, such as the need to traverse mountains or other difficult terrain, or the need to traverse a large body of water such as a wide, navigable river. Consequently, access to the tunnel may be difficult, due to a combination of factors including site remoteness, terrain, and harsh winter conditions.

Some pipeline tunnels are backfilled or flooded. These are not accessible and and thus have no fire-life safety issues. However, other tunnels remain accessible following construction, either from a desire to access the pipeline within the tunnel, to access the tunnel for future utility (pipeline or other) expansion, or from a need to use the tunnel as a transport route to traverse the terrain to access sections of the pipeline outside of the tunnel.

**Tunnels**

Accessible pipeline utility tunnels are typically single bore, sized to be the minimum area needed to construct the tunnel, install the pipeline(s) and accommodate the required provisions for access. This may include access vehicles for maintenance and/or emergency intervention. Figure 1 and Figure 2 show examples of the interior of pipeline utility tunnels. Each image shows the customised access vehicles, known by the mining term of manrider. Additionally, the tunnels are frequently provided with some form of access control, usually secure doors, to prevent unauthorised access.
Traffic
Where vehicular traffic is employed within the tunnel, it may be either a fixed guideway system or a roadway for wheeled vehicles, depending on the owner’s preferences. Due to the aforementioned
restrictions on the size of the tunnel, it is likely to have only a single track or roadway and therefore traffic will be strictly unidirectional. Access to the tunnel may be controlled by traffic signals or similar, so as to ensure the unidirectional operation of the tunnel. Depending on the specifics of the tunnel, the traffic direction may be allowed to be reversed from time to time e.g. to allow maintenance vehicles to return to their point of origin. However the traffic must remain unidirectional at all times, unless passing places are provided, which is unlikely.

**Occupants**

For accessible pipeline tunnels, tunnel occupancy is controlled and, in general, limited to trained staff and other persons duly authorised by the tunnel operator. The tunnel is normally unoccupied, hence life safety risks are in general low, except during inspection and maintenance operations. Consideration must be given to the type of maintenance access, and vehicles, if used. The tunnel may also be used as a private access route for pipeline workers to the far side of the tunnel.

**HAZARDS AND RISKS**

The hazards and risks attendant to an energy pipeline tunnel may be significant. For both oil and gas pipelines, the principal fire-related hazard is that of a product release within the tunnel. Should this be combined with an ignition source, there is the potential for fire and/or explosion within the tunnel. For gas pipelines, the product will be released as vapour, and explosion is the most significant ignition-related hazard. For oil pipelines, a product release would result in a spillage, and fire is the most significant ignition-related hazard. Factors affecting the risk include tunnel length and location, product volatility, and the product’s transport pressure. Other risks include risk of oil spillage reaching the environment, risk of asphyxiation from a gas cloud, and other risks arising from exposure to the specific product being transported, including skin irritation and lung damage.

**Product Spills**

The primary major hazard is of a product release within the tunnel, leading to a product spillage. In the event of an oil release, it could lead to a significant spillage of flammable liquid within the tunnel. In the event of a LPG or LNG release, it will vapourise on release, leading to a significant release of flammable vapour within the tunnel. For gaseous natural gas pipelines, the product is already in a gaseous state and a product release would likewise release flammable vapour within the tunnel. In each case this is a serious hazard with significant potential fire-life safety consequences. The probability of such an event is low, however the consequences are potentially severe, depending on the specific incident profile. The probability of such an event occurring with persons in the tunnel is extremely low.

Even if a product release were not ignited, a release would represent a major environmental and health hazard, requiring rapid intervention to control and rectify. Both propane gas and natural gas are flammable and asphyxiants. Crude oil and related processed petrochemical products are flammable and toxic. Oil is a general term for a variety of different products, ranging from unprocessed bitumen, to heavy crude, to light crude, to condensate. Each variety has differing properties and hazards, however, with respect to fire safety, the principal variations in properties are the differences in viscosity and flash point. As an illustrative example, Reference [3] gives examples of the differing properties of diluted bitumen and condensate. Condensate is used to dilute raw bitumen for transport, since undiluted bitumen is too viscous for transport via pipeline. Condensate has typical densities between 675-861 kg/m³ and viscosity between 0.5-6.3 cSt. Diluted bitumen has a maximum density of 940 kg/m³, while the viscosity must not exceed 350 cSt. These represent the upper and lower bounds on viscosity of oil products, with other products such as heavy, medium and light crude falling somewhere between these values. The flash point of oil can vary significantly. Some blends have flashpoints as low as -30°C, while others may be as high as 40°C or more.

**Product Fires**

In the event of a product release, there is the potential for fire or explosion if an ignition source is present. For oil products combined with an ignition source, fire is most probable as the release will result in a large amount of spilled liquid, with smaller amounts of vapours. Both jet fires and pool
fires are possible, depending on the precise nature of the ignition source. The size of the potential fire load will be equivalent to the volume of oil contained within a section, defined by the spacing of the RSVs, diameter of the pipeline, and the time taken to close the RSVs upon detection of a loss of pipeline integrity. As an example, depending on the specifics of the pipeline, the volume of spilled product could be as much as 40000-50000 bbl \((7 \times 10^6 \text{ L}, 7000 \text{ - } 8750 \text{ m}^3)\) or more. Discharge rate will be proportional to the size of the leak, but a discharge rate of 100 L/s is a reasonable assumption. The potential fire size of such a release could be more than 300MW, however in the tunnel environment the fire is likely to be oxygen-limited and 300MW is a reasonable assumption for an upper bound on the fire size.

Duration of the fire could be lengthy, as response times may be significant for remote locations. If no persons are at risk, the emergency responders would most likely allow the fire to burn out prior to entering the tunnel.

**Product Explosions**

For a gaseous release, the primary hazard is the potential for explosion. Gas products are shipped at much higher pressures than liquid products. A vapour cloud explosion is the most likely form of event. Within the confines of the tunnel, the effects of any such explosion would be directed longitudinally along the tunnel axis and could impact on areas directly outside the tunnel.

**Maintenance Fires**

Fire hazards may arise due to maintenance activities within the tunnels. The specific hazards will depend on the specific activities, but activities such as welding, grinding, etc. carry obvious risks while electrical maintenance may result in sparking or other ignition risks.

The fire risk will be dependent on potential fuel sources within the tunnels. Aside from the oil, other potential fuel sources should be limited, by good housekeeping and maintenance practices, so the potential fire load, excluding the products in transport, should be small. The tunnel’s ventilation system will be operated whenever maintenance activities are in progress.

However, it should be noted that certain maintenance activities may carry significant risk of sparking or other ignition risks and consequently all maintenance activities should be subject to a rigorous risk assessment and a comprehensive method statement should be developed prior to carrying out any maintenance activity. These would usually be expected to form part of the standard operational health and safety considerations and so robust risk mitigations would be in place prior to commencement of these activities.

**Vehicle Fires**

Vehicle fires are a specific subcategory of maintenance fires but possess a greater fire hazard than the hazards associated with the actual maintenance activities. Thus they are considered a separate hazard. Specific hazards will depend on the type of vehicles used. E.g. if diesel engine vehicles were to be used, the hazards and risks would potentially be more significant than if electric vehicles are used.

**Risks to Pipeline Asset and Product**

Unless the pipeline is fire-protected, e.g. by being buried within the invert, maintenance fires present a hazard to the pipeline and the product. The fire could elevate the temperature of the pipeline and/or its support structure, which could lead to structural failure of the pipeline resulting in a product release and potential involvement of the product in the maintenance fire. Alternatively, the heat load on the pipeline could lead to adverse effects on the product within the pipeline.

**Emergency Access**

Pipeline tunnels are frequently located in remote areas, and may be difficult to access at times of the year, such as in winter when weather conditions may make access problematic. Emergency access to the tunnel may therefore be non-trivial and intervention times may be significant.
Owner’s lack of familiarity with tunnel environments
An additional hazard may arise due to the owner/operator’s lack of familiarity with tunnels. This may be dealt with via education, however the risk of inappropriate response in an emergency should not be discounted and suitable measures, including suitable emergency response planning, and appropriate education and training, need to be implemented to minimise this risk.

REGULATORY FRAMEWORK
Utility tunnels typically do not come under the jurisdiction of regulations and standards developed for transportation tunnels. The regulatory framework derives from occupational health and safety regulations, and regulations governing the specific utility industry. The industry regulations do not in general consider the routing of the utility infrastructure within tunnels and there are few, if any, requirements that recognise the specific hazards and risks arising from the tunnel environment.

Industry Standards
Industry standards govern issues such as the design of the pipeline infrastructure, the safe operation of the pipeline, and appropriate emergency measures. These standards implicitly assume that the pipeline is either installed in the open or in a shallow trench, taking no account of tunnel routing. Examples of industry codes are found in References [4] - [6] and others, according to jurisdiction.

Depending on the jurisdiction, a general fire life safety standard such as NFPA 101 [7] may be applicable.

Additional requirements, mainly pertaining to the pipeline itself, may be found in the standards and guidance of the company constructing the pipeline.

Occupational Health and Safety (OHS)
In developing a set of requirements for the safe operation of a pipeline utility tunnel, the primary requirements will be the appropriate occupational health and safety regulations. Examples of relevant OHS codes are found in References [8] – [11]. OHS regulations typically only consider specific underground spaces, usually spaces under construction and mines. Completed underground facilities are often not specified explicitly and so definition of the underground space may require consultation and agreement with stakeholders. Central to these discussions is the question of whether the space should be defined as a confined space or not. The decision will be influenced by elements such as length, access, egress, ventilation, etc.

Building Code and Fire Code
Building code and fire code for the jurisdiction may be applicable, particularly if service structures are required at the portals. Examples of these are found in References [12] – [15]. The applicable electrical code for the jurisdiction may be applicable, for example Reference [16].

Guidance from Transportation Tunnels
The industry with the best developed standards for safety within tunnels is the transportation industry. Portions, or all, of these standards may therefore be adopted as best practice guidance documents at the discretion of the owner and the authority having jurisdiction. Examples include NFPA 130 [17] and NFPA 502 [18]. The choice and extent of application of such standards for additional guidance will be influenced by a number of factors, including but not limited to frequency of access, types of operations, length of tunnel, location of tunnel, type of vehicle, if any, used for access, assessment of the hazards and consequent risks, etc. It is important to remain cognizant of the differences between utility tunnels, which typically have very low-frequency access (with good control over tunnel occupants), and public-access transportation tunnels, which normally have very high-frequency access (with relatively little control over the tunnel occupants), and assess the requirements accordingly.
FORMULATION OF REQUIREMENTS
Minimum requirements for a pipeline utility tunnel will be formed from the set of applicable OHS regulations, and industry legislation and regulations. However these regulations will not typically directly consider the unique challenges of the tunnel environment. Transportation tunnel fire safety standards may be adopted, wholly or in part, to capture the specific hazards, consequent risks, and appropriate mitigations for tunnel environments. HAZID/HAZOP processes may be required to determine the specific set of requirements appropriate for a specific tunnel.

PROJECT EXAMPLE: PROPOSED CONFIDENTIAL OIL PIPELINE
An example project for pipeline utility tunnels is a proposed oil pipeline in the Canada jurisdiction. The project remains confidential at this time so details of Owner and location are redacted. At time of writing the project has reached a preliminary design stage and has developed a comprehensive set of approved fire-life safety provisions.

Project Description
The project proposed a pipeline to transport oil from source site to port through western Canada for onward shipment to refineries. A return pipeline would transport returned product back to the originating site for re-use.

To reach the port, it was necessary to route the pipeline through mountainous terrain, via a lengthy tunnel. The tunnel would be in a remote location, with the nearest town to the portals ranging from 60km to 120km distant, depending on the specific portal location. Service buildings for the tunnel would be located at each portal, containing tunnel systems equipment, and maintenance vehicles and equipment.

Key Stakeholders
Key stakeholders with a stake in the fire-life safety of the tunnel were as denoted in Table 1. Note that the Owner is not just the Operator but also the First Responder. This is customary for pipeline infrastructure.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner</td>
<td>Owner, Operator, First Responder</td>
</tr>
<tr>
<td>National Energy Board</td>
<td>Regulator &amp; Authority Having Jurisdiction</td>
</tr>
<tr>
<td>BC Office of the Fire Commissioner</td>
<td>Enforcement of Fire Safety Legislation within BC</td>
</tr>
</tbody>
</table>

Applicable Legislation and Standards
As noted above, the primary set of statutory requirements for an accessible pipeline tunnel is derived from applicable Operational Health and Safety regulations. In Canada, energy pipelines are federally regulated, and so the pipeline overall is subject to federal regulations. However province-specific sub-contractors involved in activities with the pipeline, e.g. maintenance of access vehicles, would be regulated by the relevant province, e.g. Province of British Columbia, in the location of the tunnel. Thus both federal and provincial OHS regulations would apply to the operation of the tunnel.

The principal applicable legislation and regulations are shown in Table 2.

<table>
<thead>
<tr>
<th>Jurisdiction</th>
<th>Applicable Legislation / Regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federal OHS</td>
<td>Canada Labour Code [8]</td>
</tr>
<tr>
<td>Federal OHS</td>
<td>Canadian Occupational Health &amp; Safety Regulations (COHS) [9]</td>
</tr>
<tr>
<td>Provincial OHS</td>
<td>Workers Compensation Act (BC), Part 3 – Occupational Health &amp; Safety [10]</td>
</tr>
<tr>
<td>Provincial OHS</td>
<td>WorkSafeBC Occupational Health &amp; Safety Regulations (WSBC) [11]</td>
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The OHS regulations stipulate specific minimum requirements for tunnel systems as summarised in Table 3.

Table 3. Tunnel Systems Specific Requirements

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<thead>
<tr>
<th>Tunnel System</th>
<th>OHS Regulatory Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation</td>
<td>WorkSafeBC OHS Regulation Clauses 7.26 – 7.38; also Clauses 9.27-9.33 (Confined Spaces)</td>
</tr>
<tr>
<td>Lighting</td>
<td>WorkSafeBC OHS Regulation Clauses 4.64-4.69; Part 19</td>
</tr>
<tr>
<td>Electrical services</td>
<td>WorkSafeBC OHS Regulation Clause 5.27; Part 19; also Clause 9.50-9.51 (Confined Spaces)</td>
</tr>
<tr>
<td>Communications &amp; SCADA</td>
<td>WorkSafeBC OHS Regulation Clause 3.18</td>
</tr>
<tr>
<td>Fire detection &amp; alarm</td>
<td>No requirements in OHS Regulation</td>
</tr>
<tr>
<td>Fire-fighting systems</td>
<td>No requirements in OHS Regulation</td>
</tr>
<tr>
<td>Drainage &amp; spill containment</td>
<td>No requirements in OHS Regulation</td>
</tr>
</tbody>
</table>

Applicable Codes and Standards
The principal applicable codes and standards are:

- Fire Code of Canada [12]
- Building Code of Canada [13]
- Fire Code of British Columbia [14]
- Building Code of British Columbia [15]
- Canada Electrical Code [16]

and all relevant referenced standards within the above named documents. The Owner additionally has numerous corporate standards related to design and operation of the pipeline, however none of these are tunnel-specific.

Hazardous Area Classification
The primary applicable requirement for the tunnel arising from this set of codes is the Hazardous Area Classification for the tunnel, per Reference [16].

The volatile flammable liquids in the pipelines are normally confined within the closed system of the pipeline and can only escape as a result of accidental rupture or breakdown of the system. Ignitable concentrations of flammable gases or vapours will normally be prevented by operation of the tunnel ventilation system. A hazard may arise as a result of failure or abnormal operation of the ventilation equipment.

Explosive gas atmospheres would not be likely to occur in normal operation of the tunnel, and if they were to occur would be of short duration, for the following reasons:

- Pipelines within the tunnel are continuous welded pipes with no flanges, bends, valves or through-wall fittings.
- The pipes therefore form a containment system within the tunnel.
- Oil remains completely segregated from the tunnel environment unless there is a failure of the pipe containment.
- Quality control of the welding process and regular internal and external inspection of the pipes for onset of corrosion make failure of the pipe containment unlikely.
- The tunnel is provided with remotely monitored hydrocarbon vapour detection systems.
- The tunnel is provided with a permanent, remotely controlled tunnel ventilation system.
In the event of hydrocarbon vapour being detected, the tunnel ventilation system would be activated to dilute and disperse the flammable vapours, maintaining the tunnel environment below the required fraction of the Lower Explosive Limit (LEL).

In the event of hydrocarbon vapour being detected, alarms would be triggered in the Control Centre.

The Control Centre will take the appropriate action on an alarm.

The tunnel environment therefore fits the definition of a Class 1 Division 2 (Class 1 Zone 2) Hazardous Area under the definition of the Canadian Electrical Code (CEC). All electrical equipment would therefore, as a minimum, be required to be CSA/UL-certified with the correct EX rating for operation in this environment. The project decided to exceed this minimum requirement and so the tunnel environments would be defined as Class 1, Division 1 (Class 1, Zone 1) Hazardous Areas.

Best Practice Guidance Documents for Tunnel Fire Safety
Furthermore, it was recognised by the project and its stakeholders that the suite of industry regulations and standards and the applicable OHS standards did not sufficiently address the unique hazards of a long, remote pipeline tunnel. Nor were standards from other jurisdictions globally found that would provide a comprehensive set of safety requirements for a pipeline tunnel. Consequently the project adopted aspects of the following fire-life safety standards as guidance in developing the systems requirements within the tunnel:

- NFPA 101 Life Safety Standard
- SFPE Handbook of Fire Protection Engineering, Society of Fire Protection Engineers
- NFPA 130 Standard for Fixed Guideway Transit and Passenger Rail Systems

It is important to note that due to the tunnel’s normally unoccupied state and its low occupancy during the infrequent occasions when access would be required, these documents were only used to provide guidance on general tunnel fire-life safety principles.
Project Assumptions
To facilitate preliminary design, a series of assumptions were made regarding fire-life safety issues. These assumptions are summarised in Table 4. The intent would be for these assumptions to be resolved and replaced by confirmed design parameters as the project progresses.

Table 4. Assumptions Made for Preliminary Tunnel Design

<table>
<thead>
<tr>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The tunnel will be treated as a Confined Space.</td>
</tr>
<tr>
<td>• The maximum maintenance work crew size within the tunnel will be not more than twenty.</td>
</tr>
<tr>
<td>• The minimum maintenance work crew size within the tunnel will be not less than two.</td>
</tr>
<tr>
<td>• Maintenance vehicles to be used within the tunnel will be electrically powered via on-board batteries.</td>
</tr>
<tr>
<td>• All vehicles operating within the tunnel will be equipped with on-board portable fire extinguishers for use by staff.</td>
</tr>
<tr>
<td>• All vehicles operating within the tunnel shall be compliant with the Hazardous Area Classification for the tunnel.</td>
</tr>
<tr>
<td>• Safe working procedures for any hot works required within the tunnel will take into account the risks arising from the vehicle type in use.</td>
</tr>
<tr>
<td>• The largest maintenance vehicle to be operated within the tunnel will be approximately the size of a mine locomotive.</td>
</tr>
<tr>
<td>• No vehicles carrying hydrocarbons will be allowed to operate inside the tunnel.</td>
</tr>
<tr>
<td>• No other vehicles containing any cargos defined as Hazardous Loads will be allowed to operate inside the tunnel.</td>
</tr>
<tr>
<td>• Planned maintenance activities will occur at approximately six month intervals.</td>
</tr>
<tr>
<td>• The maximum possible volume of oil resulting from a spillage will be equivalent to the contents of the pipeline(s) within the tunnel between adjacent remote sectionalizing valves and will be a function of the response time required to close the valves.</td>
</tr>
<tr>
<td>• The largest potential fire is that resulting from a spillage that ignited.</td>
</tr>
<tr>
<td>• The possibility of this occurring during a period when the tunnel is occupied is sufficiently low as to be negligible.</td>
</tr>
<tr>
<td>• The largest potential fire with life safety implications would be that of a maintenance vehicle that catches fire. The peak heat release rate of such a fire will depend on the type and specification of maintenance vehicle, and on the load carried by the vehicle.</td>
</tr>
<tr>
<td>• No through wall fittings will be mounted to the pipelines within the tunnel.</td>
</tr>
<tr>
<td>• Attached surface-mounted fittings may be mounted to the pipelines within the tunnel.</td>
</tr>
<tr>
<td>• The pipeline(s) will be mounted on racks inside the tunnel and will not be buried in the invert.</td>
</tr>
<tr>
<td>• All tunnel systems designs shall support pipeline operations at the ultimate annual average capacities. It is assumed that any maintenance fire that may occur will not spread to the pipeline contents or compromise the pipeline and its support structure.</td>
</tr>
</tbody>
</table>

Application of the agreed set of requirements, combined with the design requirements and the project assumptions yielded a set of operational modes (Table 5), with an associated set of tunnel systems specified for each mode of operations (Table 6). These were used in developing the preliminary design for the tunnel systems.
### Table 5. Summary of Operational Modes

<table>
<thead>
<tr>
<th>Operational Mode</th>
<th>Sub-Mode</th>
<th>Activity</th>
<th>Estimated frequency; Occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>none</td>
<td>Normal operation of tunnel</td>
<td>Normal state; Occupancy zero</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Routine inspection</td>
<td>Routine inspection of pipeline &amp; systems; e.g. pipeline coating &amp; supports, tunnel liner, etc</td>
<td>2-4 per year; 2-5 persons</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Minor maintenance</td>
<td>Minor maintenance activities; e.g. replacement of sensors, luminaires, etc</td>
<td>&lt;1 per year; 2-5 persons</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Major maintenance</td>
<td>Major maintenance activities; e.g. replacement of pipe section, jet fan, etc</td>
<td>Infrequent, dependent on activity; 10-20 persons</td>
</tr>
<tr>
<td>Emergency</td>
<td>Spillage emergency</td>
<td>Responding to product spillage inside tunnel</td>
<td>Rare; Occupancy incident dependent</td>
</tr>
<tr>
<td>Emergency</td>
<td>Non-fire emergency</td>
<td>Emergency inside tunnel not involving spill or fire; e.g. accident involving maintenance staff</td>
<td>Rare; Occupancy incident dependent</td>
</tr>
<tr>
<td>Emergency</td>
<td>Fire emergency</td>
<td>Fire inside tunnel involving human occupancy; e.g. maintenance vehicle fire</td>
<td>Rare; Occupancy incident dependent</td>
</tr>
</tbody>
</table>

Note that the final set of selected systems included systems that were not required under OHS mandatory minimum requirements. These additional systems (fire detection and alarm, fire-fighting systems, and drainage and spill containment) were deemed to have a sufficiently positive net contribution to the safety of the tunnel that the project chose to include them in the final set of systems requirements for the project.

### Table 6. Tunnel Systems Requirements for Operational Modes

<table>
<thead>
<tr>
<th>System</th>
<th>Normal</th>
<th>Maintenance</th>
<th>Emergency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel ventilation</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Pipeline monitoring</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Atmospheric hydrocarbon monitoring</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Tunnel temperature monitoring</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>SCADA</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Seepage drainage</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Seepage treatment and discharge monitoring</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Electrical services</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Fire detection &amp; alarm system</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>CCTV</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Tunnel lighting</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Communications</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Portable fire extinguishers*</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>First aid equipment*</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Maintenance vehicles</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Task lighting</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Spillage collection and containment</td>
<td></td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Emergency communications</td>
<td></td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>System</td>
<td>Normal</td>
<td>Maintenance</td>
<td>Emergency</td>
</tr>
<tr>
<td>----------------------------</td>
<td>--------</td>
<td>-------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Emergency lighting</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Emergency egress</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Emergency intervention</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Refuges</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Fire fighting systems</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

NOTE: * - denotes equipment to be carried into tunnel by maintenance crews, and to be provided at portals.
NOTE: Required functionality of systems may vary depending on type of operation.

**Acceptance process for fire-life safety requirements**

A consultative process was used to reach consensus for the final set of project tunnel fire-life safety requirements. HAZID/HAZOP workshops were held to assess hazards and consequent risks via a what-if methodology using a team of subject-matter-experts, senior project staff and stakeholders. From this a set of requirements, as detailed above, was presented to the project for approval. Upon approval, the set of requirements was encapsulated within the formal design basis documentation for the project.

**CONCLUSIONS**

Pipeline utility tunnels are used infrequently by energy product shipping companies. However as new pipeline projects are developed, there are locations where routing the pipeline through a tunnel is desirable. In some cases, the Owner may deem that the tunnel is required to be accessible. In these instances, the existing framework of industry legislation, regulations and standards fail to provide a complete set of safety requirements appropriate to an accessible tunnel environment. It is therefore necessary to develop a set of requirements that is acceptable to the project and to the stakeholders, and that provides the necessary safe environment for operation of the pipeline within a tunnel environment. The set will include mandatory industry requirements for the pipeline asset, applicable OHS requirements, and should incorporate tunnel safety best practices from appropriate standards, as appropriate. This process has been illustrated with the example of a confidential oil pipeline project in a Canadian jurisdiction. Other similar projects would need to adopt a similar process appropriate to the location of the proposed asset and the associated legislative and regulatory jurisdiction.

**REFERENCES**

4. National Energy Board Act of Canada
5. CSA Standard Z662 Oil & Gas Pipeline Systems
7. NFPA 101 Life Safety Standard
10. Workers Compensation Act, British Columbia
12. Fire Code of Canada
13. Building Code of Canada
14. Fire Code of British Columbia
15. Building Code of British Columbia
16. Canada Electrical Code, CSA C22.1
17. NFPA 130 Standard for Fixed Guideway Transit and Passenger Rail Systems
18. NFPA 502 Standard for Road Tunnels, Bridges and Other Limited Access Highways
Interval of Reasonable Threshold on Automatic Fire Detection in Road Tunnels

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2Shanghai Tunnel Engineering Co., Ltd., No. 239 Zhaojiabang Road, Shanghai, China

ABSTRACT
The concept of interval of reasonable threshold is suggested for the thermal fire alarm system used in road tunnels. The upper and lower limits of the interval are provided by pool fire test and analysis of rate of temperature rising in the protected tunnel. This method is capable of localizing the alarm threshold at an optimum level with acceptable rate of failed-fire-alarm and false-fire-alarm simultaneously, which also conducts an on-line evaluation technology for functional fire detection. The study implies that the threshold of fire alarm system is highly individual, depending on both, the detectors and the protected tunnel.

KEYWORDS: Fire alarm, FBG, threshold, thermal detector, road tunnel

INTRODUCTION
Automatic fire detectors are essential elements in a fire protection system of urban road tunnel longer than 500 meters according to the design regulations of Chinese Transport Administration. The detectors should provide alarm rapidly and correctly in an initial stage of a fire in a tunnel, in order to successfully start up an emergency system. However, higher alarm sensitivity may result in higher risk of false alarm that will damage system’s stability and may even cause a traffic disruption. Decreasing the sensitivity makes the detectors prolong the fire response time, and even causes an alarm to fail which may be a more critical mistake. It seems to be a trade-off between the false-alarm-rate and failed-alarm-rate by adjusting the threshold. Many countries are still skeptical regarding the use of automatic fire detectors and feel that false alarms would be the major obstacle [1]. To the best of our knowledge, there is no quantitative measurement that could be used to evaluate the function of alarm system on line, particularly for thermal fire detection. It means that the tunnel authorities are unable to know whether a commercialized fire detector works well or not in an operating tunnel, until a real fire occurs. This paper’s objective is to overcome this obstacle by introducing a new concept: interval of reasonable threshold.

Fire factors:
Special radiation, heat and smoke are considered as general fire factors. The function of an automatic fire detector is to provide warning when certain fire factor reaches a given threshold. In order to
recognize a fire in tunnel, the suitable fire factor should originate from the fire itself and emerge right after its ignition. Theoretically, fire is a violent chemical reaction accompanied by an enthalpy variation before and after, consequently the reaction heat under a constant pressure, $Q_p$, is an unique fire factor serving to detect thermal detections.

$$ Q_p = H_2 - H_1 = \Delta H $$

When the reaction is roughly considered under an adiabatic condition, the $Q_p$ results an increase in tunnel temperature immediately. Here $C_p$ average is the average thermal capacity of the tunnel environment around a fire between $T_1$ and $T_2$.

$$ Q_p = C_p \text{average} \cdot (T_2 - T_1) = C_p \text{average} \cdot \Delta T $$

The scale of a fire can be defined as heat-release-rate (HRR):

$$ \frac{dQ_p}{dt} = C_p \text{average} \cdot \frac{dT}{dt} $$

Therefore, the heat-release-rate leads to temperature-rising-rate (TRR). Full scale tunnel fire tests demonstrate that the temperature is always too low to reach a given threshold in the early stage of a fire since reaching this threshold requires heat accumulation [1,2]. On the other hand, the TRR can respond to fire immediately therefore should be the suitable fire factor particularly in the setting of a tunnel demanding speedy reaction.

**Reasonable alarm threshold:**
The rate of failed-fire-alarm and the rate of false-fire-alarm are major characteristics of fire detection. Both depend on the level of alarm threshold, but each follows opposite tendency. The challenge is to find out the threshold working at the optimum level for both rates, which must rely on the performances of fire detectors, traffic conditions, structure of tunnels, as well as preferences of tunnel’s administrators.

Fire alarm sensitivity in a given tunnel is specified under the following boundary conditions: required minimum HRR, required alarm response time and longitudinal wind speed (LWS). Different countries, even different tunnels, demand different fire definition values. A new requirement from the Swedish Transport Administration is that the alarm systems should be able to detect a 0.5 MW fire within a time period of 90 seconds [1]. For the thermal fire detection, any event causing HRR that is higher than the fire definition value should be recognized in required time period; otherwise it is identified as a failed-fire-alarm. This means that an event could be overlooked, if its HRR is less than the fire definition value, even if there is a real flam. The TRR resulted from pool fire tests with defined HRR value is accepted as the upper limit of the interval of reasonable threshold.

Although, fire is a rare event in an operating tunnel, there are many other thermal events that may create high TRR and even touch the threshold to generate a false alarm. These are mainly due to noises of detectors and thermal shocks of heavy traffic in a running tunnel [3]. It is impossible to eliminate false alarm completely, therefore an acceptable false alarm rate must be provided by the transport
administration. The probability of events with TRR higher than a given value can be statistically predicted in a given tunnel. The TRR of thermal events corresponding to the acceptable false alarm rate is consequently named as the lower limit of the interval of reasonable thresholds.

It must be emphasized that the fire detection system refers not only to the fire detectors, but also to the protected tunnel. Therefore, the employed threshold should be selected in accordance with local fire tests, statistical analysis of TRR recorded during the operation and preference of the tunnel’s administration. This concept generates a powerful on-line tool to evaluate any specific operating thermal fire detection system.

**EXPERIMENTS:**

Linear fire detectors based on optic fiber Bragg grating (FBG) technology[4,5] were installed in tunnel D and Y across the Huangpu River, Shanghai, China. The detectors were spaced about ten meters apart in series covering a total of three kilometers in both directions. Local temperatures as a function of time and corresponding locations of detectors are collected by an interrogator in order to generate alarm as soon as temperature-rising-rate deviated from usual.

Three diesel pool fire tests of 0.8 MW have been completed at location 2, 3, and 6 in the tunnel D (fig.1). Longitudinal wind speed (LWS) was adjusted from 0 to 5 meter per second for different tests.

![Diagram](image)

*Figure1 Scheme of tunnel D for pool fire tests of 0.8MW. The diesel pool was positioned at 2, 3 and 6, respectively. The quasi-distributed FBG fire detectors were installed on the ceiling of tunnel from 1#1 to 1#6. Arrow shows wind direction.*

**RESULTS AND DISCUSSION:**

According to the concept of interval of reasonable thresholds, the upper limit of interval characterizes rate of failed-fire-alarm, meaning when threshold is set higher than the upper limit, the system may be unable to trigger alert for fire with required HRR. Three diesel-pool-fire-tests in tunnel D were employed to measure the TRR of the minimum detectable fire according to the regulations of Chinese road tunnels [6]. As a function of time, the TRRs are shown in Fig.2, and the maximum values in 60 seconds after ignitions are recorded in Table I. The fire tests carried out at different locations, from middle of the tunnel to one side of the tunnel, and different wind speeds, from 0 to 5m/s, in order to cover all the potential scenarios. The smallest TRR among them is chosen as the upper limit of the reasonable threshold interval for the protected tunnel, for example 26°C/min in tunnel D (table 1). In
fact, the upper limit of the interval of reasonable threshold might not be the same for different cross sections in a tunnel, but it has to be approximated as a constant along the whole tunnel practically.

![Figure 2](image-url)  
*Figure 2  Measured TRR of detector 1#3, 1#4 and 1#5 as a function of time in the diesel pool fire test at location 6 with longitudinal wind speed of ~ 5m/s. The detector 1#3 was heated to reach maximum TRR of 73.1 °C/min in the first 60 seconds.*

Table 1  
*Results of fire tests in tunnel D (alarm threshold = 10 °C/min).*

<table>
<thead>
<tr>
<th>Fire location</th>
<th>Ignition at</th>
<th>Alarm at</th>
<th>Response time(s)</th>
<th>LWS(m/s)</th>
<th>Maximum TRR in a minute after ignition (°C/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>16:11:57</td>
<td>16:12:28</td>
<td>34</td>
<td>3</td>
<td>58.0</td>
</tr>
<tr>
<td>6</td>
<td>17:08:35</td>
<td>17:09:20</td>
<td>45</td>
<td>5</td>
<td>73.1</td>
</tr>
</tbody>
</table>

The lower limit of the interval of reasonable threshold characterizes false-alarm-rate. In an operating tunnel, TRR values recorded by a FBG thermal detector always fluctuate due to noises of the signal processing procedures, as well as the shocks of the thermal events in the tunnel. Some TRR may reach the threshold and trigger false alerts in normal operation. The amplitude of TRR fluctuation depends on behavior of the detector, traffic conditions and tunnel structure. Fig. 3 shows TRR recorded for 24 hours on July 6th, 2016, from a randomly selected detector of tunnel D and Y, in Shanghai. Both tunnels have similar structure and dimension, but traffic vehicle flowrate of Tunnel Y is 77,812 instead of 25,632 of Tunnel D this day. The TRR fluctuation in tunnel D is supposed mainly due to the detector’s noise. The strong TRR peaks found in tunnel Y should correspond to some thermal shocks caused by slowly moving vehicles during daytime rush hour. The latter desires a threshold with higher value in order to avoid a potential high false-alarm-rate. These evidences support that any fire alarm system should be individualized, particularly in terms of the choice of threshold.
Fig. 3  TRR as a function of time recorded by a randomly selected FBG fire detector, on July 6th, 2016, in tunnel D (A) and tunnel Y (B). The strong TRR peaks in tunnel Y are resulted from thermal shock phenomena caused by slowly moving heavy vehicles in time period of daytime rush hour.

When a tunnel operates under normal traffic conditions, as a random variation, the TRR recorded in each second is assumed to follow a normal distribution, $N(0, \sigma)$. Standard deviation, $\sigma$, is available based on big data of TRR collected on line by a FBG detector. If a threshold is defined as $c\sigma$, the probability of false alarm of a detector is expressed as

$$P_c = f(c) = \int_{c\sigma}^{\infty} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{t^2}{2\sigma^2}} dt$$  \hspace{1cm} (4)$$

If the required probability of false alarm is proposed to be less than ones per year for a system consisted of 600 FBG detectors, the constant $c$ equals to 7.69 by numerical calculation [7]. Therefore, the contribution of detector noise to the lower limit of reasonable threshold is considered as $7.69\sigma$ in the case of tunnel D.
Fig. 4  Interval of reasonable alarm threshold for FBG fire detectors along the tunnel D, Shanghai.

Thermal shock also contributes to the TRR fluctuation with greater impact than the detector noise. The maximum TRR per day, $R_{\text{max}}$, can act as a random variation that follows another normal distribution. The required probability of false alarm, once per year, corresponds to $\sim 3\sigma'$. Therefore, the sum of $7.69\sigma$ plus $3\sigma'$ acts as the lower limit of reasonable threshold interval. Parameters of $\sigma$ and $\sigma'$ are established from data analysis of TRR of all detectors along tunnel D in a whole year operation, shown as lower limit in Fig. 4.

The space of the interval has been used to quantify the function of fire alarm system. Wide interval implies that system has enough sensitivity and stability, i.e. it can rapidly respond to an initial fire with low false alarm rate. However, the interval may shrink to zero and even negative, when the defined fire size is small with tight required response time, and/or when the detector noise is too high with severe traffic jam. In the latter case, the detectors may still be on, but the alarm function is no longer operating. Based on this technique an automatic evaluation module is triggered to review an individual system on line and give suggestions to the administration regarding solutions.

CONCLUSION:

Concept of reasonable threshold interval provides a method to characterize a fire alarm system made by thermal detectors in road tunnels. The upper and lower limit of the interval can localize an alarm threshold that functions under acceptable rate of failed-fire-alarm and false-fire-alarm, simultaneously. Our experiments imply that an alarm system is specific to detectors and protected tunnel. The new concept will lead to an on-line evaluation technology to provide fully functional and readily available fire detection.
REFERENCES:


Methods of Grasping Smoke Movement During Road Tunnel Fires ~Aim for Safer Road Tunnel Construction~

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³ Central Nippon Highway Engineering Tokyo : m.yokota.aa@c-nexco-het.jp

ABSTRACT

It is essential to ensure a safe evacuation environment when a fire has broken out in a road tunnel. In Japan, fire sensors that detect flame are widely used to detect the breakout of fires, but they may fail in certain circumstances. Inside a tunnel with a steep ramp and with branching or merging locations, it is difficult to prevent the spread of smoke by controlling wind speed, and methods of effectively controlling smoke need to be investigated. But before this, studies of detecting the fire are apparently needed. This paper reports experiment data for early fire detection and the behavior of smoke.

KEYWORDS: Fire in tunnel, Early detection, Smoke movement, Smoke spread, Evacuation, Ventilation control

INTRODUCTION

A road tunnel is a closed special space, so in a case of a fire, it is important to ensure a safe evacuation environment. In order to achieve this, it is necessary to exhaust and control smoke appropriately considering the traffic condition. This paper reports on methods of early detection of fires in diversifying expressway tunnels and present studies to clarify the behavior of smoke.

BACKGROUND

Diversifying expressways
In Japan, the Tokyo Outer Ring Road is being constructed as an urban expressway that will link radiating intra-city expressways that connect regional cities to Tokyo at entrances to Tokyo (see figure 1). This road is constructed in a city area, 16 km-long deep tunnel is planned to be constructed. The junctions will be constructed underground and it will be node connecting with radiating intercity expressways. It also has branches and merges in the underground tunnel (see figure 2 & 3).

Complex structure and safety during a fire
On the deep tunnel on the Tokyo Outer Ring Road, there are 3 junctions and 1 interchange. The Chuo Junction in particular features more complex structures because it connects the expressway with ordinary roads, including the number of lanes changes, steep ramps, sharp curves, and even branches and merging locations, and a toll gate. Table 1 shows part of the specifications of a
ramp tunnel planned for the Chuo Junction. And Figure 4 is an image of the behavior of smoke during a fire on a ramp.
When a fire breaks out inside such a complex tunnel, the behavior of smoke produced by the fire (including heat and gas) changes gradually along with the scale of the fire sources according to the geometrical structure of the fire location, traffic conditions, and the state of operation of the ventilation system. So the users must evacuate quickly and it is necessary to maintain appropriate evacuation facilities and to control smoke to preserve the evacuation environment. In ordinary to appropriately achieve these goals, it is essential to quickly detect the occurrence of fire and to clarify the location where the fire occurs and the behavior of moving smoke. [4]

Table 1 Specifications of representative ramp tunnels

<table>
<thead>
<tr>
<th>Ramp name</th>
<th>A (B-3)</th>
<th>B (A-2)</th>
<th>C (A-5)</th>
<th>D (K-E ON)</th>
<th>E (H-1)</th>
<th>F (H-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1,210m</td>
<td>265m</td>
<td>782m</td>
<td>488m</td>
<td>501m</td>
<td>210m</td>
</tr>
<tr>
<td>Steepest ramp</td>
<td>-6%</td>
<td>-1.4%</td>
<td>-6%</td>
<td>+8%</td>
<td>+6%</td>
<td>+6%</td>
</tr>
<tr>
<td>Radius of curvature</td>
<td>800m</td>
<td>500m</td>
<td>800m</td>
<td>88m</td>
<td>800m</td>
<td>1,000m</td>
</tr>
<tr>
<td>Width</td>
<td>9m</td>
<td>9m</td>
<td>9m</td>
<td>6m</td>
<td>9m</td>
<td>6m</td>
</tr>
<tr>
<td>Lanes</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Shape</td>
<td>Shield + Cut &amp; Cover</td>
<td>←</td>
<td>←</td>
<td>Cut &amp; Cover</td>
<td>Shield + Cut &amp; Cover</td>
<td>←</td>
</tr>
<tr>
<td>Sectional area</td>
<td>59.7 m² 63.3 m²</td>
<td>←</td>
<td>←</td>
<td>43.7 m² 64 m²</td>
<td>43.7 m²</td>
<td>43.7 m²</td>
</tr>
</tbody>
</table>

Figure 4 Example of smoke behavior during a fire on a ramp tunnel

Outline of the development

As stated above, this study establishes methods of quickly detecting a tunnel fire and of clarifying the existence and concentration of smoke. Preconditions for basic experiments to select sensors or confirm their performance in a model tunnel and in a full-scale tunnel were set.

Fire scenario

In the ideal scenario of a vehicle fire shown in Figure 5, when the fire occurrence location is considered to be an engine or vehicle interior, during the initial incubation period of the fire, smoke, CO, CO₂ and other toxic gasses and heat flow are produced. Later, during the fire growth period, in addition to the above, flame and radiant heat are produced. Therefore, quickly detecting a vehicle fire can be realized by detecting smoke, CO, CO₂, other toxic gases and hot air flow.
Existing knowledge
In Japan, as a fire suppression system in a tunnel fire, studies on water spray systems were started. At the same time, the development of fire detection equipment was proceeded so that they can spray water to the fire sources accurately.

Figure 5  HRR change of an ideal vehicle fire, added to [5]

At that time, features considered to be needed were that, (1) regardless of the wind direction and wind speed, at first, the detector closest to the fire source should detect and that water can be sprayed at the fire source and two sections downwind, (2) their structure is simple and durable and (3) they detect a model fire in a short period of time.

Later flame detection type of fire detectors were developed based on the results of various experiments, and flame detection type of fire detectors are now installed as standard equipment in road tunnels in Japan.

Table 2  Outline of sensors

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Object detected</th>
<th>Detection principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoke sensor</td>
<td>Smoke</td>
<td>Scattered light detector</td>
</tr>
<tr>
<td>Laser gas sensor</td>
<td>Smoke, CO, CO₂</td>
<td>Measure the concentrations by observing the changes in light intensity according to optical absorption spectrum of the specific substance after propagating visible light and infrared light into air. Measure the average density in the air along with optical path.</td>
</tr>
<tr>
<td>Photodiode sensor</td>
<td>Smoke</td>
<td>Illuminance (lighting level) measurement</td>
</tr>
<tr>
<td>Cs densitometer</td>
<td>Smoke</td>
<td>Measurement of opacity by comparing optical transmitter with receiver</td>
</tr>
<tr>
<td>Fire detector (standard)</td>
<td>Flame</td>
<td>Detection of specific flame spectrum (for comparison)</td>
</tr>
</tbody>
</table>

Selection of detection methods
Flame detection type fire detectors cannot detect smoke or toxic gases produced accompanying smoldering, which is the initial stage (incubation stage) of a fire shown in Figure 5. Therefore, we focused on the detection of fire in the incubation stage based on elements other than smoke
and the detectors shown in Table 2 was selected. Laser gas sensors in particular, measure the concentration of gas, but can also measure smoke concentration based on the attenuation of laser light, so it is expected that they can be applicable to fires in electric vehicles and in next generation fuel vehicles which will increase in the future. [7], [8], [9], [10], [11]

**EXPERIMENT PLAN**

In order to see if the selected sensors can detect smoke generated from a fire, two experiments were conducted. In the first experiment, the pre-experiment (steady state) was performed using a model scale tunnel to check if the selected sensors can measure the smoke density generated from different types of fuels. For laser gas sensor and photodiode sensor in particular, the experiment focused on whether they can detect the smoke or not. The second experiment (unsteady state) was performed using a full scale tunnel to see if the selected sensors can detect the smoke density which was changing with every moment.

**Model tunnel experiment**

Confirmation experiments were performed to confirm whether or not the selected sensors can detect the existence of smoke and measure its concentration. The experimental apparatus was a rectangular model tunnel of 0.6 m in height, 0.6 m in width, and 10 m in length, made of calcium silicate boards and it was installed in a laboratory. Ethanol, n-heptane, and kerosene were burned inside the tunnel, filling it with smoke, and the state of detection by the sensors was confirmed. The quantities of the fuels were varied to fill the model tunnel with smoke at differing concentrations to confirm the ability of the sensors to measure the smoke concentration. And an experiment case was added to confirm the state of response of sensors to smoke produced by smoldering wood. Figure 6 is a schematic diagram of the experiment apparatus and Table 3 shows the experiment cases.

**Table 3**  Model experiment cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Fuel</th>
<th>Quantity burned: ml</th>
<th>Gross calorific value: MJ/kg</th>
<th>Sensors used</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ethanol (D = 0.1m fire pan)</td>
<td>5</td>
<td>30</td>
<td>Smoke sensor Laser gas sensor Photodiode sensor Standard Cs sensor</td>
<td>After filling the tunnel with smoke and measuring the smoke density etc., open the tunnel door and suck out smoke (use Fan) Both portals of the tunnel were closed during combustion</td>
</tr>
<tr>
<td>2</td>
<td>Ethanol (D = 0.1m fire pan)</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Ethanol (D = 0.1m fire pan)</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Ethanol (D = 0.1m fire pan)</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>n-Heptane (D = 0.1m fire pan)</td>
<td>5</td>
<td>46</td>
<td>Laser gas sensor Photodiode sensor</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>n-Heptane (D = 0.1m fire pan)</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>n-Heptane (D = 0.1m fire pan)</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>n-Heptane (D = 0.1m fire pan)</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Kerosene (D = 0.1m fire pan)</td>
<td>5</td>
<td>46</td>
<td>Standard Cs sensor</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Kerosene (D = 0.1m fire pan)</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Kerosene (D = 0.1m fire pan)</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Kerosene (D = 0.1m fire pan)</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Smoldering (Wood)</td>
<td>-</td>
<td>16 (15 % water)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experiment results and discussions

Figure 7 to 11 show the results of experiment case 8. Smoke sensors could not obtain useful values because there was almost no wind in the model tunnel, smoke could not penetrate their measuring part inside the sensor. Windless conditions inside an actual tunnel cannot be expected and specifications of equipment describes that wind speed should be at least 1.5m/s. Therefore, it was decided to use the wind speed in the case that there is wind in full-scale tunnel experiment.

Figure 7 shows the measured values of the Cs concentration with time measured by the standard Cs sensor and Cs concentration based on the attenuation of the laser measured by the laser gas sensor with time. A comparison of the results obtained by the standard Cs sensor and laser gas sensors shows that although the Cs values differ, the change of the Cs value tends to conform and that it is possible to detect the event.

Figure 8 shows the changes in the converted value from voltage ratio into Cs concentration of the photodiode sensor with time. The conversion to Cs concentration was made by the Lambelt-Beert equation using the voltage ratio and $L=0.375\text{m}$, which is the distance between the photodiode sensor and the light source. It shows an agreement with the result in Figure 7 and that it is possible to detect the event.

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**Figure 6** Schematic of the model experiment apparatus

**Figure 7** Comparison of experimental results of standard Cs sensor and laser gas sensor

**Figure 8** Experiment results of photodiode sensors
Figure 9 shows changes in CO concentration with time, and Figure 10 shows changes in CO2 concentration with time. Similarly, it shows a trend which conforms to the change over time in Figure 7 and that it is possible to detect the event.

Figure 9  CO concentration results  
Figure 10  CO2 concentration results

Figure 11 shows dispersion of the converted value of Cs concentration by the laser gas sensor and the values measured by each sensor during the time span of a quasi-steady state (480 to 780 seconds). Some scattering of the photodiode sensor and CO concentration are seen, but high correlation of the standard Cs concentration and CO2 concentration can be confirmed.

All sensors showed a reaction to smoke that filled the tunnel, and similar trends in change over time, so it can be stated that it is possible to detect the existence of smoke.

Figure 11  Results of testing of each sensor and confirmation of state of dispersion by standard Cs gages
Issues facing the full-scale tunnel experiment

Issues for experiment in a full-scale tunnel were summarized because the model experiment clarified fixed trends in the measurement of the existence of smoke and smoke concentration for each sensor.

- It is necessary to decide where to install each sensor in a large space. It is necessary to install sensors in the transverse and longitudinal directions in the top part in order to locate them considering the movement of the flow of heated air, and also necessary to decide the direction of the measurement according to the characteristics of each sensor. And their locations must also be decided considering future instrument maintenance.
- It is necessary to strictly decide measurement locations because only 3 laser gas sensors and 3 smoke sensors can be provided.
- It is necessary to determine standards to judge the fire from the values measured by each sensor.

A full-scale tunnel experiment plan was proposed considering these issues.

Full-scale tunnel experiment

A 700 m long full-scale experiment tunnel with cross section of 57 m² (concrete) owned by the national government was used to confirm the state of detection and state of measurement of smoke concentration for each sensor while producing smoke and performing combustion simulating those of an actual fire. In addition to cases where fuel was ignited to produce flame, in an experiment case, smoldering was also reproduced to clarify the state of detection for each sensor. The fire pan used for ignition was a 1 m² fire pan, the fuel was n-heptane, which is used as substitute fuel for gasoline during combustion experiments, and a smoke candle was used to reproduce smoldering. The smoke production rate of smoke candle used in the tests is approximately 0.9 g/s per candle. 5 smoke candles were used at the same time in the tests, thus the smoke production rate is approximately 4.5 g/s [12]. The wind speed inside the tunnel was set and 0 m/s and 2 m/s. In the case of 0 m/s, the experiment was done with the shutters at both portals closed completely, while in the 2 m/s case, it was done using a jet fan with its rotation speed controlled by an inverter in order to maintain the wind speed at a constant level. And at the same time, the state of detection of fire sensors installed as standard equipment in Japan was clarified, the state of response until fire occurrence detection was compared, and a thermocouple was used to evaluate the hot air flow. Figure 12 is a photo of the experiment apparatus, Figure 13 is a layout of the sensors inside the experiment facility, and Table 4 shows the experiment cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Equipment used</th>
<th>Heat release rate</th>
<th>Wind speed</th>
<th>n-heptane</th>
<th>Smoke candle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 m² fire pan</td>
<td>2.5 MW</td>
<td>0 m/s</td>
<td>10 min. combustion (46ℓ)</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>2 m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1 m² fire pan + smoke candle</td>
<td>2.5 MW</td>
<td>0 m/s</td>
<td>Used at same time as ignition</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1 m² fire pan + smoke candle</td>
<td>2.5 MW</td>
<td>0 m/s</td>
<td>5 min. combustion (23ℓ)</td>
<td>Used before ignition</td>
</tr>
<tr>
<td>5</td>
<td>(reproduces vehicle fire)</td>
<td></td>
<td>2 m/s</td>
<td>Ignited 5 min. after smoke produced in smoke candle</td>
<td></td>
</tr>
</tbody>
</table>
Figure 12  Photo of experiment facility

Figure 13  Layout of sensors in the full-scale tunnel

EXPERIMENT RESULTS AND DISCUSSIONS

Figure 14 to Figure 20 show results for experiment case 2. Figure 14 shows the results of measurements by standard Cs concentration sensors (LED light source) installed at points 1 to 9 on the center of the tunnel near the ceiling. With ignition time considered to be 0, the fire burned
out at 798 seconds, or about 13 minutes later. It clarified the reaction time delay of sensors according to their distance from the fire pan and the fall of smoke concentration caused by the diffusion of the smoke. It revealed that after the burned out, a 2m/s wind continued to blow the smoke downstream so that the smoke concentration fell, but smoke was also backlayering so that the smoke concentration increased again.

Figure 14 Results of measurements by standard Cs sensors (case 2)

Figure 15 Results of measurements by smoke sensors (case 2)

Figure 15 shows the results of measurements obtained from smoke sensors installed at point 2 (SIG-1, 10m downstream from fire source), 4 (SIG-2, 20m downstream from fire source), and 6 (SIG-3, 40m downstream from fire source). The vertical axis shows smoke density in the graph, and it can be expressed as follows:

$$1 \text{ (mE/m)} = 0.001 \text{ (1/m)}$$  \(1\)

where, E is the Extinction coefficient.

The values measured by the smoke sensors were low at a location closest to ignition. It is assumed that the smoke sensors were installed at a high location close to the lighting fixtures on the tunnel wall surface, or that the smoke produced from the fire source inclined under the impact of the longitudinal wind speed, and at point 2 in particular, the smoke did not reach the smoke sensor because it was too close to the fire source, but the smoke did reach points 4 and 6 downstream. Under the Switzerland tunnel safety standard, the smoke concentration defined as a fire is 20 mE/m, but about 30 seconds after ignition, the standard concentration was reached. On the other hand, after the fire source burned out, the increasing in smoke concentration again caused by the smoke going downstream was not observed. This is assumed to be a result of the fact that the smoke that flowed back upstream was higher than the smoke sensors or that it flowed downstream in the center of the tunnel.

Figure 16 shows the results of measurements by the laser gas sensors in the transverse direction of the tunnel. The Cs concentration converted from the CO₂ concentration is low, but measurements using laser light with varying wave length obtained values almost identical to those of the Cs densitometer which is the standard. This probably occurred because these sensors are installed at low positions, so the increasing in Cs concentration caused by the smoke going downstream was not observed.
Figure 16 Results of measurements in transverse direction of tunnel by laser gas sensors (Case 2)

Figure 17 Results of measurements by Cs densitometers installed near laser gas sensors (Case 2)

Figure 17 shows the results of measurements by Cs densitometers with halogen light sources installed at the same locations as the laser gas sensors. The laser gas sensor and N_CS2 shown in Figure 16 were installed at identical locations and their measurement results generally conformed. This shows that using laser gas sensors selected primarily to measure toxic gas concentration can simultaneously measure smoke concentration.

Figure 18 shows change over time of the voltage ratio, which is the output of the photodiode sensors installed at points 5, 7, and 9. In the full scale tunnel experiment, the light source and photodiode sensor were not one-on-one. Since the changes in the lightness of a surrounding environment (transparency/scattering light) was observed, the voltage ratio is shown in the vertical axis. Regarding the behavior of the output voltage ratio of photodiode sensors, at points 5 and 7, the voltage ratio rose immediately after ignition. This occurred because presumably under the impact of light from the fire source flame produced immediately after ignition, the later movement of the smoke reduced the quantity of light received, lowering the voltage ratio, with the result that the arrival of the smoke was detected.

Figure 19 shows the results of measurement of the carbon monoxide concentration measured by the laser gas sensors. In this experiment, the maximum carbon monoxide concentration was under 10ppm, the relative concentration was low, and at L-1, the trend was similar to that of change of the relative Cs concentration, but at L-2 and 3, no correlation is observed. However a rise of concentration immediately after ignition was confirmed.
Figure 19 Results of measurements of CO density by laser gas sensors (Case 2)

Figure 20 Results of measurement of CO$_2$ density by laser gas sensors (Case 2)

Figure 20 shows the results of measurements of carbon dioxide concentration by the laser gas sensors. A comparison of the carbon dioxide concentration with the results of measurements of the halogen light source Cs densitometer in Figure 17 shows very similar trends, suggesting that it is possible to detect the existence of smoke by measuring carbon dioxide concentration.

Figure 21 Results of measurements by standard Cs sensors (Case 5)

Figure 22 Results of measurements by smoke sensors (Case 5)

Figures 21 to 27 show the results of experiment case 5. Smoke was produced by a smoke candle to reproduce the initial stage of a simulated vehicle fire at time 0 second, then 360 seconds later, the fire source was ignited and the sensors started to measure changes of the environment inside the tunnel.

Figure 21 shows the results of measurements by the standard Cs densitometers, revealing that they grasped smoke produced by the smoke candle before ignition of the fire source. It confirmed that after ignition of the fire pan, the delay of smoke measurement according to distance from the fire pan, and the increasing in smoke concentration caused by smoke from the smoke candle induced by the fire plume generated from the fire pan. About 600 seconds after ignition, the fire source burned out, and the smoke concentration fell, but smoke that had backlayering was pushed back causing the smoke concentration to recover to its former level.

Figure 22 shows the results of measurements by the smoke sensors. As previously stated, sensors located a certain distance from the fire source grasped smoke from the smoke candle and smoke after ignition, revealing that the smoke reached 20mE/m in about 30 seconds.
Figure 23 and 24 show the values measured by the laser gas sensors and the halogen light source Cs sensors. A comparison between the smoke concentrations reveals that large and small differences in measured values occur, but that smoke from the smoke candle and smoke during combustion of the fuel were grasped.

Figure 23 Results of measurements in transverse direction of tunnel by laser gas sensors (Case 5)

Figure 24 Results of measurements by Cs densitometers installed near laser gas sensors (Case 5)

Figure 25 Results of measurements in longitudinal direction by photodiode sensors (Case 5)

Figure 25 shows results of measurements by the photodiode sensors. Also in this case, the voltage ratio is shown in the vertical axis since the light source and photodiode sensor were not one-on-one. During the time period when it is assumed that the smoke from the smoke candle arrived, the voltage ratio rose above its initial value. The voltage ratio rose above its initial value in this way presumably because the sensors detected light of surrounding lighting fixtures and light produced by the fire source. And the results of measurements made after ignition of the fire source also show repeated unstable hunching, revealing that according to the qualities of the smoke and the surrounding light environment etc., it will be necessary to carry out further investigations of the measurement properties of the photodiode sensors.

The measurements of carbon monoxide concentration shown in Figure 26 are as unstable as in case 2. However only L-2 that was installed at a low location detected smoke, although unstably, after ignition of the smoke candle, suggesting that it is necessary to consider the installation location and properties of the gas to be detected.
Among the measured values of carbon dioxide concentration in Figure 27, carbon dioxide was not detected in the smoke from the smoke candle, but after ignition of the fire source, carbon dioxide was measured as a product of the combustion. It is assumed that the actual smoke of the smoldering fire contains carbon dioxide, so it will be necessary to clarify the properties of detection in large spaces.

![Figure 26 Results of measurements of CO concentration by laser gas sensors (Case 5)](image1)

![Figure 27 Results of measurements of CO₂ concentration by laser gas sensors (Case 5)](image2)

For this full-scale tunnel experiment, flame detection type of fire sensors, which are installed as standard equipment in Japan, were also installed, and fire was detected within 30 seconds after ignition of the fire source. On the other hand, the smoke sensors, laser gas sensors, and photodiode sensors used for this experiment also found the great fluctuation of values after ignition. Therefore, if threshold value and conditions for certifying a fire are set by adding not only values such as concentration but also the change rate etc., the fire detection performance identical to that of fire detectors will be ensured. However, if a smoldering fire is hypothesized, a flame detection type of fire sensor will naturally not detect smoke from a smoke candle. This reveals that smoke sensors, laser gas sensors and photodiode sensors, which detect smoke, can quickly detect the occurrence of a fire.

CONCLUSIONS

The capabilities of smoke and toxic gas detection for each sensor obtained in the model scale experiments are as follows:

Smoke sensors:
- Correct measurements were not obtained since they are originally designed on the assumption that they are used under wind condition.

Laser gas sensors
- Smoke concentration is different from the standard Cs concentration, but there was a high correlation between their trends with time
- For CO and CO₂, there was a high correlation with changes in smoke concentration with time

Photodiode sensors
- The moving average values of Cs concentration converted from PD voltage ratio correlate with other smoke sensors.
- From the results mentioned above, the findings obtained by the full-scale tunnel experiments conducted to identify the further characteristics are as follows:

**Detection of Smoke**

**Smoke sensor**
- If a sensor was located too close to the fire source, it could not measure since the smoke did not reach it in some experiments.
- They detected smoke from smoke candle (low temperature, white smoke) and from n-heptane combustion (high temperature, black smoke) very well.
- Comparison with the measurement by Cs densitometers (measurement method is different) was not conducted. However, the trend conformed to each other.
- After the fire burned out, the smoke going downstream was not observed since it was installed at low position.

**Laser gas sensor**
- The measurement from standard Cs densitometers approximated that from halogen light source.
- After the fire burned out, the smoke going downstream was not observed since it was installed at low position.
- They can detect well smoke from smoke candle and from fire pan.

**Photodiode sensor**
- For smoke from fire pan, voltage ratio was registered more than 1 at the same time as ignition.
- After that, the voltage ratio went down to below 1 since the smoke was going downstream. So, the sensors could detect the existence of smoke.
- For smoke from smoke candle, voltage ratio increased significantly more than 1 since lighting source reflected on white smoke.
- Smoke detection characteristics seemed to be influenced by the light from fire source or lighting source depending on the location of installation and smoke characteristics (location, white or black smoke).

**Flame detectors**: These could not detect any fires by smoke from smoke candle. However, they can detect flames from fire pan quickly.

**Gas detection**

**Laser gas sensors**
- For CO, they can detect immediately after ignition although the concentration was low and unstable.
- For CO₂, they can not detect smoke from smoke candle. However, they can detect after fire pan was ignited.
- For CO and CO₂, their measurement were different from each other depending on the location of installation.

**REMAINING ISSUES & FUTURE ACTIVITIES**

It has been learned that the sensors used for this experiment can detect the existence of and concentration of smoke, and that laser sensors can detect toxic gas. However excluding smoke
sensors, it is necessary to study initial state of a fire and detection characteristics of sensors and cases where threshold values settings etc. are used as sensors. It was confirmed that laser sensors and photodiode sensors can detect smoke, but it is necessary to specify acceptance criteria to judge fires (abnormal situations). In cases where they are used in road tunnels, it is necessary to reproduce the hot air flow by CFD to propose the sensor layout plan, and to build a system to apply it to tunnels with complex structures.

Future activities are as follows

- Hot air flow will be reproduced by CFD and various case studies will be conducted.
- The layout of sensors will be decided considering the configuration of equipment and maintenance needed in tunnels.
- The ventilation equipment configuration and system to control the spread of smoke in tunnels with complex structures will be considered.
- Evacuation scenarios that ensure safe evacuation environments will be considered.
- A ventilation control algorithm matched to the evacuation scenarios will be developed.

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Development and Application of a Software System on Tunnel Fire Dynamic Early-warning, Evacuation and Rescue Technology*

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ABSTRACT

Tunnel fire has attracted extensive attention due to its heavy casualties and property losses. This paper introduces the design and implementation of a dynamic early-warning, evacuation and rescue system (DEERS). The DEERS aims to break through the limitations of current fire detecting and alarming system for road tunnels and to provide more useful support to fire fighting, rescuing and evacuating. The DEERS does not replace any existing system deployed in the road tunnel. However, it can offer helpful supports to people concerned based on processing kinds of information from multiple relevant systems. The DEERS has been deployed and tested in road tunnels in Shanghai, China.

KEYWORD: Tunnel fire safety, fire detection, evacuation, evaluation, rescue

INTRODUCTION

The impact of the fire accident in road tunnels is often much greater than that on open roads. The consequences can be extremely destructive and dangerous as the tunnel is an enclosed space. The dissipation of heat and smoke, access limitations for fire-fighting and rescue operations, difficulty in ensuring safe escape route of the tunnel users from an enclosed space increase the severity of the fire accident seriously[1]. Several major tunnel fires in recent years have resulted in heavy casualties and property losses[2].

In China, the quantity and total length of road tunnels have increased rapidly since the beginning of this century. There are 14,006 operating road tunnels with a total length of 12,684 km in the mainland of China by the end of 2015[3].

According to the requirements of Specifications for Design of Highway Tunnels[4], one of Chinese occupation standards on the road tunnel, road tunnels are classified into five types on the basis of length and traffic volume. All road tunnels which are longer than a specific length are required to be equipped with at least two types of fire detection systems and video cameras.

However, the fire detection systems and video cameras may not be sufficient to fire fighting, rescuing and evacuating in fire accident and there are mainly two reasons.

First, the functions of most fire detecting and alarming systems for road tunnels are very simple.

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Usually, the systems only offer the alarm of fire accident and the deluge zone where the fire has been detected. The length of a deluge zone is normally from 50m to 100m in China. It is too long to locate accurate position of the fire accident. These limited and inaccurate information are not only insufficient for fire fighting, resucing and evacuating, but also may lead a wrong decision for fire rescue operation.

Second, control room managers may not see clearly the real situation in the tunnel in the video because the video camera may be surrounded by thick smoke in a fire accident.

In order to reduce the impact of these problems and offer more support to people concerned, we design and implement a dynamic early-warning, evacuation and rescue system (DEERS) based on the reconstruction method for the source position, length of the inverse smoke-flow layer and cross section temperature distribution of a tunnel fire[5]. The main function of the DEERS is to offer the reconstruction and visualization of fire behaviour in case of a tunnel fire and to provide help for evacuation and rescue efforts in road tunnels. The architecture, input, and output of the DEERS will be discussed successively in this paper. The DEERS for fire safety has been deployed in road tunnels in Shanghai, China.

SYSTEM ARCHITECTURE

Relationship with relevant systems

Usually, a road tunnel consists of finite number of systems and connections among these systems[6]. Typical systems in road tunnels include central control system, power system, fire detecting and alarming system, ventilation system, fire fighting system, emergence call system, lighting system, traffic system, monitoring system, and so on.

The tunnel fire dynamic early-warning, evacuation and rescue system will receive and process information from some of above systems rather than replace any of above systems. Among above systems, fire detecting and alarming system, ventilation system, and traffic system have a closer relationship with the tunnel fire dynamic early-warning, evacuation and rescue system than other systems.

Figure 1 The relationship between DEERS and relevant systems

Figure 1 shows the relationship between the DEERS with relevant systems. The DEERS communicates with the fire detecting and alarming system, ventilation system, and traffic system via the Intranet in the road tunnel.

The fire detecting and alarming system is an essential system for fire safety in road tunnels. Frequently-used technologies for detecting fire in road tunnels include point-type flame detector, line-type temperature detector, image-type flame detector. Since the DEERS works on the basis of temperature data, only the fire detecting system with line-type temperature detector is suitable for the DEERS. According to its work principle, the line-type temperature detector can be classified into
Raman fiber detector, fiber Bragg grating (FBG) detector, etc. In the two road tunnels where we have deployed the DEERS, the fire detecting system both use the fiber Bragg grating detector. The DEERS receives the temperature data directly from the fire detecting system through TCP or UDP, then processes the temperature data into useful information to people concerned. The details of data processing will be introduced in the section Information Output.

The DEERS receives several kinds of information, both the status of fans and environmental parameters, from the ventilation system. Typically, the ventilation system saves the environmental parameters including visibility (VI), CO, NO2, wind speed and direction into the tunnel database. Then the DEERS reads the environmental parameters from the tunnel database on demand.

The traffic system usually provides the volume and speed of the traffic to the DEERS. Like the ventilation system, the traffic system also saves its data into the tunnel database from where the DEERS reads data needed.

A GSM Modem is also connected with the DEERS, which can send short phone message to people concerned when a certain event happens.

**Module structure**

The DEERS consists of two main parts: data engine and user terminal as shown in Figure 2. The main functions of data engine are to execute the operations involved with all kinds of data, and the user terminal mostly provides interactions between users and the DEERS. The data engine also is called the back-end, and the user terminal is named the front-end.

![The module structure of the DEERS](image)

The data engine has six modules which are classified into three layers. The module TCP/UDP Socket and SQL Interface, which belong to the bottom layer, are the interfaces of accessing the Intranet of the road tunnel. The DEERS receives the temperature data from the fire detecting system through the TCP/UDP Socket. The SQL Interface is used for exchanging kinds of data with the tunnel database by the DEERS.

Usually the fire detecting system, who serves as the server, is waiting for the connection request from the clients (e.g. DEERS). The fire detecting system will send a message to the DEERS periodically after the request has been accepted. Once the TCP/UDP Socket received a message from the fire detecting system, it will send the message to the module Message Decoder.

The task of Message Decoder is to disassemble the received messages in order to obtain the desired
data and information. The type and format of messages vary with different fire detecting systems. One example will be introduced in the section Data Input. To the DEERS, the alarming signal and temperature data are the interested data and information in the message from the fire detecting system.

Other two modules in the middle layer of Data Engine are Database Reader and Database Writer which both work based on the SQL Interface. The Database Reader receives the command of query database from the module Data Processor and History Data Query, then convert the command into SQL statement. The SQL statement will be sent to the module SQL Interface and be executed. The result of query command will be fed back to the originator of querying through the SQL Interface and Database Reader. The function of Database Writer is similar with Database Reader, but the directions of their data flows are opposite.

The module Data Processor is a core module of the DEERS. Its main task is to process the data and information from Message Decoder and Database Reader according to the algorithms[5]. The results of processing will be sent to multiple modules to be displayed in charts, or be saved into the tunnel database via the Database Writer.

The module User Terminal consists of seven modules and its main task is to provide the human-computer interaction. Chart Generator can plot the charts of temperature and smoke distribution in the road tunnel based on the information from Data Processor. History Data Query provides an interface to user to query history data from the tunnel database according to chosen conditions. Once special events happens, SMS Sender would send short message to tunnel administrators through the SMS modem. The Log Recorder will save the important operating information of DEERS into the system log file. In Emergence Plan Manager and Facility Manager, system user can manage the information of emergence plan and facilities in the tunnel. The operation advice is a dynamic one because it varies with the parameters of fire accident. In a fire accident, the Emergence Plan would give a set of dynamic operation advices to the people concerned based on the result of Data Processor. System Setting provides three setting dialogues in which user can configure basic parameters of the tunnel, parameters of the fire detecting system, and parameters of the system interface.

**DATA INPUT**

**Types of Input Data**

The DEERS is a compositive information system that receives data from multiple relevant systems, and it doesn’t need any hardware to collect data about tunnel’s environment parameters directly.

The main input data of DEERS include:

1. The temperature values of entire tunnel, and the location of fire accident from the fire detecting system are the essential data of DEERS. Based on the temperature values, the DEERS not only can draw the curve of temperature in the tunnel, but also can plot the smoke distribution in the tunnel. The typical distance between two adjacent collection points of temperature value is 10m. The shorter the distance is, the better effect DEERS will provide to users.

2. The environmental parameters, including the value of CO concentration and visibility, are collected by the ventilation system. The DEERS can calculate whether fans should be turned on and the number of fans needed according to the current environment condition in the road tunnel.

3. The traffic information, including the vehicle speed and the number of vehicle per minute from the traffic system, is used for forcasting when fans should be turned on or off. In road tunnels, the environment condition will vary with the traffic evidently, and therefore the traffic information is useful to the DEERS.
Interface between DEERS and the fire detecting system

The fire detecting system is an important and essential system to DEERS. Since the start of developing DEERS, we have tried to connect DEERS with four kinds of fire detecting systems which can provide the necessary data to the DEERS.

There are three types of interface between DEERS and the fire detecting system. The most popular one is the custom protocol based on TCP or UDP which is defined by the developer of the fire detecting system usually. With the custom protocol, the DEERS receives data directly from the fire detecting system. Nevertheless, the database is an indirect interface between DEERS and the fire detecting system. The fire detecting system saves temperature value and alarming information into the database from which the DEERS queries data continuously. Another type of interface between DEERS and the fire detecting system is the ModBus, a standard industrial fieldbus. However, only few fire detecting system can support the ModBus.

Compared to database interface, the custom protocol and ModBus have the advantage of high efficiency. Once connected with the fire detecting system through the custom protocol or ModBus, the DEERS can automatically and periodically receive data from the fire detecting system rather than send a request to the database or the fire detecting system continuously.

But the custom protocol is defined by the developer of the fire detecting system, the DEERS has to do more coding work to cope with different custom protocols, which is the major shortcoming of the custom protocol.

In Dalian Road Tunnel and East Yan’an Road Tunnel, the DEERS communicates with the fire detecting system through the custom protocol. Figure 3 shows one message sample of the custom protocol used in the East Yan’an Road Tunnel.

```
                  0  7  8  15  16  23  24  31
Beginning Flag(16bits)  Version Number(8bits)  Type of Message(8bits)
                      Length of Body(32bits)
                      Temperature Value 1(32bits)
                      Temperature Value 2(32bits)
                      ......
                      Temperature Value N(32bits)
                      Gradient Value 1(32bits)
                      Gradient Value 2(32bits)
                      ......
                      Gradient Value N(32bits)
```

*Figure 3  The format of the temperature message in a custom protocol*

Each message consists of two parts: header and body. In figure 3, the message header is highlighted in gray background. The first field of the message header is a Beginning Flag whose length is 16 bits. The Beginning Flag indicates the beginning of a message, and any message without the beginning flag should be discarded. The Version Number, the second field of the message header, shows the version of the custom protocol. The third field, i.e. Type of Message, indicates the type of message and the format of the message body. The Length of Body, the last field of message header, can be used to judge where is the end of the message. The sample message, showed in figure 3, is a temperature message containing the temperature data from the fire detecting system to the DEERS. In
the temperature message, the Length of Body can be used to calculate the number of records the body has. Each record includes two float numbers whose lengths are both 32 bits. One is the temperature value, and another is the gradient value. In the temperature message, all temperature values follow the header of the message and are followed by the gradient values. The body’s length of the temperature message with \(N\) records should be \(N \times 64\) bits.

INFORMATION OUTPUT

The DEERS is a typical decision support system for tunnel fire safety. It processes the data and information from the fire detecting system, traffic system, and ventilation system, then offers more useful information on fire accident in road tunnel to the people concerned including fire brigades, tunnel manager, safety manager, operation manager, control room manager, policemen, etc.

A visualized fire scene

In the normal condition, the DEERS will work in the normal view as shown in Figure 4. The main area in the middle of the normal view shows the real-time temperature values through the yellow curve and the background with gradually changing color. The main facilities in the road tunnel, including fans, escape routes, emergency exits, fire hydrants, water sprays, etc., are also shown in this area. And all alarm and failure information will be listed in the list box in the bottom-center of the normal view.

![Figure 4 The normal view of the DEERS](image)

Once a fire accident happens, the DEERS will switch automatically to the fire view as shown in Figure 5. The fire view, one of the main highlights of the DEERS, shows a visualized fire scene with the fire location, the variation of fire heat release rate (HRR), the temperature variation, the smoke flowing, etc. And more importantly, the visual smoke flowing in the fire view can help operators in the control room know the status of fire field which couldn’t seen through monitor cameras due to the dense smoke in the fire zone.

The two blue bars show the visual smoke flowing from two perspectives. The upper bar is a top view, and the bottom bar is a side view. In the top view, the smoke flowing is plotted with a gradually changing gray rectangle. It means the corresponding area in the tunnel has obvious smoke. Similarly, the side view shows that the smoke gathers in the upper half of the tunnel. Combining the top view and the side view, operator can know the range and altitude of smoke flowing in real-time.
There are two floating panels, the left and small one shows a chart with the HRR and the highest temperature value. The right one shows the action guides for the emergency situation.

A dynamic emergency action guide

In order to cope with the fire accident rapidly and effectively, the administration of the road tunnel usually formulated a set of emergency plans which guide the actions of the people concerned in the emergency situation. However, the action guides in the emergency plan are static and changeless, and it may not be adaptive and effective to all the fire accidents. In the DEERS, the action guides of the emergency plan are dynamic and adaptive according to the real fire situation in the road tunnel. The DEERS will give the control room manager advices on how passengers can be evacuated from the tunnel, which fans should be powered on, and so on.
APPLICATION IN SHANGHAI ROAD TUNNELS

The Huangpu river divides Shanghai into two areas, Pudong and Puxi. A large number of bridges and road tunnels have been built to connect Pudong and Puxi. In Shanghai, there are 18 operating road tunnels which vary from 1.7km to 8.95km in length [7]. Fourteen of the tunnels pass through the bottom of Huangpu river as shown in Figure 6.

We chose Dalian Road Tunnel (2.5km in length,) and East Yan’an Road Tunnel (2.2km in length) as testbeds for the DEERS. We also carried out a fire test at the Dalian Road Tunnel as shown in the Figure 7. And the Figure 5 shows the results of this fire test in DEERS.

![Figure 7: The fire test in Dalian Road Tunnel, Shanghai](image)

There are two fibers deployed on the tube roof of the Dalian Road Tunnel. The fiber in the east tube have 168 FBG detectors, and the fiber in the west tube have 165 FBG detectors. The spatial distance between any two adjacent FBG detectors is 10m. The fire detecting and alarming system collects the temperature value of FBG detectors each second and sends them to the DEERS.

![Figure 8: The temperature change around the fire place](image)

In the fire test in Dalian Road Tunnel, we used a fire pan whose size is 80cm length × 80cm width × 10cm height. The fire pan was placed on the centre of the left lane where is about 435m far from the entrance of west tube. The bottom of fire pan was covered with a layer of water which was 3cm in
depth. As the fuel for the fire test, 1.5L diesel oil was poured into the pan.

The fire test started at 0:37:30, lasting about 9 minutes and 30 seconds to 0:47:00. Figure 8 shows the temperature change of five FBG detectors close to the fire place. The red label ① marks the firing time of the test, i.e. 0:38:00. At 0:38:27, marked with Label ② in the figure 8, the DEERS received the fire alarming message from the fire detecting and alarming system. The fire was extinguished by operator work at 0:39:48, marked with Label ③ in the figure 8. During the fire test, the highest temperature value collected by all FBG detectors is 44.5 ℃ from FBG detector #44.

FUTURE WORKS

On the basis of application and testing of the DEERS system in more road tunnels, more new functions in the next versions of DEERS are to be expected, which may include mobile terminal, message multicasting, etc.

REFERENCES

Numerical study of smoke and heat detection on a moving train

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ABSTRACT

The majority of tunnel fire detection studies have involved static fires and fixed fire detection systems. The ability of fixed systems to detect fires on moving vehicles is currently unknown. A numerical model was built in FDS to investigate the capabilities of heat and smoke detectors with regard to moving fires. The scenario modelled was a two carriage train in a square section tunnel. Most of the simulations concerned a 3 MW fire. The considered smoke and heat detection systems could not detect this 3 MW fire at typical running velocities. At slower velocities the fire became detectable. However, it was shown that smoke detection systems may prove more useful than heat detectors at identifying small fires on moving trains.

KEYWORDS: fire detection, smoke detection, CFD, rail tunnels

INTRODUCTION

Fire detection underlies all other aspects of fire strategy for vehicle tunnels. Until a fire is detected (and, in some cases, confirmed), emergency procedures cannot be initiated; the ventilation system will remain operating as normal, the vehicles will carry on moving as normal, and the emergency responders will be oblivious to the incident. Early response, therefore, relies on early detection.

Detection systems may be fixed installations in the tunnel, or they may be fixtures on the vehicles themselves. As tunnel operators often have limited control over the systems and maintenance of vehicles passing through their tunnels, the primary means of detection of fire in transport tunnels is often using fixed installations. However, the ability of such systems to detect fires on vehicles which are moving is currently untested.

REVIEW OF TUNNEL FIRE DETECTION RESEARCH

Fires are sources of heat, light, various gases and particulate soot. Fire detectors generally aim to identify a fire by monitoring the levels of one or more of these characteristic features. A positive detection is generally triggered if the monitored quantity rises above a certain threshold value, or rises sharply in value within a predefined time period. However, there are other sources of heat, light, gas and particulates in vehicle tunnels (most importantly, the vehicles themselves!), so a detection system must be able to reliably distinguish between fire events and non-fire events. Typical tunnel fire detectors include: spot and linear heat detection systems, ionisation and photoelectric smoke detectors, flame detectors (i.e. detectors of UV and IR radiation), carbon monoxide detectors, and video-based fire detectors [1]. A number of experimental test series have been carried out in recent years to investigate the capabilities of tunnel fire detection systems in tunnels. Their findings are briefly summarised here.

A series of large scale fire tests were carried out in the 2nd Benelux tunnel in the Netherlands in 2000/01 [2]. The conclusions relating to linear heat detection systems were: that such systems were able to detect a slow growing fire only if the tunnel airflow was below 1 ms\(^{-1}\); that it was possible to
detect a fast growing fire within 3 minutes, irrespective of airflow; and that airflow tended to reduce the location accuracy of such systems.

A series of detection tests was carried out in the Runehamar tunnel in Norway in 2007, investigating linear heat detection systems and spot smoke detectors [3]. The conclusions include: rate-of-rise linear heat detectors worked well for open pool fires, but not well for car fires; smoke detectors worked better for car fires.

The most comprehensive study to date was carried out by the Fire Protection Research Foundation and the National Research Council of Canada at Carleton University and in the Carré-Viger Tunnel, between 2003 and 2008 [4]. The conclusions included: longitudinal airflow hinders detection using spot detectors and linear systems; fires under vehicles take longer to detect; longitudinal ventilation reduces the location accuracy of linear systems; spot heat detectors were unable to identify fires smaller than 1.5 MW; flame detectors are not good at identifying partially covered fires; flame detectors are good at identifying small but unobstructed fires; smoke detectors good at identifying pool fires, and longitudinal ventilation may help detection as more smoke is produced; optical flame detectors were able to detect a small, moving fire; other systems were not able to detect a moving fire.

A series of fire tests were carried out in the Tornskog and Northern Link tunnels in Sweden in 2013/14 [5]. Some conclusions from this study are: both flame and smoke detectors respond quickly to a 0.5 MW fire subject to a 6 ms\(^{-1}\) airflow; flame detectors can identify a fire up to 60 m away; smoke detectors 100 m away from the fire can still detect it; video and smoke detector systems identified a 0.5 MW fire in less than 90 s; the linear heat detection system was able to detect a 2.5 MW fire within 90 s.

Finally, a series of 13 fire tests were carried out in the Eastbound Mount Baker Tunnel in Seattle, USA in 2013 [6]. These tests investigated the capabilities of video fire detection, spot and linear heat detections systems. It was found that: in general, video detections systems performed faster than heat detectors; video systems are slower at detecting shielded fires, but still manage it; and all tested systems were able to detect fires within 90 s.

The primary conclusions of all the above discussed test series are that fixed fire detection systems are able to identify static fires with reasonably acceptable accuracy in acceptable timescales. However, the majority of the tests above give no information regarding the capabilities of fixed fire detection systems at identifying moving fires. Only two tests in the Carré-Viger Tunnel give any information in this regard and they are limited to being very small, unobstructed fires, moving over a short distance.

It is clear that the current state of knowledge with regard to tunnel fire detection systems cannot adequately answer the crucial question: “How big does a fire on a moving vehicle need to be to be detectable by a fixed detector?” As discussed, there is hardly any literature regarding experimental testing of detection systems for moving fires, so this question has not been answered experimentally. In this study we present a first attempt to answer this question using numerical modelling.

**SCENARIO OF INTEREST**

It is clear from the literature review that most of the research effort into detection of fires in tunnels has been directed towards road tunnels. This is perhaps not surprising as fires in road tunnels are more common than fires in rail tunnels [7]. However, generally when a fire breaks out on a road vehicle it is observed (i.e. detected) by the driver of the vehicle fairly rapidly, the incident vehicle is stopped quickly, and the tunnel operator is made aware of the stopped traffic (and hence the fire) in a matter of moments. This sequence may not apply in rail tunnels where the driver of the train could be far from the fire location and unaware of it for many minutes. For example, in most of the various fire incidents which have occurred in the Channel Tunnel [8,9,10], the first detection of the fire came from a fixed installation in the tunnel, and it was the tunnel operator who notified the train driver about the fire. Of course, many modern trains are equipped with on-board fire detection systems,
however these are not the subject of the current study. Also, if a fire starts externally on a train with fire detectors inside the carriages, it may take a considerable time for the fire to break into the carriage before it can be detected by the on-board systems.

The scenario of a fire on a moving train relies much more on the capabilities of the fixed detection system than most road tunnel fire scenarios. Thus, our primary focus in this study is to investigate the capabilities of fixed installations in detecting fires on moving trains. Due to the modelling method employed, as discussed below, it is not currently possible to investigate the capabilities of flame or video based fire detection systems, although such systems show promise in detecting moving fires. The focus of this investigation will be a comparison of smoke and heat detection systems.

**CFD MODELLING**

A simplified train in tunnel scenario was modelled using Fire Dynamics Simulator v6.5.3 (FDS) [11]. As the focus of this study is on detection, and is essentially a comparison between two detection methods, not on specific tunnel applications, an idealised square tunnel section was chosen, and a simple cuboidal ‘train’ was used, as shown in Figure 1, below.

![Figure 1](image)

**Figure 1** Part of the modelled domain, containing the simplified train model.

The modelled tunnel was 6 m high, 6 m wide and 1000 m long. The train modelled in most simulations consisted of two carriages, 4.5 m high, 3 m wide and 20 m long. The front carriage had an additional 4 m long sloping nose, to simplify the airflow over the train. In each simulation, the fire was modelled as being in a 1 m gap between the two carriages. (Some simulations were also carried out using a longer train with four carriages, but it was found that the longer train resulted in more favourable detection conditions, thus the two carriage case is more conservative, so the four carriage simulations are not described here, for reasons of brevity.)

While current computational fluid dynamics (CFD) models are able to model flow around objects moving through a computational domain, using a ‘sliding mesh’ technique [e.g. 12], the complexity of such models was not deemed necessary for the current project. Also, as far as we know, the sliding mesh technique has not yet been used with a CFD fire model, and is not currently possible in FDS. Thus, we decided to keep the train stationary in the modelling domain and ‘move’ the detector through the domain, selecting airflow velocities to be equivalent to those experienced by a moving train.

Rather than model a discrete (and moving) detector in the domain, a sequence of detector points, with 1m spacings, along the entire ceiling of the model was included in each simulation. While these detection points are static, the conditions a ‘moving’ detector would be exposed to can be calculated by interpolation between the detector points, taking into account the supposed speed of the train and the imposed airflow in the domain. Provided it can be assumed that the heat and smoke detectors protrude slightly into the tunnel environment, and are not flush with the wall, the effects of modelling the ‘wrong’ wall boundary condition (i.e. the wall should be moving, relative to the train, but it is modelled here as static) should be negligible, as will be discussed. Figure 2 shows a schematic of the real situation, the ideal model, and the model assumptions actually used. (The assumption that the airflow is approximately half the train velocity is based on the author’s experience with (unpublished) flow measurements in a few tunnels. This approximation is deemed sufficient for this project.)
Figure 2  The case modelled: (a) reality, (b) the ideal model scenario, with the frame of reference fixed on the train, and (c) the actual scenario modelled.

In the FDS model the default values of the turbulence parameters were used, the fuel was modelled as heptane, with a default soot yield of 0.015 kg/kg (note, some sources have experimentally determined the soot yield to be as much as 0.037 kg/kg [13], but the default value is retained in this study for simplicity as it is the comparison between simulations that matters, not the absolute values), and the walls were initially modelled as smooth, although this assumption was investigated as part of the study, as will be discussed. Various different mesh sizes were investigated and compared, in accordance with good modelling practice. It was found that a cell size of 0.125 × 0.125 × 0.125 m was required around the fire region for accuracy, but a larger mesh of 0.25 × 0.25 × 0.25 m was acceptable for the far field.

For each simulation, the temperature and optical density (OD) values calculated by the model were extracted and combined to provide an estimate of the gas conditions at the location of the assumed (ceiling mounted and moving) detector. Figures 3 and 4 show typical results for temperature and OD for a 3 MW fire, assumed to be moving at 10 ms⁻¹, that is, with a flow of about 5 ms⁻¹; ambient temperature is taken to be 20°C.

Figure 3  Gas temperature at detector location for a 3 MW fire on a train moving at 10 ms⁻¹.
ESTIMATING RESPONSE OF SMOKE AND HEAT DETECTORS

The FDS models provide temperature and smoke density predictions, for various fire scenarios, at a sequence of locations along the computational domain. The question remains how realistic detectors would respond to such conditions. Real, physical detectors have physical properties that need to be considered when assessing their capabilities. Specifically, the heat detecting elements of heat detectors need some time to heat up before they can signal an alarm. Similarly, most smoke detection systems feature some sort of cavity that must be filled by the smoky air before they trigger an alarm.

In this study we used the RTI method proposed and developed by Nam [14,15], and mirrored in NFPA 72 [16], for the heat detector calculations. Optical density thresholds for the smoke detectors are based on the work of Geiman & Gottuk [17]. The consideration of a ‘critical velocity’ for the airflow required to drive smoky air into a detector [18] are largely irrelevant for the tunnel environments considered here, as the ventilation flows are always significantly above the required 0.16 ms\(^{-1}\).

Response of heat detectors

Figure 5 shows the temperature evolution of the sensing element in a heat detector for different assumed RTI values. Comparison with Figure 3 shows that even for the most sensitive element (with an assumed RTI of 8.8), the temperature of the element never rises as much as 4°C above ambient. As such a temperature difference is well within normal daily fluctuations for most tunnel environments, it is clear that a heat sensor with an absolute activation threshold would not be able to detect a 3 MW fire under these conditions.

The other method used by heat detectors is by identifying a sharp rate of rise in temperature. Even if the absolute threshold is not attained, a rate of rise detector can detect a fire if its sensor changes temperature rapidly enough. Figure 6 shows the rate of rise of the temperature sensing element of a typical (but fairly sensitive) detector, compared with a typical rate of rise threshold of 0.15°C/s [15]. It is quite clear that in the case of a 3 MW fire, travelling at 10 ms\(^{-1}\), the temperature sensor never approaches the threshold for detector activation.
Response of smoke detectors

The response of smoke detectors is harder to estimate than the transient heating of a heat detector element. Geiman & Gottuk [17] surveyed published data relating to numerous different photoelectric and ionisation detectors and published OD threshold values corresponding to the activation of 20%, 50% and 80% of such detectors for flaming and smouldering fires. (Smouldering fires will not be considered here.) It has been shown that 20% of ionisation detectors would activate at an optical density of 0.007 m\(^{-1}\), 50% would activate at 0.021 m\(^{-1}\), and 80% would activate at 0.072 m\(^{-1}\). For photoelectric sensors, the values are 0.031, 0.063 and 0.106 m\(^{-1}\). These threshold values are shown in Figure 7, compared to the simulated optical density for the case of the 3 MW fire, travelling at 10 ms\(^{-1}\).
From this it is clear that only the most sensitive of ionisation detectors (i.e. those most likely to return false alarms) would be able to detect a 3 MW fire on a train moving at 10 ms\(^{-1}\).

**Sensitivity to input parameters**

All the results presented above have been for the scenario of a 3 MW fire on a train moving at 10 ms\(^{-1}\), that is, a modelled airflow of 5 ms\(^{-1}\). It is likely that detectors will be better at identifying fires on slower trains. (However, it should be noted that 10 ms\(^{-1}\) is only 36 km/h, which is rather slow for a train in a tunnel.) Simulations were also carried out for trains with a velocity of 4 ms\(^{-1}\) (14.4 km/h) and also for stationary trains. As expected, these scenarios produced results which would be much easier to detect. The stationary train triggered the rate-of-rise detection criterion within 5 s, reached typical absolute temperature thresholds well within a minute, and exceeded the 80% thresholds for both detector types within 10 s. However, the 4 ms\(^{-1}\) moving train proved hard to detect, as the rate-of-rise criterion was never achieved, the maximum absolute temperature of a low RTI sensing element reached a peak of 14°C above ambient within 90 s, and the optical density only (just) reached the 50% photoelectric limit, about 80 s after the train passed.

It was intended to investigate larger fire heat release rates, but the models experienced numerical instabilities at higher heat release rates, and these issues have not been resolved in time for the paper submission deadline. These results will be published in the future.

The largest assumption of the study concerns the influence of the stationary wall on the model outputs. To investigate the dependence of the results on the wall conditions, simulations were carried out using the extremes of wall friction available in FDS, designated the ‘free-slip’ (i.e. no friction) and ‘no-slip’ (i.e. extreme friction, with gas velocities beside the wall forced to be 0 ms\(^{-1}\)). Neither of these conditions can simulate the real situation of the wall moving rapidly with respect to the train, but it is expected that this real situation would not be as extreme as the ‘no-slip’ condition.

The free-slip, smooth wall and no-slip simulation results are compared for gas temperature and optical density predictions, for the standard scenario of a 3 MW fire moving at 10 ms\(^{-1}\), in Figures 8 and 9.
It is clear from the above figures that the ‘free-slip’ condition does not yield results significantly different from the smooth wall model used for most of the simulations presented here, and that the ‘no-slip’ condition, which may be closer to reality, actually results in less favourable detection conditions. However, the differences between the two extremes of friction are not massive, so it is assumed that broadly similar results would have been produced, even if we had modelled the wall as moving relative to the fire.

It should also be noted that heat transfer would be different for a moving wall condition, but as the temperature difference between the gas and the wall is only a few degrees, and convective heat transfer is governed largely by temperature difference, the actual heat losses to the walls are negligible compared to the cooling effect of the diluting inflowing air, so the heat transfer may be neglected.

**Influence of real vehicles**

In the scenario modelled, the fire is the only source of heat in the domain. Of course, in reality, the
locomotive itself would be a source of heat in normal operating conditions. A 4000 horsepower locomotive has a power rating of about 3 MW, and between 30% and 60% of that energy could be ‘lost’ as heat into the tunnel. That is, the normal operation of a locomotive could be thermally equivalent to a 1 to 2 MW fire. This means that thermal thresholds for heat detectors in tunnels need to be set high enough not to be triggered by locomotives in normal operation. This effectively renders heat detectors unable to detect fires until they have become large.

Diesel engines also release a lot of particulates into the tunnel environment, so again, optical detection thresholds have to be set sufficiently high to avoid everyday false alarms. The general trend towards electric trains will eventually allow this threshold to be lowered, but this may still be decades away.

CONCLUDING COMMENTS

As a fire on a train grows, it undoubtedly becomes more detectable. This study set out to answer the question “How big does a fire on a moving vehicle need to be to be detectable by a fixed detector?” Unfortunately, the question remains unanswered. From the simulations carried out it appears that rate-of-rise and threshold heat detectors would struggle to identify fires as large as 3 MW on trains travelling at normal operating velocities. However, it was found that such a fire could possibly be identified by a subset of ionisation smoke detectors, with low activation thresholds.

This study has demonstrated a methodology for assessing the capabilities of heat and smoke detectors in tunnels at detecting moving trains. Unfortunately, given the lack of experimental testing of moving fire experiments, there is no way as yet to validate this method.

It is clear that the question of detection of fires on moving trains is an important and unresolved one. While numerical studies like this one can compare heat detection and smoke detection systems, they are not able to predict the capabilities of optical and video fire detection systems. Such systems may be the future for train tunnel fire detection, but this remains to be seen. Future experimental detection studies must investigate the abilities of different system types for moving fires, and also provide data for validation of numerical methods like this one.

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Blast Wave after Hydrogen Storage Tank Rupture in a Tunnel Fire

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ABSTRACT
Hydrogen-powered vehicles are already on roads including tunnels. The data shows that 35% of CNG vehicle tanks rupture in a fire is due to pressure relief device failure. Rupture of onboard storage tank of hydrogen-powered vehicle in a fire poses a serious threat to life and property. The situation is even more hazardous if the accident takes place in confined space like a tunnel. Consequences of such event, e.g. a blast wave, could be devastating depending on amount of stored hydrogen and tunnel dimensions. To formulate prevention and mitigation strategies the phenomenon should be understood first. This study aims to understand a blast wave dynamics after a hydrogen tank rupture in a tunnel based on a conservative scenario, i.e. tunnel with one of smallest cross-section area and one of the highest amount of onboard hydrogen storage in a vehicle. The results of simulations allow to assess a harm of propagating blast wave on humans in a tunnel.

KEYWORD: Blast wave, CFD model, fire, hydrogen, tank rupture, tunnel

INTRODUCTION
There is a number of safety concerns for use of hydrogen-powered vehicles in a tunnel. One of the main knowledge gaps is a blast wave that can be generated by catastrophic onboard tank rupture in a tunnel caused by fire. It is known that the blast wave generated in a tunnel will propagate along the tunnel practically without decay whatever is the tunnel length [1]. This could have serious safety implications. The regulation requires that each onboard storage tank is equipped by thermally activated pressure relief device (TPRD) to prevent tank rupture in a fire by releasing stored hydrogen. However, a TPRD can fail to function, be blocked from a fire during accident, or be not affected in case of localised fire. Weyandt [2] performed a bonfire test with type 4 tank of 72.4 L volume and storage pressure of 34.3 MPa without TPRD to estimate the blast wave and fireball parameters. This information is of primary interest for public and especially for first responders.

Experiments in full-scale tunnels is unaffordably expensive. The use of CFD eliminates this restriction and allows to use realistic scenarios. Following experimental studies by Zalosh and Weyandt [3], Kim et al. [4] simulated the blast wave and fireball in their test numerically. The realizable k-ε turbulence model was applied and combustion was simulated by the eddy dissipation model. The simulation results reproduce the experimental trends [2], [5]. In 2015 an original theoretical model was developed that allows to calculate parameters of a blast wave from a tank rupture in a fire at different distances in the open atmosphere [6]. In this paper, it was concluded that about 5% of chemical energy of released hydrogen contributes to the blast wave strength through its combustion for a stand-alone tank, and 9% of chemical energy for an under-vehicle tank. The harm to people and damage to buildings from a blast wave was used to assess hazard distances [6].

There are different accident scenarios with hydrogen-powered vehicle in a tunnel. For example, a tank leak can lead to flammable hydrogen-air cloud formation inside the tunnel. This cloud cause serious harm to humans as hydrogen can easily be ignited. Venetsanos et al. [7] considered this scenario in their numerical study. Unfortunately, a catastrophic rupture of high-pressure hydrogen tank in a fire in a tunnel was not addressed up to now. This study aims to address this knowledge gap.
PROBLEM FORMULATION

Model description
All simulations were performed using Fluent compressible solver using Redlich-Kwong real gas equation of state for hydrogen. The realizable k–ε model was used to for turbulence simulation. It is an improved version of the standard k–ε model, it processes turbulent flows with a new formulation of turbulent viscosity and a new transport equation for the dissipation rate. One of the weaknesses of the standard k–ε model lies in the dissipation rate equation. The realizable model satisfies some mathematical constraint on Reynolds stresses while the standard and RNG k–ε model do not. The realizable k–ε is one of the most accurate and reliable RANS model capable to treat efficiently different kind of turbulent flows. The two main changes brought by the model proposed by Shih et al. [8] are the fact that $C_{\mu}$ is no longer a constant and the equation for dissipation rate $\varepsilon$ is now based on the dynamic equation of the mean-square vorticity fluctuation.

The laminar finite rate (LFR) model was chosen to simulate combustion as the one amongst many models that determines the reaction rates of chemical mechanisms involved in the combustion. The effects of turbulent fluctuations at sub-grid scale are not taken into account in this model. The reaction rates are only determined by the Arrhenius kinetic expressions and temperature in a cell. The net source of chemical species $i$ due to a reaction can be computed as the sum of the Arrhenius reaction sources over the $N_R$ reactions, where the species participate in:

$$R_i = M_{w,i} \sum_{r=1}^{N_R} \dot{R}_{i,r}$$

where $M_{w,i}$ is the molecular weight (g/mol) of species $i$; $\dot{R}_{i,r}$ is the Arrhenius rate of creation/destruction of species $i$ in the reaction $r$ (consistent units).

LFR is recommended for turbulent flows where the complex chemistry is employed. This is our case, when the reaction mechanism contains 37 reactions and 13 species [9]. Moreover, Gao et al. [10] investigated the efficiency of the LFR model for supersonic turbulent combustion flows involving hydrogen as a fuel. After comparisons with the experimental studies of Cheng et al. [11] and Burrows-Kurkov [12], it was concluded that the model gave acceptable results for the properties investigated, i.e. mean temperature, mean species concentrations and self-ignition prediction. The blast wave after high-pressure hydrogen tank rupture has supersonic properties.

The Discrete Ordinates model was used to calculate radiation heat transfer [13]. This model is efficient for different combustion problems and covers the entire range of flame optical thicknesses. It allows to calculate radiation for opaque walls, which is a property of all wall in the problem studied. This model solves the radiative transfer equation (RTE) for a finite number of discrete solid angles. Each solid angle is associated with a vector direction $\hat{s}$. The Discrete Ordinates transforms the RTE equation into a transport equation for radiation intensity in the spatial coordinates $(x,y,z)$. It solves as many equations as there are directions $\hat{s}$. The angular $4\pi$ discretisation in polar and azimuthal direction, i.e. Theta and Phi divisions, were resolved by 10 control angles each. The control angle overhang is accomplished by pixilation and each solid angle is resolved by 3x3 Theta and Phi pixels divisions.

In the case of hydrogen fire the combustion products which will radiate is water vapour. The absorption coefficient of the water to compute properly radiation effects using chemical reaction mechanism for hydrogen-air combustion has to be determined. The absorption coefficient was calculated using user-defined function (UDF) that utilized Planck Mean Absorption for water vapour [14]:

$$\alpha_p = k \cdot X_w \cdot p$$

where $\alpha_p$ is the Planck Mean Absorption coefficient of water, (m·atm)$^{-1}$; $X_w$ is the water mole fraction; $p$ is a pressure in the cell, (atm); $k=1.2234 \cdot 10^{7} \cdot T^{-2.1564}$ is the power equation and $T$ is the temperature in the cell (K) used for determination of $k$. This method allows to calculate the water absorption coefficient in any particular cell based on the temperature and partial pressure of water vapour.

Tunnel description
The cross-section of a tunnel depends on several factors. The clearance gauge for infrastructure, ventilation and safety systems, the traffic lanes for vehicles to circulate, which can vary depending on the planned traffic flow, the structural conditions, regarding the ground and the pressures that can be applied on the tunnel. Finally, the cost efficiency of the construction. All above can influence the
dimensions. For a given clearance gauge, the most economic cross-section requiring the least excavation, support technology and the optimal machinery will be applied [15]. Different kind of tunnels exist with different shapes and sizes. Indeed, all tunnels do not have to handle the same amount of traffic so they can be designed differently.

The tunnel with smaller cross-section area presents the higher hazard and associated risks for the same hydrogen storage tank when it ruptures in a fire. By this reason, to get a conservative estimate of harm effects from a blast wave a standard tunnel with the smallest minimum cross-section area was selected for simulations [15]. Maidl et al. [15] report minimum dimensions for a standard solution road tunnels (see Figure 1). The carriageway width is 7.7 m. In simulations the total width of the tunnel to include emergency pavement were chosen 9.0 m. A triangle shaped space was discounted in the rectangle area to calculate tunnel total area. “Two small rectangles” under the verges were also removed from the rectangle area in the simulation domain.

Figure 1 Schematic of a standard solution tunnel [15].

Tunnel length for simulations was determined based on the size of a possible fireball. The method to figure out this distance was inspired by [6]. The onboard hydrogen tank of Honda Clarity 2017 has volume of 140 L and storage pressure of 70 MPa [16]. The mass of hydrogen in the tank is 5.5 kg.

The number of hydrogen moles is \( n = \frac{m}{M} = \frac{5.5 \text{ kg}}{0.002016 \text{ kg/mol}} = 2728.2 \text{ moles.} \) Thus, 5.5 kg of hydrogen would occupy \( 2728.2 \text{ mol} \times 22.4 \text{ L/mol} = 61.1 \text{ m}^3 \) in the atmosphere. The amount of air required for complete combustion of hydrogen can be found from the following combustion reaction: \( 2\text{H}_2 + (\text{O}_2+3.76\text{N}_2) \rightarrow 2\text{H}_2\text{O} + 3.76\text{N}_2 \). This implies that 1 mole of hydrogen consumes \((1+3.76)/2 = 2.38\) moles of air, i.e. \( 2728.2 \times 2.38 = 6493.1 \) moles of air will be needed for the combustion of hydrogen stored in the tank. One mole of released hydrogen creates \((1+2.38) = 3.38\) moles of hydrogen-air mixture. The volume of stoichiometric hydrogen-air mixture that could be created by the amount of hydrogen stored is \( 2728.2 \text{ mol} \times 3.38 \times 22.4 \times 10^{-3} \text{ m}^3/\text{mol} = 206.6 \text{ m}^3 \). The combustion products expansion coefficient for stoichiometric hydrogen-air mixture is \( E_i = 6.85 \). Thus, the volume that would be occupied by the combustion products is \( V_b = V_u \times E_i = 206.6 \text{ m}^3 \times 6.85 = 1414.9 \text{ m}^3 \).

The distance the combustion products volume will occupy can be calculated from the cross-section area of the tunnel, i.e. \( 1414.9 \text{ m}^3 \div 44 \text{ m}^2 = 32.2 \text{ m} \). The tunnel length was chosen to allow enough space for blast wave to propagate and stabilise while keeping the fireball inside the tunnel. The tunnel length in simulations was chosen to be 100 meters, i.e. 3 times longer compared to the length of combustion products after complete combustion of stored in the tank 5.5 kg of hydrogen.

MODEL VALIDATION

Validation experiment
Before application of the CFD model to simulate the tunnel scenario, it was validated against experimental data on the stand-alone type 4 hydrogen tank rupture in the bonfire test in the open
atmosphere [2], [3], [17], [18]. The external size of the tank was 0.84 m in length, 0.41 m in diameter, with internal volume of 72.4 l. The storage pressure was 34.3 MPa at the beginning of the test. The tank was placed 0.2 m above the ground over a propane burner with heat release rate of 370 kW as shown in Figure 2 (left). The tank ruptured in the fire after 6 min 27 sec of exposure. The pressure sensor locations are shown in Figure 2 (right). The measured maximum blast overpressures were 300 kPa, 83 kPa and 41 kPa at distances 1.9 m, 4.2 m and 6.5 m respectively. The maximum diameter of the fireball about was 7.7 m.

![Figure 2](Bonfire test setup (left) and pressure sensor locations (right) [17].)

**Validation of simulations results**

Conditions in simulations were the same as per Weyandt’s experiment [2]. The block-structured hexahedral grid was used with a total number of control volumes (CVs) 371,596. It is shown in Figure 3. About 82% of CVs were located in the fireball zone, within 20 m distance from the tank to provide better resolution nearby the tank.

![Figure 3](The computational domain and the grid: side view of the domain (left), side view of the fireball zone (centre), and the tank boundary wall grid (right).)

The simulation starts with the instantaneous removal of the tank wall. This generates the starting shock propagating outwards. The spontaneous ignition of hydrogen in air was observed in simulation at the contact surface between heated by the shock air and expanding hydrogen. This numerical ignition imitates the ignition in the experiment from the surrounding the tank fire. In reality, the spontaneous ignition observed in the simulations is probably not possible due to finite time of tank wall removal.

Experimental data and results of blast wave decay prediction by analytical model and numerical simulations are shown in Figure 4. The analytical model [6]is the real gas model that accounts for contribution of combustion into the blast wave strength (solid curve). The analytical model reproduces the peak overpressure at distance 1.9 m somewhat higher than in the experiment, however, at distances 4.2 and 6.5 m from the tank the experimental overpressures are reproduced in simulations well same as in analytical model.
Figure 4  Blast wave decay: comparison between experimental [6], analytical [5] and numerical overpressure peaks at different distances.

Figure 5 shows experimental pressure transients (solid black lines) versus simulated ones (dashed grey) at three different locations of pressure sensors. The model reproduces the overpressure dynamics at different distances quite well. The first peak at 1.4 ms is overestimated in simulations by about 60 kPa. This is thought due to the fact that no energy is consumed in the simulation to rupture the tank, to produce projectiles, to destroy burner, and to crater the ground.

Figure 5  Pressure transients at different sensor locations.

The percentage and mass of hydrogen burned was also computed. At about 11 ms after the tank rupture, the blast wave reached the last sensor located at 6.5 m. At this moment 23% of released hydrogen reacted in combustion according to the simulation (see Figure 6). This value is higher compared to the value of 5% of burned hydrogen contributed to the blast wave strength as estimated by the use of analytical model [6]. In fact, there is no contradiction between these two values. Indeed, the CFD model estimated the total amount of burnt hydrogen as 23% of the released (stored in the tank) amount. There is a time lag for sound waves to transfer released energy to the leading front of the blast wave. Contrary to the CFD model, the analytical model estimated the fraction of energy of burned hydrogen, which had time to reach the leading front of the blast and contributed to its strength, as 5% of the released hydrogen.
Figure 6  Amount of hydrogen burned as a function of time after rupture.

The mass balance of hydrogen in calculation domain was controlled during the simulations. It is an important factor to check, as a poor mass balance means that errors in solving conservation equations are occurring. It is normal that mass losses or gain occur due to numerics, however if this value rises significantly, simulation results cannot be considered as reliable. The hydrogen mass disbalance was growing almost linearly down to about –0.2% at 13 ms. Hydrogen was lost in the simulation. This error is considered as negligible to influence the simulation results.

GEOMETRY AND CALCULATION DOMAIN

The geometry and calculation domain utilised to run simulations can be separated into two main elements: inside and outside the tunnel. The overall geometry and the calculation domain are shown in Figure 7.

Figure 7  Computational domain, tunnel and tank geometry and mesh.

The calculation domain is a rectangular prism with length 300 m, width 100 m, and height 75 m filled with a polyhedral grid totalling 79,720 CVs. In the middle of the calculation domain there is a tunnel of sizes $L \times H \times W = 100 \times 9 \times 4.5$ m meshed with a hexahedral grid totalling 300,760 CVs. The tank is represented for the simplicity of this scoping study by a hemisphere of 0.81 m diameter with 14,800 CVs. The tank is located at the centre of the tunnel on its floor. Hemisphere diameter was calculated to provide the same volume as for one of the latest tanks with volume 140L and storage pressure 70 MPa. Calculation domain boundaries dimensions were designed to allow sufficient space
outside the tunnel to minimize the effect of boundaries. The authors are in understanding that location of onboard tank under the vehicle at the moment of rupture would decrease the blast wave strength as described in [6]. However, here we look a conservative scenario, which could be considered to some extent as a simulation of overturned vehicle, when the propagation of blast is not hindered by the vehicle body.

**INITIAL AND BOUNDARY CONDITIONS**
Two simulations were performed at the same initial and boundary conditions. The temperature was uniform and equal to 300 K, hydrogen tank was represented by a hemisphere having a volume of 0.14 m³ at a pressure of 70 MPa. The rest of the domain was quiescent air with mass fractions were set as 23% for oxygen and 77% for nitrogen, and atmospheric pressure of 101325 Pa. The tunnel walls were set as no-slip boundaries with no roughness. The calculation domain volume is about 50 times larger than the tunnel’s one. The domain boundaries in the open air have non-reflecting properties.

**NUMERICAL DETAILS**
The pressure-based segregated solver was used to perform all simulations. The gravity effects are taken into account to get as close as possible to realistic conditions, and the value of this acceleration is set as 9.8 m/s². Pressure Implicit with Splitting of Operator (PISO) algorithm was chosen to treat pressure-velocity coupling for a pressure-based solver. Second order upwind was applied for spatial discretisation of density, momentum, turbulent kinetic energy and dissipation rate, species and radiation, while second order was used for pressure. The under-relaxation factors values were defined according to Fluent User’s guide for supersonic flows. The time-step was set as an adaptive due to the change of the flow and blast wave’s velocities. A function was included in the UDF file to automatically determine a reliable time-step based on Courant–Friedrichs–Lewy (CFL) condition, and the CFL number assigned was 0.9. Finally, to use the Discrete Ordinates radiation model, a function was associated in the UDF file to compute the absorption coefficient of water for every cell.

**RESULTS AND DISCUSSION**
To assess the contribution of combustion on the strength of blast wave, the simulations with and without combustion were performed.

**Tank rupture at the centre of the tunnel without combustion**
Figure 8 demonstrates the blast waves propagation along the tunnel. Only left part of the tunnel is shown. At time 0.005 s after the tank rupture, the leading shock reaches tunnel ceiling. At time 0.020 s, the blast wave is strengthened by the second reflection at the tank location. This blast wave had a higher velocity than the first one and they both are combined at 0.060 s after the rupture. The series of blast waves are produced by the third and fourth reflection, and the fourth and fifth ones. They are distinguishable at t=0.060 s, t=0.080 s and 0.100 s. The maximum overpressure remains mainly at the bottom, within 1 m from the tank. The pressure varies by height significantly. At 0.040 s after the rupture, the maximum overpressure at the bottom of the tunnel is higher by about 40 kPa than the rest of the blast wave, but at 0.080 s after the rupture, this difference increases to 80-100 kPa. This difference in pressure by height of the tunnel can have devastative consequences, e.g. to overturn cars and ground people.
Figure 8  Blast wave in the tunnel: central plane cross-section of pressure contours.

Figure 9 shows overpressure transients at height 0.25 m above the ground in the tunnel at different distances with 5 m step. Five peaks can be noticed at 5 m from the tank location at time 7 ms, 19 ms, 45 ms, 65 ms and 114 ms. The first three peaks are "preserved" until 30 m, afterwards they reach the leading shock and it becomes difficult to distinguish them and only the leading pressure wave is noticeable.

Blast front velocity was also analysed at height of 0.25 m (see Figure 9). Dashed line was drawn to connect leading blast front from 5 m to 50 m. The line is passing almost perfectly at every first pressure peak at different distances. This average velocity of the leading blast front is about 400 m/s, i.e. about 50 m/s above the speed of sound in the air.

The distance is an important factor when the blast wave overpressure is estimated. While the blast wave at 5 m from the tank location has a mean overpressure of 100 kPa (with a maximum value at 185 kPa), at 25 m the average overpressure drops to only 50 kPa. At 45 m from the tank position, overpressures did not exceed 25 kPa, the maximum value at 5 m is 7.4 times higher than the maximum value at 50 m as can be seen in Figure 9.
Figure 10 shows maximum overpressure along the tunnel at heights 0.25 m, 1.5 m and 2.5 m. Overpressures at heights 1.5 m and 2.5 m are similar except near field (within 4 m) of the tank. However, overpressure in the blast at height 0.25 m is significantly higher. The reason of this is location of the tank on the tunnel floor level in the considered scenario. Beyond 4 m, the maximum overpressure difference is maximum at distance from the tank between 4 m and 8 m. At distances 8-24 m the maximum overpressure at 0.25 m height is on average twice higher than at 1.5 m and 2.5 m. The difference diminishes starting from 29 m and eventually disappears at 40 m. The overpressure throughout the empty tunnel height becomes uniform and constant at about 25 kPa up to the tunnel exit.

![Figure 10](image)

**Figure 10**  Maximum overpressure with distance at different heights.

**Comparison of blast wave for cases without and with combustion**

The second simulation was performed to include combustion modelling in order to estimate the effect of combustion on the blast wave strength. The ignition modelling were done same to the validation case. Figure 11 shows the maximum overpressures resulting from scenario with and without combustion at the height of 0.25 m, where they are at the highest values. The maximum overpressures are significantly higher close to the tank location in the case with combustion (thin solid line) as expected.

![Figure 11](image)

**Figure 11**  Unignited and ignited cases maximum overpressure comparison at 0.25 m height.

Between 2 m and 4 m distance from the tank, maximum overpressures are about twice larger in the case with combustion than in the case without combustion. Between 4.4 m and 6.4 m, the maximum overpressures from the reacting case are lower than non-reacting ones, this can be explained by a different interference of primary and reflected blast waves for cases with and without combustion.
Again, as expected, after 6.4 m, the overpressures for the case with combustion are higher than without combustion. It can be seen that the pressure is somewhat lower in the case with combustion at distance between 14 and 30 m. However, after 30 m to 40 it remains nearly the same as in case without combustion and after 40 till the end of the tunnel it stays constant without decay at value about 40 kPa which. It is worth mentioning that by time when the blast wave left the tunnel at 125 ms the amount of burned hydrogen is 31% which is resulated in about 50% increase of pressure after 40 m compared to the case without combustion.

Blast wave harm assessment

The tank rupture in the tunnel generates multiple interacting shocks due to reflections from walls, ceiling and floor. The quasi one-dimensional geometry of the tunnel prevents the blast wave decay as compared to the tank rupture in the open atmosphere, when the blast decays quickly due to continuous increase of the blast wave area. In the near field and contrary to the tank rupture in the open, people will undergo a harm from a series of shocks. Then, the more uniform by height blast wave propagates throughout the whole duration of the tunnel without decrease of its peak at distances further than 40 m for the case without combustion and 30 m for the case with combustion. Here, we consider harm effects of blast wave on people present in the tunnel without accounting for any “protecting” effects when people are inside a vehicle, etc. Quotes for “protecting” mean that we cannot estimate whether or not a vehicle will be damaged by the blast wave thus producing secondary harm effect to passengers inside the car. Total impulse of the blast was calculated for every 5 m from the tank location until 50 m at the height of 1.5 m and 0.25 m. Knowledge of overpressure and impulse allows to use the Baker’s harm diagram (see Figure 12 and [6]) to estimate harm to people in the tunnel following the considered here scenario.

The hazard thresholds at height of 1.5 m were studied and shown in Figure 12 (crosses) as it is the closest to the lungs and ears for a standing person. The “fatality” overpressure threshold (horizontal dashed line at 100 kPa) is associated with 1% chance of lung haemorrhage by the blast and “injury” with 1% of eardrum rupture (horizontal dashed grey line at 16.5 kPa). However, these two “simplified” thresholds do not consider the impulse. The “lung damage threshold” curve is more appropriate to estimate the possibility of fatalities. People standing at 5 m from the hydrogen tank are about to reach the fatality threshold. At closer to the tank distances the chance of lung haemorrhage increases drastically. For example, the overpressure at 2 m is 2.5 times larger than at 5 m as can be seen in Figure 10.

![Figure 12](image-url)  
*Figure 12  The blast pressure and impulse at 0.25 m (crosses) and 1.5m (triangles) heights, [6].*  
From 10 m to the end of the tunnel, people will have injuries, in particular, their eardrums will
rupture. There is no “no harm” zone in the tunnel. All humans in the tunnel would be are exposed harm in the form of fatality of serious injury.

For different reasons people may lay or sit on the ground after an accident occurs, whether in the case where victims are injured or unconscious, people who fall when trying to leave the tunnel or wait for emergency services to come. In these situations, the pressure and impulse they are exposed to are higher. As can be seen in Figure 12 (dymonds and triangels) at 5 m from the tank, survival chances are very low. If the impulse is not taken into account, an overpressure of 200 kPa leads to 99% chance of lung haemorrhage [19], causing the death of almost all the persons hit by the blast wave. At distances between 10 m and 20 m from the ruptured tank, the fatality threshold is still met but the probability drops to a smaller percentage. However, the chance of serious injury with eardrum rupture remains high at about 50%. Similar to the 1.5 m height case, the further from the tank (until 40 m for the case without combustion), the smaller the probability of eardrum rupture. Humans do not have time to react on the blast wave. It takes less than 0.2 s after tank rupture for all blast waves to exit the tunnel passing distance of 50 m.

Besides the pressure effects from the blast wave, other hazards and associated risks exist. People can be hurt by projectiles or pushed down by the blast causing secondary injuries. Surely, the thermal effects of a fireball is another source of hazards and risks. However, this is out of the scope of this study and will be addressed in our future studies.

CONCLUSIONS
The CFD model for simulation of blast wave and fireball created by high-pressure hydrogen tank rupture in a fire is developed. The model is validated against bonfire test with tank rupture in the open atmosphere. It is shown that to the moment when blast wave reached a pressure sensor located at distance 6.5 m the amount of burned hydrogen was 23% of the released from the tank fuel. This finding does not contradict the previous result indicating that only 5% of released hydrogen contribute to the blast wave strength. The difference can easily be explained by the fact that there is a time shift between the release of energy during combustion and "delivery" of this energy by sound waves to the leading front of the blast wave.

The validated model is applied then to simulate the blast wave after a tank rupture in a fire in a tunnel, both with and without combustion to estimate the effect of combustion of the blast wave strength. The regularities of the shock wave dynamics and overpressure distribution along the tunnel, including difference in maximum overpressure over heights, are discussed. For the storage tank of 140 L with 5.5 kg of hydrogen and the selected tunnel cross-section area the quasi-steady blast wave of 25 kPa amplitude (blast without combustion) establishes at 40 m and about 37 kPa (blast with combustion) establishes at 30 m from the tank location. Then it propagates without change of the amplitude till the end of the tunnel at 50 m. The consequences analysis based on the comparison of harm criteria with pressure and impulse generated at different locations from the tank rupture has shown that there is no “no-harm” zone and people in the tunnel would be either injured or killed by the blast. This is unacceptable situation. It is worth mentioning that we have considered the worst-case scenario with the maximum onboard inventory in one tank for currently available fuel cell cars and the tunnel with minimum cross-section area. More research should be done to find out the maximum onboard inventory to exclude injuries and fatalities, and develop innovative safety technologies to exclude tank rupture in a fire at all. One of such technologies called leak-no-burst is currently under development at Ulster.

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Explosions in Road Tunnels
Part 1: A Study into the Explosion Scenarios
According to the Eurocode

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ABSTRACT
In the Eurocode it is stated that explosion loads must be taken into account in the design of road tunnels. Based on the information in the Eurocode, it is not possible to design tunnels adequately for explosion loads. It might be questioned whether the given examples of explosion loads in the Eurocode are representative for accident scenarios resulting from the transport of dangerous goods. Furthermore Annex D of Eurocode EN1991-1-7 is limited to gas explosions only, while for example also BLEVES may occur. Therefore, in this paper, the explosion loads in the Eurocode have been studied in further detail, in particular to identify those scenarios (in terms of instantaneous and continuous release of liquified gas amounts) that may lead to the specific explosion loads as mentioned in the Eurocode. This study is part of a larger research into the risk of explosions in road tunnels.

KEYWORDS: Eurocode, LPG, explosions, gas explosions, BLEVE, deflagration, detonation, road tunnels, design, probability, consequences, risk, quantitative risk analysis, QRA, QRA-tunnels, scenarios, design load, pressure, impulse

1. INTRODUCTION

In “Eurocode - Basis of structural design” one of the basic requirements is that: “A structure shall be designed and executed in such a way that it will not be damaged by events such as explosion, impact and the consequences of human errors, to an extent disproportionate to the original cause” [1]. In section 5.1 of EN 1991-1-7 on accidental actions [2,3], regarding the field of application of internal explosions, it is stated that “Explosions shall be taken into account in the design of all parts of the building and other civil engineering works where gas is burned or regulated, or where explosive material such as explosive gases, or liquids forming explosive vapour or gas is stored or transported (e.g. chemical facilities, vessels, bunkers, sewage constructions, dwellings with gas installations, energy ducts, road and rail tunnels)”. Thus, in every country where the Eurocode is applied, explosions need to be taken into account in the design of road tunnels. Details of requirements, design assumptions and analyses, however, are up to national authorities.

From the 1st of April 2012 the Dutch Building Code requires the direct use of the Eurocode standards. Therefore explosion loads must be taken into account in the design of road tunnels. The Eurocode offers two possibilities to do so. The first method is based on design values for loads and resistances (Annex D of EN 1991-1-7 [2,3]). Alternatively a risk analysis can be done (also called the \"accepted risk\" criterium). This method is elaborated in Annex B of EN 1991-1-7 [2,3]. The method for risk analysis is closely related to the Quantitative Risk Analysis method currently used in The Netherlands for calculating the internal risk (risk of death for people in the tunnel. Structural damage is not considered) in road tunnels (QRA-tunnels).

1.1 Problem definition
Both Annexes B and D of EN 1991-1-7 are informative and therefore not obligatory. Both annexes have several unclearities with respect to the application [4], amongst others the values for the
explosion loads that need to be applied. The background document [8] and other relevant literature [9] could not solve these unclearities. Based on these annexes alone, it is not possible to design tunnels for explosion loads in an adequate and economic optimal way.

In practice, for the majority of the applications it is common to use an (accepted) calculation method. For the indications given in Annex D of EN 1991-1-7 [2,3] an unambiguous relation with the transport of dangerous goods is missing. It is suspected that the given examples of explosion loads are not representative for accident scenarios resulting from the transport of dangerous goods in The Netherlands and either too low or too high values are being used. Furthermore, Annex D is limited to gas explosions only, while for example also BLEVES can occur. Therefore the explosion loads in Annex D have been studied in further detail, in particular which scenarios may lead to these specific explosion loads. The central research question is:

| Which scenarios (in terms of instantaneous and continuous release of liquified gas amounts) lead, under Dutch circumstances, to the explosion loads mentioned in the Eurocode? |

1.2 Approach
As a first step of a larger research project, in this paper the conditions which result in the explosion loads given by the Eurocode have been studied (for instance what size and circumstances). Then the comparison between the explosion loads and the loads following from the “rules of thumb” has been made. These rules of thumb have been defined in 2001 [10] and 2010 [11]. This comparison has lead to the circumstances where these kind of explosion loads may be expected.

In the next step the scenarios leading to these circumstances have been studied, by means of dispersion calculations. The sensitivity for explosion of the mixture and the release (instantaneous or continuous) have been taken into account as variables.

Finally the extent to which the scenario conditions are realistic for the typical Dutch circumstances (e.g. relatively short tunnels) with respect to the transport of dangerous goods have been taken into account by means of a comparison with the background information on the explosions that are taken into account in QRA-tunnels.

1.3 Scope
In this paper Annex D of the Eurocode is discussed. The scope in Annex D, and therefore of this paper, is limited to gas explosions (deflagration and detonation) only. The consequences of explosions are mainly related to the people in the tunnel and in the immediate surroundings of the tunnel and to the tunnel structure. In this research only the consequences for the tunnel structure have been considered.

2. ANALYSIS OF EXPLOSION LOADS IN ANNEX D

2.1 Type of explosions
In Annex D two types of explosions are presented; a deflagration and a detonation. Implicitly the starting point for the Annex has been the release of a liquefied reactive gas and the ignition thereof, leading to either a deflagration or a detonation (chemical explosions). However, besides these two types of explosions, also BLEVEs and bursting vessels are types of (physical) explosions. Annex D is therefore not complete in the explosion types that are taken into account. In Figure 1 an overview of possible types of explosions is given.
2.2 Explosion loads according to Annex D: deflagration

For a *deflagration* the following pressure-time characteristic $p(t)$ in the Eurocode [2] is suggested:

$$p(t) = 4 \cdot p_0 \cdot \frac{t}{t_0} \left(1 - \frac{t}{t_0}\right) \text{ for } 0 \leq t \leq t_0$$  \hspace{1cm} (1)

where:
- $p_0$ is the peak pressure for a certain type of material [kN/m²]
- $t_0$ is the time constant [s]
- $t$ is the time [s]

The representation of this load has been schematized in Figure 2, which shows that the load is characterized by a parabolic increase and decrease. The load is independent of the distance to the source.
Although eq. (1) is a general formula, Annex D contains example values for the constants. Liquefied Natural Gas, LNG, has been taken as an example with the following values:

\[ p_0 = 100 \text{ kN/m}^2 \]
\[ t_0 = 0.1 \text{ s} \]

Based on these example values, a pressure-time diagram according to Figure 3 has been drawn. The load has a total time of occurrence of 100 ms (determined by \( t_0 \)) and a peak pressure of 100 kN/m\(^2\), determined by the chosen value for \( p_0 \).

Except the peak pressure, the explosion load is also characterised by the impulse, the released energy, that can mathematically be calculated as the surface under the pressure-time diagram. From Figure 3 follows that the impulse is approximately 7 kN/m\(^2\)·s (I=6.67 kN/m\(^2\)·s).

\[ p(x, t) = p_0 \cdot \exp \left\{ -\frac{t - \frac{|x|}{c_1}}{t_0} \right\} \quad \text{for } \frac{|x|}{c_1} \leq t \leq \frac{|x|}{c_2} \]
\[ p(x, t) = p_0 \cdot \exp \left\{ -\frac{|x|}{c_2} \cdot \frac{2 \cdot |x|}{c_1} \right\} \quad \text{for } \frac{|x|}{c_1} - \frac{|x|}{c_2} \leq t \leq \frac{|x|}{c_2} \]
\[ p(x, t) = 0 \quad \text{for all other conditions} \]
$p_0$ is the peak pressure (material dependent) [kN/m$^2$]

c_1 is the propagation velocity of the shock wave [m/s]

c_2 is the acoustic propagation velocity in hot gasses [m/s]

t_0 is the time constant [s]

t is the time [s]

|x| is the distance between the pressure sampling point and the centre of the explosion [m]

From the formulas as well as the diagram in Figure 2b the explosion load of a detonation is not only dependent of the time $t$ but also of the distance to the source $x$.

As with the deflagration, the Eurocode suggests general formulas. However, for the constants in equations (2) and (3) example values are given for LNG:

\begin{align*}
p_0 & = 2000 \text{ kN/m}^2 \\
c_1 & \approx 1800 \text{ m/s} \\
c_2 & \approx 800 \text{ m/s} \\
t_0 & = 0.01 \text{ s}
\end{align*}

Based on equations (2), (3) and (4) and the example values for LNG, the pressure-time diagram for an LNG detonation can be determined. From Figure 4 appears that at the start of the detonation a peak pressure $p_0 = 2000 \text{ kN/m}^2$ occurs, but the time duration of this peak is very short. This can be seen from Figure 4a, where the load at 1 m distance from the source is shown in detail. Figure 4b shows the same diagram as a straight line when a larger time scale is used.

![Figure 4: Pressure-time function at multiple distances from the source in case of an LNG detonation (b). The load at 1 m distance from the source is shown in detail in (a)](image)

From Figure 4 it follows that the larger the distance to the source, the longer the duration of the load, while the peak pressure hardly reduces. The constant pressure level that is reached after the peak pressure, reduces more and more as the distance to the source becomes larger until a constant value is reached. The reduction of the peak pressure $p_0$ over the length of the tunnel ($l=1000$ m) is for the given example values almost linear and reduces from 2000 kN/m$^2$ to 1500 kN/m$^2$ (given the source is at the beginning of the tunnel).

For the above model it appears that the impulse at the source ($x=0$) is equal to 0, while the impulse increases at a larger distance of the source. This has been illustrated in Figure 5 where the calculated impulse from the situation in Figure 4b is drawn as function of the distance to the source. The increase of the impulse is clearly shown. Furthermore it appears that the impulse is at its maximum at approximately 75 m from the source ($l=43 \text{ kN/m}^2 \cdot \text{s}$) and reduces at larger distances to the source (see also [15]).
Figure 5: Impulse as function of the distance to the source in case of a detonation

2.4 Discussion of the Eurocode explosion loads

From studying the Eurocode we may conclude that the Eurocode is not complete in the type of explosions that are taken into account, since e.g. BLEVEs are missing. For gas explosions rather general formulations are given in relation to the size of the explosions, which are not enough detailed to use for the design of tunnels.

In relation to the type of goods, the Eurocode is limited to LNG and no suggestions for the values for other goods are given. From earlier studies however has been concluded that LPG, Liquefied Petroleum Gas, is the most transported and therefore representative good in the Netherlands. Many of the existing explosion models and parameters are therefore based on LPG [10, 11]. In the current research presented in this paper LPG is therefore used as basis for the calculations.

3 CALCULATION MODELS FOR EXPLOSION LOADS

To be able to determine which scenarios lead to the given explosion loads in the Eurocode, calculations have been done. The calculations are, by lack of models for LNG, done for LPG.

3.1 Basic assumptions

For the calculations basic assumptions have been made regarding a.o. the geometry, the air velocity in the tunnel and the type of good. The assumptions have been made in such a way that they are closest to a typical road tunnel in The Netherlands. A typical road tunnel has a length \( l = 1000 \text{ m} \) and comprises either two lanes with a total width \( w = 9 \text{ m} \) or three lanes with a total width \( w = 13.5 \text{ m} \). The cross sectional area \( A \) belonging to this width is 50 resp. 72 m\(^2\). The air velocity \( v \) in the tunnel is assumed to be 2 m/s during normal operation and 5 m/s during incidents. These values for air velocity are used in quantitative risk analyses with QRA-tunnels as well. The calculations have been done for LPG as representative good. The maximum volumes of LPG that are carried in bulk are 50 m\(^3\) (25,500 kg LPG).

3.2 Cloud length

The central question of this research is “Which scenarios lead to the explosion loads in the Eurocode?” From research [10] done in light of the rules of thumb for LPG that have been put up by TNO it follows that the explosion load can reasonably be related to the size of the explosive cloud. Calculations show that approximately:

- The pressure load of the Eurocode deflagration (1) occurs at an explosive cloud length of 10 m, assuming ignition occurs at the edge of the explosive cloud;
- The pressure load of the Eurocode detonation (2), (3) and (4) occurs at an explosive cloud length of more than 50 m, assuming ignition occurs at the edge of the explosive cloud.

The load profiles (pressure-time lapse) in reality and the models differ from the strongly schematised forms in the Eurocode. To illustrate this, Figure 6 shows the profile for a deflagration.

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In [10] the index numbers for (i) the time to reach peak pressure $\Delta t_1$, (ii) load duration $\Delta t_2$, (iii) maximum pressure $P$ and (iv) impulse $I$ have been determined and presented in a table. The parameters for an explosive cloud length of 10 and 50 m are presented in Table 1. From [10] follows that the pressure for explosive cloud lengths larger than 50 m increases very fast and the mechanism turns from deflagration into detonation.

Table 1: Parameters for edge-ignited clouds of 10 m and 50 m, calculated on 6 locations over the entire tunnel length [10]

<table>
<thead>
<tr>
<th>explosive cloud length</th>
<th>$\Delta P$ (kPa)</th>
<th>position (m from the upstream tunnel entrance)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>10 m</td>
<td>$\Delta P$ (kPa)</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>$I$ (kPa)</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_1$ (s)</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_2$ (s)</td>
<td>0.02</td>
</tr>
<tr>
<td>50 m</td>
<td>$\Delta P$ (kPa)</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>$I$ (kPa)</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_1$ (s)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_2$ (s)</td>
<td>0.08</td>
</tr>
</tbody>
</table>

According to the Eurocode we have either pure deflagration with peak load 100 kN/m$^2$ and total duration 0.1 s, or a detonation with peak load 2000 kN/m2 and duration 0.0013 s. Reality shows a much more diverse result.

3.3 Approach

Table 1 shows that it is necessary to define when, in the case of instantaneous or continuous release of gas, explosive cloud lengths of 10 m and of more than 50 m can develop. In [11] exploratory calculations have been made regarding the dispersion of a non-reactive gas in a long tube according to a method developed by Taylor [12]. The method has been applied to the case of the accidental release of LPG in a road tunnel. It is unclear whether this is sufficiently representative for application in a tunnel with a rectangular cross section, filled with vehicles.

If we assume that the dispersion of LPG ($\rho \approx 1.9$ kg/m$^3$) in a long tunnel with traffic follows the physics of Taylor based on an empty circular tube, the development of the length of a (downstream)
explosive cloud can be calculated, depending of the way the gas has been released (instantaneous or continuous). The results of these calculations have been presented in the next paragraphs. The following remarks have been made:

- Only worst-case scenarios have been taken into account: the gas has been released at the (upstream) tunnel entrance, enabling the cloud to disperse in principle along the entire length of the tunnel \( l = 1000 \text{ m} \).
- The gas-air mixture is only potentially explosive when the LPG concentration is within a certain band. From [11] it follows that an LPG mixture is explosive only if the amount of LPG is between 3% and 7% volume. These boundaries are indicated as the Lower Explosion Limit (LEL = 3%) and the Upper Explosion Limit (UEL = 7%).
- In reality the explosion limits of an LPG-air mixture are between 2% and 9%. In [11] has been argued that the characteristics that determine the explosion power of a gas-air mixture are strongly reduced towards the explosion boundaries. The “rules of thumb” [10] were based on the assumption of a homogeneous stoichiometric mixture over the cloud length, while in reality the concentration of gas varies over the cloud length between the LEL and the UEL. This conservative approach leads to adopting the starting point in the current study of “effective explosion limits” between 3% en 7%.

3.4 Results

In this paragraph the results of the dispersion calculations are presented for both the continuous and instantaneous release of the gas.

3.4.1 Instantaneous release

With an instantaneous release of gas from a tank, a cloud develops with at first instance a high concentration of gas. Due to the influence of wind/ventilation, the cloud moves downstream, resulting in a lower concentration and a larger cloud length. Because LPG is only explosive within the limits of 3% and 7%, multiple situations may lead to an explosion. This is illustrated in Figure 7.

![Figure 7: Distribution of the gas concentration](image)

The shaded parts in Figure 7 show the area where the air-propane mixture is explosive (i.e. between 3% and 7%, the black lines). Two situations are shown: in the first figure (a) a mixture with a relative high maximum propane-air concentration is shown (>7%). The maximum propane-air concentration is in the centre of the cloud. Outside the edges of the cloud, there is no propane and the concentration is 0%. At the edges on both sides of the cloud two explosive zones are present. This part of the cloud is called the explosive gas cloud. If the relative amount of gas is less or when the cloud has driven away further downstream, a situation occurs where there is only one explosive zone in the middle of the gas cloud (b). In the end also the maximum concentration will be under the Lower Explosion Limit. From that point on the mixture of the entire gas cloud is not explosive anymore.

3.4.2 Calculation results

A complete overview of the calculations of instantaneous released LPG can be found in appendix B of [5]. An illustrative example is given in Figure 6 for the instantaneous release of 200 m³ expanded LPG, where the results have been given for the calculated gas concentration downstream of the gas source in a tunnel with a cross section of 72 m² and with an air velocity of 2 m/s. The explosive
boundaries (i.e. LEL=3% and UEL=7%) have been marked with horizontal black lines. From the
figure appears that in the beginning a gas cloud occurs with two explosive zones on both sides of the
centre of the cloud. As soon as the cloud has moved downstream from the gas source for
approximately 200 m, the situation occurs with one explosive zone in the middle of the cloud. At the
end of the tunnel, at approximately 900 m, the cloud is diluted such that there is no longer an
explosive zone.

![Figure 8: Distribution of the gas concentration downstream the gas source with an expanded volume
of 200 m$^3$ ($v=2$ m/s, $A_{tun}=72$ m$^2$). Nine distributions are shown for nine different
moments in time.](image)

In appendix B of [5] similar figures are presented for volumes of $V = 200$ and 1000 m$^3$, tunnel cross
sections $A_{tun} = 50$ and 72 m$^2$ and air velocities of $v = 2$ and 5 m/s. In Table 2 an example from [11] is
given of the length of the explosive gas cloud as function of the distance to the source and the volume
of the gas cloud ($V$). The results in the table relate to four different gas cloud volumes (500, 1000,
2000 and 5000 m$^3$). The air velocity for the calculations has been $v = 1$ m/s.

**Table 2: Explosive lengths of the gas cloud (in m) at instantaneous release of LPG. The results relate
to different volumes of the gas cloud and distances to the source. All results are at an air
velocity of 1 m/s**

<table>
<thead>
<tr>
<th>distance to source $X$ (m)</th>
<th>volume of the explosive gas cloud [m$^3$]</th>
<th>500 m$^3$</th>
<th>1000 m$^3$</th>
<th>2000 m$^3$</th>
<th>5000 m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>$2\times4$</td>
<td>$2\times3$</td>
<td>$2\times3$</td>
<td>$2\times3$</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>$2\times6$</td>
<td>$2\times5$</td>
<td>$2\times5$</td>
<td>$2\times5$</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>$2\times10$</td>
<td>$2\times8$</td>
<td>$2\times8$</td>
<td>$2\times7$</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>$2\times20$</td>
<td>$2\times14$</td>
<td>$2\times12$</td>
<td>$2\times11$</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>$2\times44$</td>
<td>$2\times23$</td>
<td>$2\times18$</td>
<td>$2\times16$</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>112</td>
<td>$2\times39$</td>
<td>$2\times28$</td>
<td>$2\times22$</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>60</td>
<td>214</td>
<td>$2\times53$</td>
<td>$2\times39$</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>0</td>
<td>222</td>
<td>$2\times96$</td>
<td>$2\times60$</td>
<td></td>
</tr>
</tbody>
</table>

Based on the results of the calculations from this research as presented in appendix B of [5] and
illustrated in Figure 7 for different gas amounts, the explosive gas cloud length can be calculated as
function of the distance to the source. The results of these calculations are given in Figure 9 (for $v=2$
m/s) and Figure 10 (for $v=5$ m/s).
Both figures look alike. In the beginning the explosive cloud length increases on both sides of the middle. At a certain point this length doubles quite suddenly. This is the moment where the two explosive clouds on both sides of the middle join into one large cloud. Thereafter the cloud increases slowly and at a certain point the cloud gets smaller. This behavior is in principle comparable for every combination of cloud volume and air velocity (see figure 9 and Figure 10).

From Figure 9 follows that the joining of the two explosive gas clouds into one explosive gas cloud for the larger volumes of released gas (>400 to 500 m$^3$) only happens in tunnels with a length larger than 1000 m. Gas cloud volumes of this size will therefore never achieve an explosive gas cloud length of 50 m, meaning that in this category tunnels (1000 m) a detonation will not occur. Gas amounts smaller than 200 m$^3$ will also not lead to an explosive cloud length of 50 m. This also holds for an air velocity of 5 m/s (Figure 10).

Explosive cloud lengths of 10 m are achieved in all cases, independent of the released amount of gas and independent of the air velocity. That means that every instantaneous released gas cloud may lead to a deflagration as defined in the Eurocode. The larger the gas cloud volume, the further away from the source this happens.
Based on the extrapolation of the results in Figure 9 and Figure 10 follows that with a cloud volume of 3000 m$^3$ to 4000 m$^3$ an explosive cloud length of 10 m will not be achieved in a tunnel with a length of 1000 m. Based on an expansion factor of 275 this equals a tank volume of 11 to 14,5 m$^3$. Based on a tank volume of 50 m$^3$, the tank is filled for 22% to 29%.

3.4.3 Conclusions instantaneous released gas
Based on the results presented above and on the expansion factor of 275, the following conclusions for instantaneous released gas may be drawn:
- Explosive cloud lengths that can lead to the specific deflagration as given in the Eurocode can occur in all the considered situations, unless the cloud volume is larger than 3000 m$^3$ to 4000 m$^3$.
- Explosive cloud lengths that can lead to a detonation as given in the Eurocode can only occur at volumes of 200 m$^3$ < V < 500 m$^3$, similar to a liquefied gas volume of LPG of 0,7 m$^3$ < V < 1,8 m$^3$. This means an almost empty tank.
The results are almost independent of the air velocity.

3.4.4 Continuous release
In case of a continuous release there is a constant flow of gas. The air velocity plays an important role in this case, contrary to an instantaneous release. A constant flow of gas and air velocity result in a homogeneous concentration if the effects of the walls are neglected. The homogeneous concentration downstream can be calculated from:

$$C = \frac{Q}{\rho \cdot v \cdot A_t}$$  (5)

where:
- $C$ is the constant downstream concentration (-)
- $Q$ is the flow of the released gas (source strength in kg/s)
- $\rho$ is the vapour density of LPG (=1,9 kg/m$^3$)
- $v$ is the air velocity or ventilationspeed (m/s)
- $A_t$ is the surface of the cross section of the tunnel (m$^2$)

If the relation between the source strength and the air velocity is between certain limits and leads to concentrations between the values for LEL and UEL, the entire length of the tunnel will be filled with an explosive mixture.

For an air velocity of 2 m/s the downstream composition of the explosive mixture will be between the explosion limits for a source strength between 8 and 19 kg/s (8 kg/s < Q < 19 kg/s). For an air velocity of 5 m/s the source strength needs to be between 21 and 48 kg/s (21 kg/s < Q < 48 kg/s). For source strengths lower than the aforementioned values, the constant downstream concentration will be lower than the Lower Explosion Limit (<LEL). Explosive concentrations will therefore only occur in the vicinity of the source. For source strengths larger than the aforementioned values, the constant downstream concentration will be larger than the Upper Explosion Limit (>UEL), which means that there will only be an explosive zone at the front of the gas cloud. Downstream of the front the concentration will be lower than the LEL (<LEL), upstream of the front the concentration will be higher than the UEL (>UEL). This is illustrated in Figure 11 where the downstream concentration is given at nine consecutive times after the activation of the continuous source. The results relate to a source strength of 30 kg/s and an air velocity of 2 m/s. The figure shows that only at the front of the cloud the concentration is over a short length between the explosion limits (LEL and UEL).
The concentrations of the explosive cloud length downstream a gas source have been given for different source strengths and an air velocity of 2 m/s in Figure 12. From this figure it appears that the tunnels fills completely with an explosive mixture (except the area close to the source), provided the source strength is between the aforementioned limits. The explosive cloud length increases with the duration of the release of gas.

If the source strength becomes larger than the critical value of 21 kg/s, the explosive cloud length is limited at the front of the cloud and increases gradually. From the figure it follows that an explosive cloud length of 10 m (deflagration) is achieved for all source strengths. An explosive cloud length of 50 m (detonation) develops only for source strengths larger than 8 kg/s and lower than approximately 22 kg/s (8 < Q < 22 kg/s).

For an air velocity of 5 m/s similar conclusions may be drawn, although different boundaries exist for the source strength at which an explosion may occur (Figure 13). A cloud length of 10 m (deflagration) occurs for all source strengths. An explosive cloud length of 50 m (detonation) only develops for source strengths larger than 21 kg/s and smaller than 52 kg/s (21 < Q < 52 kg/s).
3.4.5 Conclusions continuous release
Based on the results presented in paragraph 3.4.4 the following conclusions are drawn for the continuous release of gas:
- Explosive cloud lengths that may lead to the specific deflagration as given the Eurocode may occur in all considered cases;
- Explosive cloud lengths that may lead to a detonation as given in the Eurocode only develop if the source strength is between the following boundaries:
  - $8 \text{ kg/s} < Q < 22 \text{ kg/s}$ at an air velocity of $2 \text{ m/s}$
  - $21 \text{ kg/s} < Q < 52 \text{ kg/s}$ at an air velocity of $5 \text{ m/s}$

3.5 Conclusions resulting from the calculations
A summary of the conclusions of the calculations is given in Table 3. For the situation with an instantaneous release we assumed an expansion factor of 275 for the calculation of compressed volume ($V_c$) into expanded volume ($V_e$). The results in Table 3 are applicable for the basic assumptions as presented in paragraph 3.1.

Table 3: Summary of the conditions under which instantaneous and continuous release of LPG may lead to either of the explosion scenarios as given in the Eurocode

<table>
<thead>
<tr>
<th></th>
<th>Instantaneous release</th>
<th>Continuous release</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$v = 2 \text{ m/s}$</td>
<td>$v = 5 \text{ m/s}$</td>
</tr>
<tr>
<td>deflagration</td>
<td>Occurs in all considered cases*)</td>
<td></td>
</tr>
<tr>
<td>detonation</td>
<td>$200 \text{ m}^3 &lt; V_g &lt; 500 \text{ m}^3$</td>
<td>$8 &lt; Q &lt; 22 \text{ kg/s}$</td>
</tr>
<tr>
<td></td>
<td>$0,7 \text{ m}^3 &lt; V_{LPG} &lt; 1,8 \text{ m}^3$</td>
<td></td>
</tr>
</tbody>
</table>

*) From extrapolation of the results follows that for a cloud volume of 3000 m$^3$ à 4000 m$^3$ no deflagration can occur.

4 ANALYSIS OF THE EXPLOSION SCENARIOS IN QRA-TUNNELS

In this chapter the explosion scenarios in road tunnels currently being part of the Dutch Quantitative Risk Analysis method for road tunnels (called “QRA-tunnels” [13,14]) have been discussed in order to relate the conditions of the explosion scenarios in the Eurocode to the probability of occurrence of these scenarios. The probability (say in a year) that an explosion occurs is the product of:
1) The annual probability that an explosive gas cloud is present in the tunnel
2) The conditional probability that an ignition occurs at the same time
4.1 QRA-tunnels and instantaneous release

In QRA-tunnels two types of instantaneous release are considered: a so-called cold BLEVE (in this research defined as a bursting vessel) and a so-called warm BLEVE. The probabilities of occurrence of these events, given an accident with the release of flammable gas are [13, 14, for details see [5]:

\[
P(\text{Warm BLEVE}) = 2.87 \times 10^{-3} \\
P(\text{Cold BLEVE}) = 1.23 \times 10^{-3}
\]

For these probabilities is assumed that all instantaneous releases of gas lead to a BLEVE. In the next step the probability of ignition has been studied. In [13,14] three types of ignition are identified: direct, delayed and no ignition. The probabilities are:

\[
\begin{align*}
P(\text{direct ignition}) &= 0.8 \\
P(\text{delayed ignition}) &= 0.2 \\
P(\text{no ignition}) &= 0
\end{align*}
\]

From the above appears that ignition, either direct or delayed, is assumed to occur in all cases and the probability of ignition is assumed to be equal to 1. The probability of a gas explosion (either deflagration or detonation) after ignition then becomes:

\[
\begin{align*}
P(\text{gas explosion} \mid \text{warm BLEVE}) &= 2.87 \times 10^{-3} \times 1.0 = 2.87 \times 10^{-3} \\
P(\text{gas explosion} \mid \text{cold BLEVE}) &= 1.23 \times 10^{-3} \times 1.0 = 1.23 \times 10^{-3}
\end{align*}
\]

In QRA-tunnels [13,14] the possibility of a gas explosion (deflagration and possibly detonation) has been considered in case a (direct or delayed) ignition occurs at a BLEVE, but the gas explosion is not further detailed into the probability of either a deflagration or a detonation. The reason for that might be that a BLEVE is assumed to result in 100% letality and therefore there is no added value in studying the probabilities of occurrence of a deflagration and detonation.

Furthermore it is assumed that ignition occurs in all cases. The current research does make a distinction into deflagration or detonation. From the current research it also appears that instantaneous release does not in all cases lead to a gas explosion, depending on the length of the explosive gas cloud. The probability of a gas explosion may therefore be further refined. The refinement lies in (1) the period where an explosive concentration is present and (2) the probability that in that period ignition occurs, given that an explosive cloud length exists.

The default value for delayed ignition in QRA-tunnels has been assumed to be two minutes. Based on the scenarios defined in the current research and the probabilities of (direct or delayed) ignition and the delay time of two minutes an explosion occurs in all cases.

4.2 QRA-tunnels and continuous release

For the probabilities of occurrence of the scenarios with a continuous release, again the background information of QRA-tunnels has been consulted. For a continuous release a distinction has been made between two types of release that, relative to the truck, happen to the front or to the back. In QRA-tunnels the probabilities of occurrence are (see appendix C of [5], [13, 14]):

\[
\begin{align*}
P(\text{continuous release at the back}) &= 4.56 \times 10^{-3} \\
P(\text{continuous release at the front}) &= 3.04 \times 10^{-3}
\end{align*}
\]

The probabilities of ignition are the same as for the instantaneous release, namely 0.8 for direct and 0.2 for delayed ignition. Ignition is assumed to occur in all cases. Direct ignition results in a torch and delayed ignition results in a gas explosion (deflagration or detonation). The probability of a gas explosion for a continuous release in QRA-tunnels becomes:

\[
P(\text{gas explosion} \mid \text{continuous release}) = 0.2 \times (4.56 \times 10^{-3} + 3.04 \times 10^{-3}) = 1.5 \times 10^{-3}
\]

In QRA-tunnels it is assumed that a continuous release and direct ignition results in a torch and not in an explosion. From the current research appears that a continuous release does not lead to a gas explosion in all cases, depending on the air velocity and the source strength. The probability of an
explosion may therefore be further refined. The refinement can be found in (1) the air velocity and (2) the probability that in that period an ignition occurs, given that the source strength is within the limits mentioned.

4.3 Conclusions and recommendations
From the comparison between the results of the current research and QRA-tunnels appears that it is currently impossible to determine the probabilities of occurrence of the scenarios from the current research by means of the knowledge available within QRA-tunnels. The main reason for that being that the gas explosion scenarios in QRA-tunnels are not further detailed in deflagration or detonation.

From the viewpoint of QRA-tunnels it is logical that gas explosions are not further elaborated, because already in an earlier stage it is assumed that the maximum number of victims has been reached. For being able to determined the probabilities of occurrence of deflagration and detonation, it is important that the scenarios in QRA-tunnels are further elaborated.

In QRA-tunnels several assumptions have been done that need further research:
- In QRA-tunnels the probability of ignition is assumed to be equal to 1. We suppose that this is a conservative assumption that needs to be further refined.
- The probability of ignition is also dependent of the cloud length and therefore of the distribution of the gas concentration. It is recommended to further investigate the relation between the both of them.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions
In the current research has been studied which scenarios for LPG (in terms of instantaneous and continuous release of liquified gas amounts) lead, under Dutch circumstances, to the explosion loads mentioned in the Eurocode. From earlier research [10] appears that the pressure load of a deflagration as defined in the Eurocode occurs with an explosive cloud length of more than 10 m. From that same research appears that a detonation as defined in the Eurocode occurs at an explosive cloud length of more than 50 m. On the basis of these results we have investigated under which scenario conditions for LPG a deflagration or a detonation can occur. From the results the following conclusions are drawn:

- For instantaneous and continuous released gas all investigated cases may lead to the specific deflagration as given in the Eurocode.
- A detonation as given in the Eurocode can only occur in the following investigated cases:
  - At an instantaneous released volume V of 200 m³ < V < 500 m³
  - At a continuous released gas and a source strength Q of:
    - 8 kg/s < Q < 22 kg/s
    - 21 kg/s < Q < 52 kg/s (for v = 2 m/s)
    - 21 kg/s < Q < 52 kg/s (for v = 5 m/s)

Based on this research it can further be concluded that the loads as mentioned in the Eurocode are not representative for the total spectrum of explosion loads. From the comparison between the current research and QRA-tunnels it turned out that the explosion scenarios in QRA-tunnels are not sufficiently developed to the probabilities of occurrence of the scenarios that are relevant for the explosion loads as given in the Eurocode. For a further study into the probabilities of occurrence of specific explosion scenarios, it is important that the scenarios are further detailed.

5.2 Recommendations and further study
The recommendations for further research relate to the following subjects:
- From the current research it has become clear that the explosions given in the Eurocode can only occur under very specific circumstances and are not representative for the total spectrum of explosion loads. To be able to design tunnels for explosions, it is necessary to have an understanding of all the possible explosion scenarios that can take place, the probability of
occurrence of these scenarios and their consequences in terms of pressure and impulse (see [6,7]).

- In QRA-tunnels the probability of ignition is assumed to be equal to 1. This is assumed to be a conservative approach that needs further study (see [16]). The probability of ignition is also dependent on the cloud length and therefore on the distribution of the gas concentration. We recommend to further study this relation.

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1. NEN-EN 1990 (en) Eurocode – Basis of structural design, december 2002
13. Rijkswaterstaat, QRA-tunnels 2.0, Achtergronddocument, 2 februari 2012
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Study of fire and explosion hazards of alternative fuel vehicles in tunnels

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ABSTRACT
An investigation of fire and explosion hazards of different types of alternative fuel vehicles in tunnels is presented. The different fuels are divided into four types: liquid fuels, liquefied fuels, compressed gases, and electricity, and detailed parameters are obtained. Three types of fire hazards for the alternative fuel vehicles: pool fires, jet fires and fireballs are identified and investigated in detail. From the perspective of pool fire size, the liquid fuels pose equivalent or even much lower fire hazards compared to the traditionally used fuels, but the liquefied fuels may pose a higher hazard. For pressurized tanks, the fires are generally much larger in size but shorter in duration. The gas releases from pressure relief devices and the resulting jet fires are highly transient. For hydrogen vehicles, the fire sizes are significantly higher compared to CNG tanks, while flame lengths only slightly longer. Investigation of the peak overpressure in case of an explosion in a tunnel was also carried out. The results showed that the consequences of tank rupture and BLEVE are relatively tolerable for a position 50 m away, but the situations in case of cloud explosion are in most cases highly severe and intolerable for tunnel users. These hazards need to be carefully considered in both vehicle safety design and tunnel fire safety design. Further researches on these hazards are in urgent need.

KEYWORD: fire, explosion, alternative fuel vehicle, tank rupture, BLEVE, cloud explosion

INTRODUCTION
Environmental issues and scarcity of resources have stimulated the development and use of alternative fuel vehicles worldwide. In many countries, governments are encouraging the transformation from the use of internal combustion engine vehicles to alternative fuel vehicles by tax exemption or tax subsidization, and some even has planned to ban the use of internal combustion engine vehicles in the near future. Nowadays, the use of alternative fuel vehicles has occurred in almost every type of transportation technologies, e.g. car, bus, heavy goods vehicle, train locomotive and airplanes. For example, there have been over 600 ethanol buses running in Sweden nowadays. Another example is that Scania has produced heavy goods vehicles powered by natural gas. It can be foreseen that more and more such vehicles will be on open roads, as well as in tunnels and other underground spaces, e.g. underground garages. In comparison to traditional fuel vehicles, the risks for some alternative fuel vehicles can be much higher. For batteries of electric vehicles, a thermal runaway due to overcharging or short circuits could result in explosion. Different types of explosion could de facto occur, including gas tank rupture, boiling liquid expanding vapor explosion (BLEVE), deflagration and detonation. Another hazard is the jet fires that feature to long flame length and high temperature.

In the past few decades, many catastrophic fires occurred in tunnels [1]. These accidents show that the consequences of vehicle fires in tunnels are generally much higher than on the open roads. For use of alternative fuel vehicles in tunnels, special attentions need to be paid to the fire and explosion hazards. There have been very limited researches related to fire and explosion hazards of alternative fuel vehicles, much less on their hazards in tunnels. Weerheijm [2] illustrated the explosion risks and consequences for a large LPG tanker in a tunnel. These tankers are apparently much larger in the size compared to the fuel tanks in alternative fuel vehicles. There have also been some experimental tests on deflagrations and detonations in medium scale tunnels [3], and the data were later used for an inter-comparison exercise on modelling [4]. However, only several scenarios with hydrogen was investigated.
Despite the lack of knowledge on fire and explosion hazards of alternative fuel vehicles, these vehicles have already been used widely to some extent as mentioned previously. This de facto put the whole society in a potentially high risk. Different rules are applied worldwide. For example, the LPG vehicles with safety valves are allowed both in tunnels and garages in France while in Italy LPG should be labeled before entering the Mont Blanc tunnel [5]. The Swedish authorities, i.e. Swedish Transport Administration and Swedish Transport Agency, propose that vehicles in tunnels should have equivalent safety level as in open areas [6]. To make such a judgement or to achieve this goal, quantitative risk analysis is required. However, at present, there is no such knowledge of fire and explosion hazards of these different types of vehicles possibly running in the tunnels. Therefore carrying out such a quantitative risk analysis at present is not feasible. More basic knowledge on risks and consequences are required.

The objective of this work is to investigate the fire and explosion hazards of alternative fuel vehicles in tunnels. Specifically, it is to obtain detailed parameters for each type of alternative fuel vehicles, to identify the potential hazards for each type of alternative fuel vehicles in tunnels, and to quantify the consequences based on state-of-the-art knowledge and CFD modelling.

INCIDENTS WITH ALTERNATIVE FUEL VEHICLES

There have been many incidents involving alternative fuel vehicles occurred especially in the past decade. Most of the incidents reported refer to CNG vehicles, LPG vehicles and electric battery vehicles.

CNG vehicles

CNG is the abbreviation of Compressed Natural Gas. A list of some CNG vehicle incidents recently occurred is given in Table 1. Note that in the table, “explosion” means a gas explosion following a tank rupture in case of a fire. The incidents presented occurred on open roads or in the refueling station. The majority of these incidents started from a fire and ended with a rupture and even a gas explosion. In some incidents jet flames existed after the pressure relief devices (PRDs) functioned, but there would still be a subsequent explosion if the venting flow was not high enough to release the pressure or the tank was locally damaged.

<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>City</th>
<th>Vehicle</th>
<th>Fire location</th>
<th>ignition</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>USA</td>
<td></td>
<td>car</td>
<td>traffic in street</td>
<td>fire</td>
<td>rupture, 12 cars damaged; Rupture (explosion); debris 30 m away, rupture, driver killed</td>
</tr>
<tr>
<td>2007</td>
<td>USA</td>
<td>Seattle</td>
<td>car</td>
<td>refueling station</td>
<td>arson fire</td>
<td>no injury but a 15-20 m long jet flame</td>
</tr>
<tr>
<td>2007</td>
<td>USA</td>
<td>California</td>
<td>Car (van)</td>
<td>aside traffic</td>
<td>fire in engine</td>
<td>jet fire/explosion; damaged 4 homes</td>
</tr>
<tr>
<td>2012</td>
<td>Nether-land</td>
<td>Wassenaar</td>
<td>Bus</td>
<td>street</td>
<td>fire</td>
<td>ceiling</td>
</tr>
<tr>
<td>2016</td>
<td>USA</td>
<td>Hamilton, New Jersey</td>
<td>Refuse truck</td>
<td>outside tunnel</td>
<td>fire, ceiling</td>
<td>explosion; roof landed 30 m away</td>
</tr>
<tr>
<td>2016</td>
<td>Sweden</td>
<td>Gothenburg</td>
<td>Bus</td>
<td></td>
<td>fire</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Sweden</td>
<td>Kramfors</td>
<td>Car</td>
<td></td>
<td>fire</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Sweden</td>
<td>Katrineholm</td>
<td>Refuse truck</td>
<td></td>
<td>fire</td>
<td>truck burned.</td>
</tr>
</tbody>
</table>

2 http://www.trailer.se/fordonsexplosioner-oroar/
3 http://www.expressen.se/motor/bilnyheter/larm-om-gasfordon-som-exploderar/
4 http://www.trailer.se/fordonsexplosioner-oroar/
5 http://www.expressen.se/motor/bilnyheter/larm-om-gasfordon-som-exploderar/
The CNG bus fire incident in Wassenaar, Netherland on 29 Oct. 2012 attracted much attention from the public. The bus was a MAN Lion’s city CNG bus with 8 CNG tanks on top. The fire broke out in the engine compartment. After noticing the coming smoke, the driver continued to drive and stop at a halt on the open road. The passengers then successfully evacuated. The fire developed rapidly and when the fire brigade arrived at the site, the whole bus was on fire. Later several PRDs were activated, resulting jet flames with a length of around 15 - 20 m to shoot out in a horizontal (sideward) direction. The resulting long jet flame may potentially cause danger to personnel and result in fire spread to neighboring buildings or vehicles. As no buildings were located nearby, no damage to structure was reported although it would be if the bus was in a street instead of on the open road.

In 2016, there were three CNG vehicle incidents reported in Sweden. The most known one may be the bus explosion in Gothenburg on 12 Jul, 2016 [9]. It was a Solaris Urbino 15E CNG bus with 48 seats and a wheel chair. There were 7 composite tanks loaded on top each with a volume of 214 liters and an operating pressure of 200 bar. After the bus was found to be caught fire on the ceiling in the 712 m long Gnistaäng tunnel in Gothenburg, the driver continued driving the bus out of the tunnel and stopped aside at around 100 m outside the southern portal. The passengers were safety evacuated and then the fire fighters came to extinguish the fire. When the incident commander felt that the fire was under control, representatives from the bus company went to turn off the gas to the engine compartment. When both staff from the emergency services and bus company stood next to the bus, one of the gas tanks exploded. Two firefighters were thrown to the ground by the shock wave and injured. The consequence could be much more severe if the explosion occurred during the evacuation stage or several seconds later when the firefighters were closer.

The other two incidents occurred in Kramfors and Katrineholm in Sweden. During fire fighting of a gas car fire in Kramfors in 2016, a gas tank of the car exploded. The roof landed a few meters from a firefighter who was 30 meters from the car. In Katrineholm a gas-powered refuse truck after refueling exploded. Salvage staff could have suffered a nasty accident when they thought the other damaged tanks were empty. Fortunately quenched salvage after which the tanks, that could not be discharged otherwise, was depressurized by bombardment.

In 2013, U.S. Department of Transportation conducted a study on incidents with CNG vehicles [10, 11]. A total of 135 incidents from 1976-2010 was analyzed [10]. Among the incidents considered, 56% of them occurred in U.S. and others in Europe, Asia, and South America. The vehicles consisted of 51% trucks, 38% buses and 11% other commercial vehicles. It was found that most incidents with CNG vehicles were not caused by the CNG tank or fuel storage systems (only one in 17 vehicle fires). Instead they were started by an electrical short, brakes, or leaking fuel or hydraulic fluid impinging on a hot engine or exhaust system. Form the table, it is clear that tank rupture is the most likely consequence, followed by vehicles fires, PRD release failure, and tank leaks. It was found that most tank rupture occurred during the refueling or a vehicle fire. In about 35% of the reported fire incidents, the installed thermally activated PRDs did not work probably due to the localized fires. In 42% of all the fire incidents, PRDs worked as intended, and leaking gases were ignited in more than 50% of these. It should be noticed that although no gas explosion was included in the table, there were such incidents occurred as discussed previously.

From the above analyses, it can be concluded that rupture is a very common consequence of a CNG vehicle incident. If a fire starts at other parts of the vehicle, it could spread to the tanks unless it is suppressed. This will result in either a jet fire if the PRDs functions properly or a gas explosion following a rupture. The severity of the gas explosion depends on how much gas is released and whether the flames exist at the moment of rupture. If the flammable gases are ignited immediately after the rupture, the contribution from the gas explosion may be limited due to the small size of the flammable cloud.

LPG vehicles
LPG is the abbreviation of Liquefied Petroleum Gas. A list of some LPG vehicle incidents is given in Table 2. In most of these incidents, explosion is involved.
Table 2  A summary of LPG fire incidents.

<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>City</th>
<th>Vehicle location</th>
<th>Ignition</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>France</td>
<td>Venissieux</td>
<td></td>
<td>arson</td>
<td>explosion, 6 fire fighters severely injured</td>
</tr>
<tr>
<td>2002</td>
<td>France</td>
<td>Seine-et-Marne</td>
<td>garage</td>
<td>arson</td>
<td>explosion; one building collapsed; 39 houses damaged</td>
</tr>
<tr>
<td>2006</td>
<td>Italy</td>
<td>Collatino</td>
<td>street parking</td>
<td>arson</td>
<td>explosion; several cars, 2 garages, shops, fire spread to apartments</td>
</tr>
<tr>
<td>2007</td>
<td>Italy</td>
<td>Salerno</td>
<td>underground garage</td>
<td>gas leakage</td>
<td>Explosion; 3-store building destroyed; 5 others affected.</td>
</tr>
<tr>
<td>2008</td>
<td>Italy</td>
<td>Rovigno</td>
<td>underground garage</td>
<td></td>
<td>fire spread to nearby garage</td>
</tr>
<tr>
<td>2008</td>
<td>UK</td>
<td>South Yorkshire</td>
<td>road</td>
<td>cigarette</td>
<td>Explosion</td>
</tr>
<tr>
<td>2008</td>
<td>Malaysia</td>
<td>Mallaca</td>
<td>refueling station</td>
<td></td>
<td>explosion; passengers severely injured</td>
</tr>
<tr>
<td>2008</td>
<td>UK</td>
<td>Sampford Peverell</td>
<td>road</td>
<td></td>
<td>car burnt out</td>
</tr>
<tr>
<td>2009</td>
<td>Italy</td>
<td>Marigliano</td>
<td>parking</td>
<td></td>
<td>explosion; damaged vehicles and buildings</td>
</tr>
</tbody>
</table>

Electric battery vehicles
A summary of some electric battery vehicle incidents is given in Table 3. In most of these incidents, the vehicles hit some objects and caused mechanical failure. The subsequent fire resulted in no deaths except in the accident in Shenzheng causing 3 deaths. However, it was reported that the 3 deaths was caused by the vehicle incident rather than the subsequent fires.

The main consequence of these electric vehicle fires is the loss of the vehicles. No explosion was reported. However, there might be low speed explosion (deflagration) occurred but not clearly observed.

Table 3  A summary of fire incidents with electric vehicles.

<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>City</th>
<th>Vehicle</th>
<th>Fire location</th>
<th>Ignition</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>China</td>
<td>Hangzhou</td>
<td>Zotye M300 EV</td>
<td>road</td>
<td>overheating of fan</td>
<td>no injury</td>
</tr>
<tr>
<td>2012</td>
<td>USA</td>
<td>California</td>
<td>Karma</td>
<td>parking lot</td>
<td>crashed by a car and then run into a tree</td>
<td>3 killed</td>
</tr>
<tr>
<td>2012</td>
<td>USA</td>
<td>Washington</td>
<td>BYD</td>
<td>road</td>
<td>fire after running over large metal objects</td>
<td>fire</td>
</tr>
<tr>
<td>2013</td>
<td>USA</td>
<td>California</td>
<td>Tesla</td>
<td>road</td>
<td>fire after hitting a tree</td>
<td>fire</td>
</tr>
<tr>
<td>2014</td>
<td>Canada</td>
<td>Toronto</td>
<td>Tesla</td>
<td>Garage</td>
<td>fire</td>
<td></td>
</tr>
</tbody>
</table>

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12 Blanco, Sebastian. “Second Tesla Model S fire caught on video after Mexico crash”. Autoblog Green. (Retrieved 2017-01-01)
<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>City</th>
<th>Vehicle</th>
<th>Fire location</th>
<th>Ignition</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>USA</td>
<td>California</td>
<td>Tesla</td>
<td>Road</td>
<td>Fire after running over large metal objects</td>
<td>fire</td>
</tr>
<tr>
<td>2016</td>
<td>Norway</td>
<td>Gjerstad</td>
<td>Tesla</td>
<td>Charge station</td>
<td>Might be a short circuit</td>
<td>burnt</td>
</tr>
</tbody>
</table>

**ALTERNATIVE FUEL VEHICLES**

There are many different types of alternative fuel vehicles. According to the different fuels used, they could be divided into four types: liquid fuels, liquefied fuels, compressed gases, and electricity [13]. A study of the parameters for these vehicles has been carried out by Li [13] and a short summary is presented here.

To ensure safety of pressurized tanks, pressure relief equipment is commonly used. There are mainly two types of valves existing in both liquefied gas tanks and compressed gas tanks, i.e. pressure relief valve (PRV) for normal venting and pressure relief device (PRD) for emergent venting. Under normal operations, when the pressure inside the tank rises above around a preset value, a tank normally vents via a PRV to avoid overpressure in the tank. When the pressure returns to the normal level the PRV will automatically turn off. However, excessive venting may cause a problem. To avoid rupture of a fuel tank in an emergency case, e.g. in a fire, a PRD will be activated after the tank pressure or temperature is over a certain value, which is generally much higher than preset value for PRVs.

**Liquid fuels**

The liquid fuels mainly consist of ethanol, methanol, biodiesel and other alcohols. Ethanol is one renewable fuel and has been widely used nowadays. Methanol is another renewable fuel similar to ethanol. The fuel tanks are similar to those for traditional liquid fuels. But the boiling point at atmospheric conditions is 78.5 °C for ethanol and 64.5 °C for methanol, in comparison to 155 °C for gasoline and 180-360 °C for diesel [13]. The size of the tank is mostly 50 to 100 liters for passenger cars, and 400 to 1000 liters for heavy duty vehicles.

**Liquefied fuels**

The liquefied fuels mainly consist of liquefied petroleum gases (LPG), liquefied natural gas (LNG) and liquefied hydrogen (LH$_2$). In contrast to liquid fuels, the liquefied fuels here are the fuels that are of gas phase at atmospheric pressure and temperature. By increasing the pressure and/or decreasing the temperature, the gaseous fuels are liquefied and stored in the tanks. Note that if the liquefied fuels are exposed suddenly to atmospheric conditions, the fuels need to absorb heat for evaporation.

LNG is typically stored in a range of 4 to 10 bar. At atmospheric pressure, natural gas remains in the liquid form at a temperature below -162 °C. In a vehicle tank, the temperature is slightly higher, mostly in a range of -140 °C to -136 °C. For LNG tanks, the activation pressures of PRDs are mostly in a range of 15 to 30 bar. The LNG tanks are only used for heavy duty vehicles, e.g. buses and trucks. As cryogenic tanks are used careful maintenance is required. Normally the tanks are well insulated. For trucks, the mass of LNG is in a range of 112 kg to 450 kg, and volume of 315 l to 1080 l. For buses, the mass of LNG is in a range of 150 kg to 214 kg, and volume of 356 l to 508 l [13]. The number of cryogenic LNG tanks is mostly 1 or 2. The mass for a single LNG tank mostly varies between 110 kg and 220 kg [13].

LPG is also called “autogas”. It mainly consist of either propane (C$_3$H$_8$) or butane (C$_4$H$_{10}$), or a

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14 https://www.technologyreview.com/s/521976/are-electric-vehicles-a-fire-hazard (Retrieved 2017-01-01)
15 http://www.fvn.no/nyheter/lokalt/Tesla
mixture of them. The tank pressure is mostly in a range of 8 to 10 bar. The tank pressure in reality is a function of temperature. Therefore the exterior temperature significantly affects the tank pressure. After the pressure is over around 20 bar, the PRVs will be activated for venting the gas, and recloses or reseals after the pressure is reduced. Therefore, under normal operation, the tank pressure is a variable, between 8 to 20 bar. PRDs for LPG tanks are generally activated when the pressure is around 32 bar, while the tank is generally supposed to sustain integrity at around 46 bar. The fuel has density and heat of combustion similar to gasoline and diesel. Therefore the tanks are of similar size. For many vehicles, versions of different fuel types are available, e.g. gasoline, diesel or LPG. For personal vehicles, the fuel tank size is mostly in a range of 50 to 100 liters. For trucks, the size can be as large as 400 liters.

Quite limited vehicles have used LH2. One main reason is the low temperature of -252 °C required to keep hydrogen in liquid form. The low temperature also indicates that the tank is sensitive to ambient temperature. If a tank has been placed in ambient for a certain time, the inside temperature will increase, and the pressure relief valves will activate to release gases. The vehicles are all equipped with internal combustion engines. The mass of liquid hydrogen is in a range of 2.4 kg to 8 kg. These are mostly concept vehicles.

DME is primarily produced from waste, biomass or natural gas. At ambient conditions, dimethyl ether is a colorless gas. But it can be easily liquefied, similar to propane. The pressure to keep it in the liquid form is around 5 bar. There have been some vehicle demonstrations with LDME but it may be of more use in the future. The operating pressure and pressure values for PRV and PRD are expected to be similar to those for LPG.

**Compressed gas**

Unlike the liquefied fuels, the compressed gases are stored in gaseous form and do not need to absorb heat for evaporation. The compressed gases mainly consist of compressed natural gas (CNG), and compressed hydrogen (GH\textsubscript{2}).

Natural gas mainly consists of methane. It could be produced from fossil or biogas industry. CNG is typically stored in steel or composite containers at a pressure of around 200 bar. It may also be stored in an adsorbed tank at a lower pressure, which however is not the case of main interest in this work. The tanks can be placed at various locations. A bus generally has several small tanks and they are mostly located on the top. A truck normally has one or two large tanks and they are mostly placed in the vicinity of the driver cab. A passenger car may have one to three small tanks which are placed in the trunk or below the seats. The pressure relief devices on CNG tanks are normally activated at a temperature of 110 °C. In case of a localized fire, the pressure relief devices may not be exposed to fire and thus not activated on time. Therefore, some CNG tanks also have pressure relief devices activating at a certain pressure, e.g. around 340 bar. The venting direction may either face upwards, downwards or horizontally. Long tubes may be used in order to relieve the pressure upwards.

Many passenger cars and light commercial vehicles consist of both CNG tanks and petrol tanks, i.e. they are so called “hybrid vehicles”. For passenger cars, the mass of CNG is in a range of 11 to 37 kg. For light commercial vehicles, the mass of CNG is in a range of 12 to 39 kg. The number of fuel tanks mostly varies between 1 and 5. The mass of a single tank varies between 10 and 20 kg. For buses, the mass of CNG is mostly in a range of 160 kg and 365 kg. The number of fuel tanks mostly varies between 4 and 10. The mass of a single tank varies between 20 and 50 kg. For trucks, the mass of CNG is in a range of 81 kg and 390 kg. The number of fuel tanks mostly varies between 4 and 8. The mass of a single tank varies between 10 and 50 kg.

Hydrogen can be produced from natural gas, but also from wind, solar and even garbage. At present, the number of vehicles using hydrogen as fuels is rather limited. Hydrogen may be used as fuel for both internal combustion engine and for fuel cells. For vehicles with internal combustion engines, the mass of hydrogen tank is around 2.4 kg with the storage pressure of 350 bar, which are also equipped with a 60 liter gasoline tank. For vehicles with fuel cells, the mass of hydrogen is in a range of 4 to 6
Electricity
The electric cars could be driven either by rechargeable batteries or other fuel cells such as renewable hydrogen fuel cells. But fuel cells normally use hydrogen from pressurized tank. Here only battery will be discussed. The battery is generally of significant size and mostly placed beneath the seats. The battery pack used in an electric vehicle mostly consists of several battery modules, each of which consists of many cells.

There are different types of rechargeable batteries on the market, e.g. lead-acid, nickel-cadmium, nickel metal hydride, and lithium-ion batteries. Among these, lithium-ion battery is the most common one used in electric vehicles. Some common Li-ions batteries include Lithium Iron Phosphate (LiFePO4), Lithium Manganese Oxide (LiMn2O4), Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2 or NMC), Lithium Cobalt Oxide (LiCoO2), Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2), and Lithium-titanate (Li4Ti5O12). A battery cell mainly consists of cathode, anode and electrolyte. Graphite is normally used as the anode material. An electrolyte mainly consists of a liquid solvent (such as Lithium hexafluorophosphate, LiPF6) and a salt which facilitates transport of charge inside the battery by means of ions [14]. The main liquid electrolytes used in lithium-ion batteries are ethyl carbonate (EC), propyl carbonate (PC), dimethyl carbonate (DMC), Ethyl-Methyl carbonate (EMC) and di-ethyl carbonate (DEC). In a power optimized Li-ion battery cell, the mass percentage for the flammable solvent is around 12%, and around 12% for graphite and 5% for plastics around the cell (the “coffee bag”) [14]. For typical solvents from a battery cell, a heat of combustion of 16 MJ/kg could be used. There are mainly three types of Li-Ion batteries used, i.e. LiMn2O4, LiFePO4 and LiNiCoAlO2. For these common Li-Ion batteries, an average value of 125 Wh/kg could be used for the energy density.

A serious malfunction of the batteries or the control system can potentially result in a thermal runaway. The reason may be overcharge, electrical fault, an external fire or heating source, and etc. In case of a thermal runaway, combustible gases are released in the surrounding compartment. The amount of venting gases may vary with other parameters, e.g. state of overcharge. In an electric battery vehicle incident, the fire spread between cells/modules takes time, depending on the configurations of the battery pack and the battery type. To be on the safe side, all the flammable solvents are assumed to be released into surroundings after an incident, while considering the explosion hazards. The venting gas may auto-ignite, or be ignited by an external fire or heating source. The consequence may be a fire or an explosion, depending on how the venting gases are distributed and how the combustion starts. The venting of the gases is generally similar to a jet with a high initial velocity. In some cases, it seems to be a jet fire during a certain period.

For passenger cars, the capacity is mostly in a range of 16 kWh to 100 kWh, and the mass in a range of 200 to 540 kg. More information on the electric passenger cars can be found in the literature [15]. For electric buses, the mass is mostly in a range of 1200 kg and 2500 kg. For electric trucks, the mass mostly varies between 615 kg to 3300 kg.

FIRE HAZARDS
There are mainly three types of fire hazards for the alternative fuel vehicles: pool fires, jet fires and fireballs.

After an incident, the liquid fuels may leak and form a pool on the floor. If an ignition source exists, a pool fire will occur. Note that a pool fire may also occur for a liquefied fuel vehicle.

If a liquefied tank leaks, a two-phase jet may form and the liquid may spill to floor and form a pool. This mostly occurs when the pressure valve is located at the low level of the tank (below the liquid surface). If a liquefied tank ruptures, a pool could also be formed. The main reason is that generally there is not enough heat to evaporate all the fuels instantaneously. Therefore, a fire incident with the
liquefied fuels may involve a pool fire together with a jet fire. The burning of the pool fires is similar to a gasoline pool fire but the burning intensities, e.g. mass burning rates, are normally much higher.

For a compressed gas vehicle, the most common fire hazard is a jet fire. A jet fire may also occur for a liquefied fuel vehicle. Much of the liquefied fuel changes in phase instantaneously when it is released to the ambient. In both cases, the jet fire occurs when the pressure valve is operating properly and the tank does not rupture. If there are several tanks in the vehicle, several pressure valves may be activated and several jets and one combined jets may be formed. At the beginning of a jet fire, a fire ball is normally formed. A fire ball refers to immediate ignition after a flammable gas is suddenly released, and therefore the mixing of flammable gas with air is rather limited and a flame ball will form. Normally the concentration of flammable gas is high in the center of the cloud due to lack of mixing.

For an electric battery vehicle, jet fires are also common consequence. After a thermal runaway, the gases vent out in the form of a jet. This phenomenon is obvious mostly during the initial stage of venting of a cell or a module. The venting gases at this stage mainly consist of electrolyte. But the flame length is not expected to be as long as for a jet fire from a compressed gas tank. If a fire does not start from the battery, the fire hazard may probably be similar to an internal combustion engine car. This has been shown by Lecocq et al. [16].

Spilled pool fires
The burning of the liquid fuels considered here is similar to a common pool fire. For example, in an ethanol or a methanol fire, the flame is much less luminous and the smoke is less dense. For the liquefied fuels, a pool may also form if the fuel leaks from the liquid side of the tank. The reason is that generally the heat containing in the liquid is not great enough to support complete evaporation and thus a portion of the fuel will remain in liquid form and form a pool. For a spilled pool fire, the mass burning rate is much less than that for a corresponding deep pool fire. For the spilled gasoline fires tested, the average heat release rate per unit area is about 1/3 to 2/5 of that for a deep pool fire [17], and a coefficient of 0.37 would be used. This also applies to other fuels in this work.

Tunnels mostly have both longitudinal slopes and transverse slopes (across the section). The reason for the transverse slopes is mainly for drainage. It, in reality, also aids to reduce the fire size in case of a spilled fire. For slopping tunnels, Ingason and Li [17] proposed correlations for estimating the spillage area and also the flow rate from a hole (or nozzle) of a tank. A spillage has two key dimensions, namely the width, \( B \) (m), and length, \( L \) (m). In order to calculate \( B \), the following equation was developed [17, 18]:

\[
B = \hat{V}^{0.46}
\]  

(1)

where \( \hat{V} \) is the outflow in l/s. The total area of the spillage up to the side of the road, \( A \) (m\(^2\)), is [18]:

\[
A = BL
\]  

(2)

The length, \( L \), depends on the inclination of the road surface. If the inclination across the direction of traffic (transverse) is \( x\% \) and in the direction of the traffic (longitudinal) is \( y\% \), the road surface is \( b \) metres wide, and the transverse distance from the release point to the opposite side of the road is \( c \) metres, \( L \), can be calculated according to the following equation [17, 18]:

\[
L = \frac{(b - c)}{\cos(\alpha)}
\]  

(3)

where the deflection angle \( \alpha = \arctan(\frac{y\%}{x\%}) \). In case of a hole at the bottom of a pressurized liquid fuel tank, e.g. a LPG tank, the volume flow rate can be estimated by:

\[
\hat{V} = C_d A_d \sqrt{\frac{2(P_{\text{tank}} - P_{\text{atm}})}{\rho} + 2gh}
\]  

(4)

For a liquefied fuel tank, the term related to static pressure difference is generally much higher than
the potential energy term. Further, in such case, if the process occurs during a significantly long period, the tank pressure may probably be close to the equilibrium pressure, dependent on the liquid temperature. Therefore a constant volume flow rate could be expected.

The heat release rate per unit fuel area (HRRPUA) for different fuels is given in Table 4. The values presented here are for spilled fuels around 1 mm thick. Apparently, the values for ethanol and methanol are much less than those for gasoline and diesel (biodiesel). However, the liquefied fuels have much higher values for HRRPUA. Especially for LH2 the value is as high as 8.9 MW/m$^2$, which is around 60 times that for ethanol and methanol.

The heat release rate depends on the spill area. Here a typical road tunnel is considered where the 9 m wide tunnel has a 2% longitudinal slope and a 1% transverse slope. The tank for all the liquid fuels is assumed to be 0.2 m high (passenger cars) and has a hole of 1 cm diameter at bottom. The volumetric flow rate is estimated to be around 0.1 liter/s for all the liquid fuels but much higher for the liquefied fuel tanks. The largest spill area and the highest heat release rate are shown in Table 4. As the spill area is mainly affected by the tunnel slopes, location of the tank, and the spillage flow rate, the spill area is considered to be the same, i.e. the calculated value is 15 m$^2$ for a 2% longitudinal slope and 65 m$^2$ for a 10% longitudinal slope, but a larger hole or a larger slope will produce a larger area. For the 2% longitudinal slope, the estimated highest heat release rate is around 2 MW for ethanol and methanol, compared to 13 MW for gasoline and 8 MW for diesel. For the 10% longitudinal slope, the estimated highest heat release rate is around 10-11 MW for ethanol and methanol, compared to 58 MW for gasoline and 37 MW for diesel. Clearly, the fire sizes for alcohol fuels are much lower. As the knowledge on spillage area for liquefied fuels is not clearly known, it is assumed here that all leaked fuels are burnt. The HRR is in a range of 43 to 49 MW.

If a tank has a large hole, the liquid may release instantaneously. Tests on a road tunnel [17] showed that the spillage area caused by an instantaneous release of 2 m$^3$ liquid varied between 138 m$^2$ and 163 m$^2$, with an average value of around 150 m$^2$. This corresponding to a heat release rate of 144 MW for gasoline, 91 MW for biodiesel, 24 MW for ethanol and 27 MW for methanol. The maximum heat release rate value is considered to be high, but it would be reasonably short-lived in terms of duration.

Therefore, it can be concluded that, from the perspective of fire size, the liquid fuels pose equivalent or even much lower fire hazards compared to the traditional fuels (gasoline and diesel). However, the liquefied fuels may pose a higher hazard compared to the traditional fuels.

Table 4  Heat release rates for different fuels spilled on the floor in a tunnel with 1% transverse slope (A hole of 10 mm diameter at the bottom of the 0.2 m high fuel tank).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>HRRPUA ($\text{MW/m}^2$)</th>
<th>Spillage rate (l/s)</th>
<th>Spill area ($\text{m}^2$)</th>
<th>Peak HRR* (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ethanol</td>
<td>0.15</td>
<td>0.11</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>methanol</td>
<td>0.17</td>
<td>0.11</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>diesel</td>
<td>0.56</td>
<td>0.11</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>gasoline</td>
<td>0.89</td>
<td>0.11</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>LPG</td>
<td>1.7</td>
<td>1.6</td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>LNG</td>
<td>1.4</td>
<td>2.3</td>
<td></td>
<td>49</td>
</tr>
<tr>
<td>LH2</td>
<td>8.9</td>
<td>4.5</td>
<td></td>
<td>45</td>
</tr>
</tbody>
</table>

* longitudinal slope.

Jet fires
A fuel jet could be formed if there is a small hole or open nozzle on a tank containing compressed gas or liquefied fuels. A jet fire differs from a common fire as its initial momentum (due to high velocity) has significant influence on the flame characteristics. The fuel mass flow rate is:
The flow through the nozzle is normally choked flow (critical flow) so that the jet velocity at the nozzle exit, \( u \), can be easily calculated. Two models could be used for estimation of jet flame length, i.e. the Heskestad model [19], the Delichatsios model [20], and Lowesmith et al’s model [21].

After a PRD opens, the fuel releases as a function of time. For a 20 kg CNG tank with initial tank pressure of 200 bar and a PRD of 5 mm diameter. The transient pressure as a function of time is shown in Figure 1, together with the fuel mass in the tank, the mass flow rate through the nozzle band the flame length. Clearly, the majority of the fuel is released within 1 min.

![Figure 1](image)

**Figure 1**  Fuel and fire properties as a function of time after the nozzle opens.

As the release rate is highly transient, the initial release rate will be the focus in the following. Table 5 gives the initial release rate for varying compressed gas fuels. It is assumed that the PRDs activate due to a sudden temperature rise and the internal pressure is close to the tank operation pressure. It can be seen that for hydrogen vehicles, the heat release rates are significantly higher than those for the CNG tanks mainly due to the high value for heat of combustion. In contrast, the flame lengths for hydrogen fuels are only slightly greater than those for CNG tanks. The flame length increases with the increasing diameter of the PRDs. The flame length can be as long as 40 m. The heat flux can be up to 22 kW/m\(^2\) for CNG and 69 kW/m\(^2\) for GH2 at 10 m from the fire. This indicates that all the fuels within the perimeter will be ignited, i.e. the possibility for fire spread is very high.
Table 5  Jet fire characteristics for different compressed gas fuels under operation pressure.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Diameter of PRD/ hole</th>
<th>Release rate</th>
<th>HRR</th>
<th>Heskestad</th>
<th>Delichatsios</th>
<th>Lowesmith</th>
<th>Heat flux*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>kg/s</td>
<td>MW</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>kW/m²</td>
</tr>
<tr>
<td>CNG 200 bar</td>
<td>2.5</td>
<td>0.13</td>
<td>7</td>
<td>5.6</td>
<td>7.3</td>
<td>6.0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.62</td>
<td>34</td>
<td>13.6</td>
<td>17.9</td>
<td>10.8</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.49</td>
<td>137</td>
<td>27.2</td>
<td>35.7</td>
<td>18.1</td>
<td>14</td>
</tr>
<tr>
<td>GH2 350 bar</td>
<td>2.5</td>
<td>0.10</td>
<td>14</td>
<td>7.0</td>
<td>8.0</td>
<td>7.6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.38</td>
<td>54</td>
<td>13.9</td>
<td>16.1</td>
<td>12.8</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.53</td>
<td>217</td>
<td>27.8</td>
<td>32.1</td>
<td>21.5</td>
<td>22</td>
</tr>
<tr>
<td>GH2 700 bar</td>
<td>2.5</td>
<td>0.19</td>
<td>27</td>
<td>9.8</td>
<td>11.4</td>
<td>9.9</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.76</td>
<td>108</td>
<td>19.7</td>
<td>22.7</td>
<td>16.6</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3.06</td>
<td>434</td>
<td>39.3</td>
<td>45.4</td>
<td>27.8</td>
<td>45</td>
</tr>
</tbody>
</table>

* received at 10 m away from the flame.

Table 6 gives the initial release rate for varying liquefied fuels assuming that the outlets are on the gas phase side of the tank. It is assumed that the PRDs activate after the tank pressure exceeds the preset value. It can be seen that all the results are significantly lower than those for the compressed gas tanks. This indicates the duration of the release will be much longer than compressed gas tanks. It may also suggest that the hazard for a BLEVE is higher than that for a gaseous tank rupture when being exposed to a fire. The heat release rate and the heat flux are much lower but the flame length can still be as long as 10 to 20 m.

Table 6  Jet fire characteristics for different liquefied fuels with PRDs on gas side.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Diameter of PRD/ hole</th>
<th>Release rate</th>
<th>HRR</th>
<th>Heskestad</th>
<th>Delichatsios</th>
<th>Lowesmith</th>
<th>Heat flux*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>kg/s</td>
<td>MW</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>kW/m²</td>
</tr>
<tr>
<td>LPG 32 bar</td>
<td>2.5</td>
<td>0.041</td>
<td>1.9</td>
<td>4.0</td>
<td>5.4</td>
<td>3.7</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.165</td>
<td>7.6</td>
<td>7.9</td>
<td>10.8</td>
<td>6.2</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.661</td>
<td>30</td>
<td>15.9</td>
<td>21.7</td>
<td>10.3</td>
<td>5.81</td>
</tr>
<tr>
<td>LNG 25 bar</td>
<td>2.5</td>
<td>0.019</td>
<td>1.0</td>
<td>2.4</td>
<td>3.1</td>
<td>2.9</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.076</td>
<td>4.2</td>
<td>4.8</td>
<td>6.3</td>
<td>4.9</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.305</td>
<td>16.8</td>
<td>9.5</td>
<td>12.5</td>
<td>8.3</td>
<td>1.74</td>
</tr>
<tr>
<td>LH2 10 bar</td>
<td>2.5</td>
<td>0.003</td>
<td>0.4</td>
<td>1.2</td>
<td>1.4</td>
<td>2.0</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.011</td>
<td>1.5</td>
<td>2.4</td>
<td>2.7</td>
<td>3.4</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.044</td>
<td>6.2</td>
<td>4.7</td>
<td>5.4</td>
<td>5.7</td>
<td>0.64</td>
</tr>
</tbody>
</table>

* received at 10 m away from the flame.

If the outlets are on the liquid phase side of the tank, e.g. a car turnover, the behavior of a jet will be very different. Table 7 gives the initial release rate for varying liquefied fuels. It is also assumed that the PRDs activate after the tank pressure exceeds the preset value. It can be seen that the results are significantly higher than those with PRDs on the gas side. For heat release rates and heat flux, the ratio between them is around 3:1. Comparing the results with those for gaseous tanks shows that the heat release rates are generally lower, especially for LH2. However, the heat flux for LPG falls on the same level as the CNG tanks since the radiation fraction for LPG is higher.
Table 7  Jet fire characteristics for different liquefied fuels with PRDs on liquid side.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Diameter of PRD/hole</th>
<th>Release rate kg/s</th>
<th>HRR MW</th>
<th>Lf, Lowesmith m</th>
<th>Heat flux* kW/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPG</td>
<td>32 bar</td>
<td>2.5</td>
<td>0.10</td>
<td>4.5</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>0.40</td>
<td>18.2</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>1.58</td>
<td>72.8</td>
<td>14.3</td>
</tr>
<tr>
<td>LNG</td>
<td>25 bar</td>
<td>2.5</td>
<td>0.055</td>
<td>3.0</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>0.22</td>
<td>12.1</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.88</td>
<td>48.5</td>
<td>12.3</td>
</tr>
<tr>
<td>LH2</td>
<td>10 bar</td>
<td>2.5</td>
<td>0.009</td>
<td>1.3</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>0.036</td>
<td>5.1</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.14</td>
<td>20.2</td>
<td>8.9</td>
</tr>
</tbody>
</table>

* received at 10 m away from the flame.

Note that the initial parameters discussed above are not dependent of the size of the fuel tank. But the size of a tank indeed affects the duration of a release.

If there are external flames continuously heating up the fuel tank, the heat absorbed will raise the tank pressure or slow down the decrease in tank pressure, and the corresponding results will be somewhat different.

For a tank jet fire in a tunnel, the initial jet flame length will probably be longer than the tunnel height or width, and impingement to tunnel structure is possible. The distribution of flames around the tank is highly dependent on the positioning of the tank valve. For a valve with outlet facing upwards, the flames will probably behave in a similar way as in a normal vehicle fire, i.e. there exist upstream and downstream ceiling flames under low ventilation while only downstream ceiling flame under high ventilation. For a valve facing downwards, significant flames will exist on floor and fire spread may occur easily. For a valve facing sidewalls, the scenario is more complicated, depending on how far it is from the side wall.

Fireballs

There have been many empirical correlations proposed for the diameter of the fire ball and the duration of combustion in the open. An approximate correlation for the fire ball diameter, \( D_{\text{max}} \) (m), is directly correlated to the fuel mass, \( m_f \) (kg), [22]:

\[
D_{\text{max}} = 5.8 m_f^{1/3}
\]  \hspace{1cm} (6)

The model for the fireball diameter in the open can be interpreted as the volume produced in case of a stoichiometric combustion in the open. Assuming the same relation between the fuel mass and flame volume for a fireball in a tunnel with cross-sectional area, \( A \) (m²), the following correlation for the longitudinal fireball length, \( L_{\text{max}} \) (m), can be proposed:

\[
L_{\text{max}} = 102 \frac{m_f}{A}
\]  \hspace{1cm} (7)

A comparison of the fireball diameter in the open and the fireball length in a 50 m² tunnel is shown in Figure 2. Clearly, the fireball length in a tunnel is much longer than the fireball diameter when the fuel mass exceeds around 5 kg.

A fireball in the open refers to a low flame speed and a negligible overpressure. In contrast, the scenario in a tunnel is different to a large extent due to the confinement of the tunnel structure. In a tunnel, the flame speed may continuously increase with distance from the ignition center, which may
cause significant overpressure, i.e. a deflagration. Therefore, there may not be typical fireball in a
tunnel, i.e. an initial fireball may probably result in a deflagration in the tunnel. The average burning
rate may be significantly increased, in combination of reduction in fireball length and duration.
Therefore, the above equation may tend to be conservative.

**Figure 2**  Comparison of fireball diameter in the open and fireball length in a 50 m² tunnel.

**EXPLOSION HAZARDS IN TUNNELS**

There is no simple and robust model to predict the blast waves in tunnels. Therefore, a one
dimensional CFD program is developed to simulate compressible flows in tunnels in case of tank
rupture, BLEVE and gas cloud explosion [13], which has been validated against test data for BLEVE
and cloud explosion in tunnels [13]. Afterwards, the program has been used to simulate the
phenomena for various fuel types and hazards. Some of the results are presented in the following.

**Gas tank burst**

The rupture pressure of a compressed gas tank may vary from case to case. Tank rupture due to
physical failure is one typical scenario, which is assumed by default. During a rupture of a high
pressure gas tank, the instantaneous energy released normally causes a blast wave. Generally, it
should be reasonable to assume that: (1) only one tank ruptures in an incident; (2) or even if more than
one tank ruptures the blast waves can be separately considered from the perspectives of explosion
safety; (3) the tank is full before rupture. The tunnel geometry also affects the results and it is
assumed to have a cross section of 5 m (H) × 10 m (W) by default in the following. Figure 3(a) shows
the peak overpressure as a function of distance from the CNG tanks of various quantities. Clearly, the
peak overpressure decreases rapidly within the first 50 m.

**Figure 3**  The overpressure vs. distance for CNG and LNG tanks of various quantities.
BLEVE
The same assumptions as for gas tank burst are applied here for BLEVE. Further, the fuels are assumed to be at superheat temperature to allow a significant amount of fuel evaporated instantaneously. Figure 3(b) shows the overpressure as a function of distance for BLEVE of LNG tanks of various quantities in a tunnel. Similar trend can be found as in Figure 3(a). By comparing the two figures, it can be found that the overpressure for 110 kg LNG is similar to that for 50 kg CNG. This indicates that the explosion energy for LNG is much lower than that for CNG of the same amount of fuels. This is mainly related to the initial high tank pressure in the CNG tank.

Gas cloud explosion
To be on the safe side, three assumptions are made in the following analysis: (1) stoichiometric mixture is assumed and thus all fuels contribute to the blast wave, in the following analysis; (2) In case of an incident, all the fuel tanks of the incident vehicle are assumed to fail and contribute to the gas cloud explosion; (3) the fuel tanks are full. For a liquefied fuel tank, the fuels involved in a gas cloud explosion should include not only the flashed fuels, but also the sprays, aerosols, and the part of the fuels that evaporate by absorbing external heat before the explosion. In such case, the total amount of the fuel is generally considered to be twice the flashed fuels. This indicates that the flash fraction for superheated fluid is in a range of 50 % and 100 %. Further, the initial temperature at the moment of rupture is not clearly known. For simplicity, in the following, it is assumed here that all the fuels are involved in the cloud explosion, which can be considered as the worst case.

Figure 4 shows peak overpressure vs. distance for cloud explosion of CNG tanks of various quantities in a tunnel. The peak overpressure for CNG tanks with fuels over 320 kg is over 24 bar. In such cases, deflagration to detonation has occurred, and there exists a rather sharp decrease in peak overpressure at around 80 m from the ignition center, after which the decay is much slower. To express the results more clearly, results for 10 kg to 80 kg CNG are also plotted. For 10 kg CNG, the pressure decay over the distance is rather slow, in contrast to that for a tank rupture or BLEVE. For 10 kg CNG, the overpressure is mostly less than 20 kPa and the corresponding explosion hazard is relatively tolerable according to the criteria proposed by Jeffries et al. [23]. Note that the assumption that all tanks fail simultaneously before ignition may not be likely to occur. Instead, a single tank or small portions of the gas tanks contribute to the gas cloud explosion may be more realistic. So the results can be interpreted in a different way.

Figure 4  The overpressure vs. distance for cloud explosion of CNG tanks in tunnel.

Comparison of various fuels in existing vehicles
A summary of the peak overpressures and explosion energies for gas tank rupture and BLEVE with various fuel tanks in existing vehicles is summarized in Table 8. The explosion energy is mostly in a range of 2 – 50 MJ. The peak overpressure is in a range of 0.1 –0.36 bar at 50 m, and 7-24 bar at 100 m from the tank. The consequences of such incidents are relatively tolerable for tunnel users at these locations.
### Table 8  Comparison of tank rupture and BLEVE for various vehicles in tunnels.

<table>
<thead>
<tr>
<th>Explosion type</th>
<th>Vehicle type</th>
<th>Calculated energy (MJ)</th>
<th>Overpressure at 50 m (kPa)</th>
<th>Overpressure at 100 m (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas tank rupture</td>
<td>CNG</td>
<td>5 - 26</td>
<td>15 - 29</td>
<td>10 - 20</td>
</tr>
<tr>
<td></td>
<td>GH2</td>
<td>5 - 18</td>
<td>10 - 15</td>
<td>7 - 11</td>
</tr>
<tr>
<td>BLEVE</td>
<td>LNG</td>
<td>7 - 30</td>
<td>22 - 36</td>
<td>15 - 24</td>
</tr>
<tr>
<td></td>
<td>LH2</td>
<td>0.08 – 0.8</td>
<td>1 - 2</td>
<td>0.7 - 1.5</td>
</tr>
<tr>
<td></td>
<td>LPG</td>
<td>2 - 14</td>
<td>10 - 16</td>
<td>7 - 11</td>
</tr>
<tr>
<td></td>
<td>LDME</td>
<td>3 - 20</td>
<td>11 - 19</td>
<td>7 - 13</td>
</tr>
</tbody>
</table>

A summary of the peak overpressures and explosion energies for gas cloud explosion with various fuels in existing vehicles is summarized in Table 9. The explosion energy is in a range of 0.2 – 23 GJ. The peak overpressure is in a range of 0.15 – 11.2 bar at 50 m, and 0.15-18.5 bar at 100 m from the ignition center. The consequences of such incidents are mostly not tolerable for tunnel users referring to [23]. Comparing the two tables clearly shows that both the explosion energies and the peak overpressures are significantly higher for gas cloud explosion.

Not that the overpressures for GH2 and LH2 are relatively low due to the fact that the fuel mass or the explosion energy is small in comparison to others. This does not mean that they are safer than the others. It only means that the hydrogen tank sizes presently used in vehicles are relatively small.

### Table 9  Comparison of energy and peak overpressure for gas cloud explosion with various fuels.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Energy</th>
<th>Overpressure at 50 m</th>
<th>Overpressure at 100 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNG</td>
<td>0.5 - 20</td>
<td>15-780</td>
<td>15-830</td>
</tr>
<tr>
<td>GH2</td>
<td>0.2 - 0.7</td>
<td>19-38</td>
<td>18-36</td>
</tr>
<tr>
<td>LNG</td>
<td>5.5 - 23</td>
<td>136-850</td>
<td>120-1850</td>
</tr>
<tr>
<td>LH2</td>
<td>0.2 - 1</td>
<td>19-84</td>
<td>18-73</td>
</tr>
<tr>
<td>LPG</td>
<td>1.4 - 11</td>
<td>30-600</td>
<td>30-223</td>
</tr>
<tr>
<td>LDME</td>
<td>1.4 - 11</td>
<td>23-300</td>
<td>22-200</td>
</tr>
<tr>
<td>Battery</td>
<td>0.4 - 9</td>
<td>37-1120</td>
<td>34-582</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

Different types of new energy powered vehicles are investigated and detailed parameters are obtained. According to the different fuels used, they could be divided into four types: liquid fuels, liquefied fuels, compressed gases, and electricity.

From the perspective of pool fire size, the liquid fuels may pose equivalent or even much lower fire hazards compared to the traditionally used fuels, but the liquefied fuels may pose a higher hazard. The pool fire hazards are related to the spillage area, which highly depends on tunnel slopes and outflow holes. For pressurized tanks, the fires are generally much larger in size but shorter in duration. The gas release from PRD and the resulting jet fires are highly transient. For hydrogen vehicles, the fire sizes are significantly higher compared to CNG tanks, while flame lengths only slighter longer.

Investigation of the peak overpressure in case of an explosion in a tunnel was also carried out. The results showed that the consequences of tank rupture and BLEVE are relatively tolerable for tunnel users for a position 50 m away, but the situations in case of cloud explosion are mostly very severe and intolerable for tunnel users.

These hazards need to be carefully considered in both vehicle safety design and tunnel fire safety design, e.g. limiting the fuels and stringent prevention of such incidents. Further researches on these hazards, especially large scale experiments, are in urgent need.
REFERENCES

Fire Incident and Fire Safety Operational Data for Major Australian Road Tunnels

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ABSTRACT
This paper sets out the process through which fire incident and fire safety operational information was collected for eleven major road tunnels in Australia. This tunnel data set are the major tunnels in Australia as defined by physical characteristics (i.e. unidirectional or length greater than 1km), their high traffic volume and urban location as well as their being monitored and controlled through a dedicated control centre that is continuously staffed. The result of this work is an extensive and high quality data set of 78 fire incidents. The period covered by the study is from the opening date of each of the tunnels, the Sydney Harbour Tunnel being the first opened in August 1992, up to and including June 2016.

The base information was processed and a normalised data set produced. This was then analysed and a series of simple clear graphs produced which advise their fire safety performance. The paper presents a process through which this current database can be updated to include future fire incidents. A fire incident questionnaire is provided, the completion of which for future fire incidents would facilitate ease of addition of future incidents to the base data set.

Of particular interest to an international audience is the performance of fixed fire fighting systems. The Australian tunnelling industry is amongst the most experienced in the design, installation and operation of this technology, given it has been applied in all major road tunnels since 1992. This paper expands on previous work [1] to provide additional detail with a focus on fire safety operational data related to the use of these systems to allow understanding of their benefits in fire safety and operational continuity.

KEYWORD: fire incident, road tunnel, detection, suppression, deluge, operational continuity

INTRODUCTION
Historic data on vehicle fire incidents in road tunnels can be a very useful reference tool at decision points in the life cycle of road tunnel assets. The March 2007 fatal crash and fire at Burnley Tunnel was intensely analysed, with recommendation that a centrally administered database of tunnel incidents be created [2]. The work presented here aligns with that recommendation by gathering and processing data from all fire incidents allowing a broader more comprehensive assessment to be made of the performance of Australian road tunnels in response to fires.

Article 15 of the European Union directive on minimum safety requirements for tunnels in the trans-European road network, requires member states to publish fire incident statistics for their road tunnel assets every two years [3]. The work referenced here are some quality examples of such data being presented at a national level [4, 5, 6]. In addition, the World Road Association (WRA) Road Tunnel Operations Committee has recently issued a report which identifies and compares road tunnel fire incident data for various countries [7]. This work presented here allows the Australia fire incident data
set to be compared to data sets for other countries.

This work has been compiled through the Austroads Tunnel Task Force (ATTF). The ATTF consists of representatives of various Australian states and New Zealand as well as representatives from industry bodies the Australasian Tunnel Operators Group (ATOG) and the Australasian Tunnelling Society (ATS). Critical to the compilation of the data has been the positive input received from ATOG. While this body is focussed on the operational phase of road tunnels, it’s members recognise the value of providing information to those focussed on the planning, development and delivery phases of projects. The ATTF, with this mixture of representatives, is therefore well placed to give a balanced view of the requirements of all phases of the road tunnel life cycle.

This work aims to combine the disparate data sets recorded at each tunnel location, and present a combined data set that reflects the performance of Australian road tunnels in response to fire incidents.

It is envisaged that the data can be used as a reference through both the development phase of projects (in order to inform designs and design standards) as well as during the operational phase of assets (as a means of demonstrating the effectiveness of the fire safety measures deployed). It is planned that the data set will be periodically refreshed, perhaps every three years, to ensure that an up-to-date reference is available. The data set does not reflect all road tunnels in the Austroads area.

TUNNEL DATASET

The road tunnels for which data has been collected and included in this work are set out in Table 1.

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Location</th>
<th>Year of Opening</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sydney Harbour</td>
<td>Sydney</td>
<td>1992</td>
<td>2.3</td>
</tr>
<tr>
<td>Eastern Distributor</td>
<td>Sydney</td>
<td>1999</td>
<td>1.7</td>
</tr>
<tr>
<td>CityLink</td>
<td>Melbourne</td>
<td>2000</td>
<td>3.4 (Burnley)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.6 (Domain)</td>
</tr>
<tr>
<td>Graham Farmer</td>
<td>Perth</td>
<td>2000</td>
<td>1.6</td>
</tr>
<tr>
<td>M5 East</td>
<td>Sydney</td>
<td>2001</td>
<td>4.0</td>
</tr>
<tr>
<td>Cross City</td>
<td>Sydney</td>
<td>2005</td>
<td>2.1</td>
</tr>
<tr>
<td>Lane Cove</td>
<td>Sydney</td>
<td>2007</td>
<td>3.6</td>
</tr>
<tr>
<td>Clem Jones</td>
<td>Brisbane</td>
<td>2007</td>
<td>4.8</td>
</tr>
<tr>
<td>EastLink</td>
<td>Melbourne</td>
<td>2008</td>
<td>1.6</td>
</tr>
<tr>
<td>Airport Link</td>
<td>Brisbane</td>
<td>2012</td>
<td>6.7</td>
</tr>
<tr>
<td>Legacy Way</td>
<td>Brisbane</td>
<td>2015</td>
<td>4.6</td>
</tr>
</tbody>
</table>

The first major road tunnel constructed in Australia was the Sydney Harbour Tunnel which opened in 1992. Therefore, this work not only includes all major tunnels but also all of the major tunnels are of relatively recent construction. Given their relatively recent construction the tunnels have many consistent characteristics. These include:

- Uni-directional
- Continuous monitoring and control via a dedicated tunnel or motorway control room
- Longer than one kilometre
- Heavily trafficked urban locations
- Dangerous goods vehicles are not allowed
- Very similar fire safety measures.

These consistent measures mean that the variance in frequency and type of incidents that occur in different tunnels can be attributed to other issues. These variables would include:
• Alignment and grade
• Age and maintenance of vehicles using the tunnels
• Percentage split of Passenger Cars, Light Duty Vehicles and Heavy Goods Vehicle using the tunnel
• Driving behaviours.

The main purpose of limiting the number of tunnels reflected in the data set was to ensure the consistency, reliability and quality of the data. For example, heavily trafficked but shorter tunnels such as the Mascot (Airport) Tunnel (550m) in NSW are not continuously monitored, and so all fire incidents are unlikely to have been captured. Also inclusion of some New Zealand tunnels was considered. The Lyttleton Tunnel (Christchurch, NZ), while monitored, is bi-directional and so introduces new fire risks (related to head on collisions) that do not exist in uni-directional tunnels.

There are a number of road tunnel projects currently (January 2018) underway in Australia and New Zealand. By 2025, the total number of tunnel lane kilometres in operation will double with most of the projects being delivered in Sydney and in Melbourne. Since the completion of this work, the Waterview Tunnel (Auckland, NZ) has been opened for operation. Future revisions to this data will reflect these new Australian and New Zealand tunnels.

Fire Safety Measures in the Tunnel Data Set

The following fire safety features are consistent across this tunnel data set:

- Fire suppression
  - Hand held extinguishers
  - Hosereels
  - Deluge
  - Hydrants
- Tunnel ventilation
- Emergency egress passages
- CCTV
- Public address
- Radio re-broadcast
- Emergency services radio networks

Fixed Fire Fighting (Deluge) Systems

All of the tunnels in the data set include a fixed fire fighting (deluge) system (FFFS). The World Road Association [8] confirms regarding FFFSs that ‘their installation provides the fixed infrastructure within a tunnel to enable fires to be addressed more quickly and more easily than if incident responders had to provide and deliver alternate systems to the fire site to respond to the event by other means’. This comprehensive set of data allows an assessment of these suggested benefits.

FFFSs are also not mandatory requirements of NFPA 502. However, many recently constructed tunnels in the United States such as the Presidio Parkway in San Francisco and the Port of Miami Tunnel are fitted with an FFFS. According to NFPA502, the inclusion of FFFSs should be the subject of engineering analysis and agreement with the authority having jurisdiction [9]. For those considering the use of FFFS, this Austroads work will provide a hitherto unavailable data set demonstrating how such systems have performed.

FFFS used in these Australian tunnels have the following characteristics:

- All major tunnels have deluge fire suppression systems and fire hydrant systems
- The design average water spray density varies from 7.5mm/min to 12mm/min (10mm/min for multi vehicular traffic current de-facto standard)
Water storage is typically sized to supply the water spray design density for a minimum of 2 hours over any 60m length of the carriageway.

The design area of operation is carriage/ramp road surface only ie. Barrier to barrier.

Total water capacity is therefore determined at the 60m length by the maximum width within the project.

Total fire water storage can be combined into common tanks however water supply distribution pipework requires separate mains pipework ie deluge and hydrant systems.

Deluge can be deployed over a longer length but a reduced water spray design density or application duration may result.

Design area of operation for Deluge zone sizes were historically up to a maximum of 300m2 (traditional building design requirement), but this has recently via project specific performance based engineering been increased up to 550/600m2.

Deluge zones are typically set out to align with 120m emergency cross-passage spacing (with multiples of 4 zones per 120m spacing).

Deluge valves are located in cross-passages.

The system is a wet system from the water supply to the deluge valve, and the system is dry from the valve to the nozzle. Climatic conditions mean there is no risk of freezing.

Duty & Standby Pumps each provide 100% capacity.

Activation is typically by manual operation at a remote tunnel control room.

There is no fire suppression enhancing additives in the water.

DATA COLLECTION

During and immediately post fire incidents tunnel operators collect and record data using the available systems and tools. Different tunnels employ varying procedures and recording methods. The key tools used for capturing the information were:

- Incident Logs (manual)
- Operational Management Control System (OMCS) Logs
- CCTV Footage
- Major Incident Reports.

It is necessary to present the base information in a consistent format and terminology in order to allow it to be analysed as a set. The following tasks were undertaken:

1) Collection of data from tunnel operators
2) Review of the data for gaps and inconsistencies
3) Confirmation that the incident was not incorrectly labelled as a fire
4) Interpretation of data to fill gaps (where deemed appropriate)
5) Revision of base data to reflect consistent terminology
6) Validation of the revised data by the respective tunnel operators
7) Compilation of a single data set in spreadsheet format
8) Analysis of the data set
9) Presentation of data

The resultant data set can be analysed by various parameters including:

- Vehicle Type
- Fire Source
- Fire Size (approximated)
- Means of Detection
- Traffic Conditions
- Means of Fire Extinguishment
- Durations
  - Tunnel Closure
  - Fire
The data set only includes vehicle fires where it is deemed that flame has been visible and sustained. The base data set included some incidents, such as car turbo blow-outs, which produced smoke but not sustained flame. These incidents are therefore excluded from the final data set. Fires that do not originate from vehicles are also excluded from the data set.

**FIRE INCIDENT DATA**

**Frequency of Fire Incidents**

Figure 1 sets out the aggregated annual vehicle kilometres travelled through all of the major tunnels for each year since the opening of the Sydney Harbour Tunnel. Step increases co-incide with the opening of new tunnels (i.e. Eastern Distributor, CityLink and Graham Farmer Tunnels in 1999/2000). Figure 2 sets out the number of fire incidents that have occurred in each year. Note that those years in which there was no fire incident are excluded.

Fire and Rescue New South Wales in their annual report publish data related to the number of vehicle fires that they attend across the state (mostly surface roads). From 2003/04 to 2013/14 recorded vehicle fires have decreased by 35% [10]. The Australian Bureau of Statistics records data on vehicle usage across Australia [11]. For a similar period, 2004 until 2014, they record an approximate 23% increase in total vehicle kilometres travelled nationally. One concludes that vehicle fire incidents are decreasing despite increasing vehicle usage.

![Figure 1 - Annual Vehicle Kilometres (Billions) Travelled through Major Australian Road Tunnels](image-url)
Table 2 - Frequency of Fires in Major Australian Road Tunnels

<table>
<thead>
<tr>
<th>No. of Fires</th>
<th>Vehicle Kilometres Traveled (vkt)</th>
<th>Fire Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>78</td>
<td>10,338,000,000</td>
<td>1 fire / 132 million vkt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 fires billion vkt</td>
</tr>
</tbody>
</table>

Table 2 provides some simple metrics related to the frequency of fire incidents. Figure 3 presents a comparison of Austroads and WRA data. The graph is formed by overlaying the results of this work on top of a graph presented by WRA [7]. The resultant graph confirms that only Italy and France have a more comprehensive data set as their data reflects more vehicle kilometres travelled. The graph identifies that the frequency of fires in the major Australian tunnels is relatively low (comparable to Austria and South Korea).

As tunnels in the Australian data set are continuously monitored, all minor fire incidents as well as major fire incidents are recorded. Tunnels in other data sets are not continuously monitored and so they may not reflect all of the minor fire incidents that have occurred.
This issue is identified by WRA [7]. Their presentation of data from Norway suggests that continuously monitored tunnels have four times the frequency of recorded fire incidents compared to non-monitored tunnels. There may be less likelihood that smaller fires are recorded given that fire brigade intervention and vehicle recovery assistance may not be required. On this basis we conclude that road tunnel fires in major Australian road tunnels occur as frequently, or less frequently, than in countries presented in the WRA data.

Table 3 – Classification of Fires by Vehicle Type in Major Australian Road Tunnels

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>No. of fires</th>
<th>Percentage of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Car / Light Duty Vehicle</td>
<td>41</td>
<td>53.9%</td>
</tr>
<tr>
<td>Light Duty Vehicle</td>
<td>20</td>
<td>18.4%</td>
</tr>
<tr>
<td>Heavy Goods Vehicle</td>
<td>14</td>
<td>26.3%</td>
</tr>
<tr>
<td>Multiple Vehicle</td>
<td>1</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

The vehicle type in two fires is unconfirmed, and so these are excluded from Table 3.

Fire Size

The vehicle fires that have occurred vary in their magnitude and consequence. Larger fires bear the risk of more significant consequences for tunnel occupants, owners and operators. However, the work aligns with international data in confirming that small fires predominate [7]. Tunnel fire safety features should also be designed to effectively and efficiently respond to smaller fires. The two key attributes of fires are the peak heat release rate (PHRR) and the fire growth rate. This document focuses on PHRR as a means of categorising road tunnel fires. While this approach is consistent with existing documentation, it also reflects the reality that fire growth rates are very difficult to accurately estimate without instrumentation of the type that might only be installed in road tunnels when specialist testing is being conducted (i.e. not in normal operation).

During the initial post incident recording of fires, there has been no attempt to quantify the PHRR. However, to inform the design of fire and incident management systems it is worthwhile gaining an understanding of fire severity as well as fire frequency. What follows is a bespoke methodology to estimate fire sizes based on the available information. Clearly, deluge systems, where deployed, will have constrained the size to which the fire may have grown. In the author’s view this methodology will conservatively overestimate the actual PHRRs for most incidents.

Table 4 sets out the methodology through which PHRR have been estimated. For example, for fires on Light Vehicles that self-extinguish as the vehicle passes through the tunnel, a PHRR of between 0 and 1 MW is assumed. For fires on Light Vehicles where deluge is judged to be required, the deluge ensures that the upper limit of 5MW is not exceeded.

Table 4 – Methodology for Estimating Fire Size

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Fire Actively Extinguished?</th>
<th>Means of Extinguishing?</th>
<th>Fire Severity Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Car / Light Duty Vehicle</td>
<td>No</td>
<td>Self Extinguishing</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Drive Through</td>
<td>5</td>
</tr>
<tr>
<td>Yes</td>
<td></td>
<td>Hand Held / Hosereel</td>
<td>4 or 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deluge</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrant</td>
<td>3 or 4</td>
</tr>
<tr>
<td>Heavy Vehicles</td>
<td>No</td>
<td>Self Extinguishing</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Driven Through</td>
<td>5</td>
</tr>
<tr>
<td>Yes</td>
<td></td>
<td>Hand Held / Hosereel</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deluge</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrant</td>
<td>1 or 2 or 3</td>
</tr>
</tbody>
</table>
For PHRR of light vehicles the methodology is informed by the work summarised in the Handbook of Tunnel Fire Safety [12]. As a result, a PHRR of 5MW has been applied to all Passenger Car fires and all but one Light Duty Vehicle (LDV) Fire. It is felt that not only is the testing referenced in [12] supporting an upper limit of 5MW, but also those Australian vehicle fires that might approach 5MW would be suppressed with deluge. There was one fire on a large LDV for which deluge was used. This was conservatively placed in Severity classification 3 designating a PHRR of between 5MW and 20MW, although the fire may not have reached the 5MW threshold. Furthermore, at a fast fire growth ($t^2$) rate, a fire will not reach a PHRR of 5MW until approximately 6 minutes after the fire started.

For deluge constrained PHRR of heavy goods vehicles (HGVs), the methodology is informed by tests undertaken by the Land Transport Authority of Singapore [13]. The tests show that large fires which have deluge applied after 4 minutes do not reach an upper PHRR limit of 50MW. Therefore an upper limit of 50MW is applied to all deluge suppressed fires in Australian tunnels. If the deluge is sufficient to extinguish the fire without application of hydrants then an upper limit of 20MW has been assumed. For those fires where both deluge and hydrants are applied, the author’s judgement has been used to assess the PHRR of the fire. Note that the Burnley tunnel fire was approximated at 30MW [2]. This is the largest fire in the data set.

The results of applying the methodology to the data set of 78 fires are presented in Table 5. The fire severity categories were chosen to best align with the data presented in the WRA report [7] so that if the opportunity arises the two data sets can be combined.

<table>
<thead>
<tr>
<th>Fire Severity Category</th>
<th>Approx. Fire PHRR</th>
<th>Non-HGV (73.7%)</th>
<th>HGV (26.3%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0 - 1MW</td>
<td>33 (41.2%)</td>
<td>12 (15%)</td>
</tr>
<tr>
<td>4</td>
<td>1 – 5MW</td>
<td>25 (31.2%)</td>
<td>1 (1.3%)</td>
</tr>
<tr>
<td>3</td>
<td>5 – 20MW</td>
<td>1 (1.3%)</td>
<td>7 (8.8%)</td>
</tr>
<tr>
<td>2</td>
<td>20- 50MW</td>
<td>-</td>
<td>1 (1.3%)</td>
</tr>
<tr>
<td>1</td>
<td>&gt;50MW</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note that only one fire was recorded as being the result of a collision. There were no fires on buses.

Means of Detection

The analysis of the fire incident data yielded the results shown in Figure 4 with respect to the means of detection of vehicle fires in tunnels.

![Figure 4 – Means by which Vehicle Fires in Major Australian Tunnels were Detected](image)

This confirms that the majority of fires were detected by the tunnel Operator with the assistance of either CCTV or OMCS tools. Initial OMCS alerts / alarms typically identify stopped vehicles. Once the stopped vehicle has been located by the Operator, through CCTV or OMCS traffic alerts, the
Operator will focus on the incident vehicle and monitor it for any developing fire.

Figure 5 – Means of Fire Detection by year

Figure 5 sets out to distinguish whether there is a trend in how fires are detected by displaying the detection method in each year. We conclude that in recent years Operator detection using OMCS and CCTV tools has predominated. This trend is likely to continue as future tunnels being delivered are longer and more complex requiring greater reliance on automated systems.

Noteworthy from Figure 4 and Figure 5 is that there is no instance of Linear Heat Detection or similar system being the first means of detection of fires.

Means of Extinguishing Fires

The data yielded the following results with respect to the means of extinguishing vehicle fires in tunnels.

Figure 6 – Means by which Vehicle Fires in Major Australia Tunnels were Extinguished

Hand held extinguishers, either those installed in the tunnel or carried on vehicles, were used to extinguish over 40% of fires. While deluge was used on 38% of fires, it extinguished 20%. Emergency Services extinguished 18% of fires using a hydrant system.

The data is not sufficiently detailed to confirm what percentage of these fires required the use of the tunnel hydrant system, and for what percentage the use of emergency service truck was sufficient. Of those fires that were eventually extinguished by hydrants, only very few required prolonged hydrant
activity (>5mins). Standard water storage per Fire and Rescue New South Wales fire appliance is 1,800 litres while the discharge rate from one hydrant is approximately 10 litres/second. This therefore provides a limited supply period of approximately 3 minutes. A small number of fires were not extinguished in the tunnel as the vehicle was driven through the tunnel without stopping.

**Deluge**

In response to the 78 fires, Operators have deployed deluge on 30 occasions. Therefore, for the majority of fires (48), Operators have determined that the use of the deluge system was not needed as the risk from the fire was low.

**Table 6 – Time from Fire Detection to Deluge Deployment**

<table>
<thead>
<tr>
<th>Duration (mins)</th>
<th>&lt;1</th>
<th>&lt;2</th>
<th>&lt;3</th>
<th>&lt;4</th>
<th>&lt;5</th>
<th>&lt;6</th>
<th>&lt;7</th>
<th>&lt;8</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Fires</td>
<td>7</td>
<td>14</td>
<td>22</td>
<td>25</td>
<td>28</td>
<td>28</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>By Percentage</td>
<td>23.3%</td>
<td>46.6%</td>
<td>73.3%</td>
<td>83.3%</td>
<td>93.3%</td>
<td>93.3%</td>
<td>96.6%</td>
<td>100%</td>
</tr>
</tbody>
</table>

This table provides an approximate guide to the delay that occurs from fire detection to deluge being applied, for those 30 fires where deluge has been used. When recording the data numbers has been rounded up to the nearest minute, therefore the resultant figures will be conservatively high. The resultant average time from detection to deluge deployment was 2.9 minutes. This average is also affected by two outliers in the data where deluge was applied some 7 minutes and 8 minutes after detection. These fires are likely to be lower risk fires that smoulder. The delay having been a result of operator monitoring the incident, identifying it as lower risk and then deploying deluge when flame can be seen.

Figure 7 confirms that out of these 30 instances the deluge system was successful in extinguishing the fire on 16 occasions. Of the remaining 14 instances, it is assumed that while the deluge system suppressed the fire, the fire will have been extinguished by the Emergency Services using a hydrant system.

**Table 7 – Duration of Deluge Deployment**

<table>
<thead>
<tr>
<th>Duration (mins)</th>
<th>&lt;5</th>
<th>&lt;10</th>
<th>&lt;15</th>
<th>&lt;20</th>
<th>&lt;25</th>
<th>&lt;30</th>
<th>&lt;40</th>
<th>&lt;45</th>
<th>&lt;55</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Fires</td>
<td>1</td>
<td>6</td>
<td>13</td>
<td>20</td>
<td>22</td>
<td>27</td>
<td>28</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>By Percentage</td>
<td>3.3%</td>
<td>20%</td>
<td>43.3%</td>
<td>66.7%</td>
<td>73.3%</td>
<td>90%</td>
<td>93.3%</td>
<td>96.7%</td>
<td>100%</td>
</tr>
</tbody>
</table>

The longest and second longest duration of deluge were 51 and 41 minutes respectively. The average and median durations of deluge deployment were 19 and 18 minutes respectfully.

While the Operator activates the deluge system, it is standard procedure that the Emergency Services determine when the system should be turned off. Some of the 16 fires that were extinguished by deluge may have been extinguished prior to the arrival at the incident of the Emergency Services. Therefore the recorded duration of deluge will be greater than was needed to extinguish the fire. Therefore the average and median figures presented may be conservatively high.
Standard operating procedure is for the Operator to apply one deluge zone, and then monitor the effectiveness of that zone in dealing with the fire. Further zones can be deployed if needed. However, Figure 7 identifies that when deluge has been deployed, two deluge zones have typically been used. This suggests that Operators may either be having difficulty in targeting the deluge zone to the fire zone or may be conservatively deploying additional deluge zones to minimise risk. On two occasions four zones were used, probably due to poor identification of the fire zone. On these occasions the duration of deluge deployment was 2 minutes and 18 minutes respectfully. To combat the Burnley Tunnel fire three deluge zones were concurrently deployed for 51 minutes.

The data was also assessed for trends in the use of deluge to combat fire incidents. Figure 8 shows the number of fires per year (bar chart) with the trend in deluge use superimposed in red line.

If one looks at the percentage of fires per year for which deluge is used, then a contrast in the data set appears between earlier years (up to and including 2008) and more recent years (after 2008). In more recent years deluge has been used in a higher percentage of fire incidents. The reasons for this are not clear but may be a consequence of:

- more serious incidents,
- vehicle occupants being less likely to take action (reduced use of hand held extinguishers),
- vehicle occupants being better informed of tunnel safety provisions,
- more congestion leading to higher perceived risk or
- change in standard operating procedures.

Impact on Tunnel Operations

Along with life safety, fire safety features in major Australian tunnels also achieve high performance in terms of operational continuity. Most tunnels are part of tollways. The fire data includes the recorded duration of fire incidents.
Table 8 – Recorded Time from Fire Detected to Fire Declared Extinguished

<table>
<thead>
<tr>
<th>Duration (mins)</th>
<th>&lt;5</th>
<th>&lt;10</th>
<th>&lt;20</th>
<th>&lt;30</th>
<th>&lt;40</th>
<th>&lt;50</th>
<th>&lt;60</th>
<th>&gt;60</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Fires</td>
<td>15</td>
<td>34</td>
<td>54</td>
<td>66</td>
<td>69</td>
<td>70</td>
<td>70</td>
<td>71</td>
</tr>
<tr>
<td>By Percentage</td>
<td>21%</td>
<td>48%</td>
<td>76%</td>
<td>93%</td>
<td>97.2%</td>
<td>98.5%</td>
<td>98.5%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 8 reflects 71 of the 78 fires in the data set. Full data is unavailable for 3 fires and there were 4 fires where the vehicle drove through the tunnel (i.e. fires were not extinguished). Of all fires, 48% were declared extinguished within 10 minutes while 98.5% were declared extinguished within 50 minutes.

Emergency Services declared the Burnley Tunnel fire under control 81 minutes after the fire started [2].

Table 9 – Recorded Time from Fire Detected to Fire Declared Extinguished (deluge deployed fires)

<table>
<thead>
<tr>
<th>Duration (mins)</th>
<th>&lt;5</th>
<th>&lt;10</th>
<th>&lt;20</th>
<th>&lt;30</th>
<th>&lt;40</th>
<th>&lt;50</th>
<th>&lt;60</th>
<th>&gt;60</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Fires</td>
<td>1</td>
<td>6</td>
<td>20</td>
<td>27</td>
<td>28</td>
<td>29</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>By Percentage</td>
<td>3.3%</td>
<td>20%</td>
<td>66.7%</td>
<td>90%</td>
<td>93.3%</td>
<td>96.7%</td>
<td>96.7%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 9 only reflects those fires where deluge was used. It is assumed that Operators assessed these fires to be higher risk warranting use of deluge and associated tunnel closure. The data shows that where deluge was used, the Emergency Services were able to declare 90% of fires extinguished within 30 minutes of the fire starting.

Table 10 – Recorded Time from Fire Detected to Tunnel Re-opened (deluge deployed fires)

<table>
<thead>
<tr>
<th>Duration (mins)</th>
<th>&lt;20</th>
<th>&lt;40</th>
<th>&lt;60</th>
<th>&lt;80</th>
<th>&lt;100</th>
<th>&lt;130</th>
<th>&lt;160</th>
<th>&lt;250</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Fires</td>
<td>2</td>
<td>6</td>
<td>12</td>
<td>17</td>
<td>23</td>
<td>27</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>By Percentage</td>
<td>6.9%</td>
<td>20.7%</td>
<td>41.4%</td>
<td>58.6%</td>
<td>79.3%</td>
<td>93.1%</td>
<td>96.6%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 10 shows the time taken from detecting fires to the time to re-opening the tunnel for normal operation. This is known (in Australia) as the rectification period. Following extinguishment of the fire the rectification period may also include tidy-up of fire suppression material, recovery of the affected vehicle(s), inspection of the tunnel and procedures for re-opening the tunnel.

Table 10 only includes those fires where deluge was deployed. As Operators only deploy deluge on those fires deemed to be higher risk, these are the fires which have greatest impact on tunnel operations. This table is presented in order to allow assessment of the operational continuity benefits of installing FFFS. In incidents where deluge has been used, the average time to rectification is 74 minutes, while the median time to rectification for incidents in which deluge was deployed is 71 minutes.

Note that the Burnley Tunnel fire is not represented in Table 10 due to it being such a significant outlier in the data. The Burnley tunnel was re-opened approximately 4 days after the 2007 fire occurred. It is understood that engineering and operational measures had been completed which would have enabled the tunnel to re-open earlier, but other factors meant that the re-opening of the tunnel was delayed.

Evacuation

Of the 78 recorded fire incidents, operators deployed procedures for emergency evacuation from the incident to the non-incident tunnel on only four occasions. Three of these incidents were relatively minor fires. They occurred in tunnels that had recently opened and which have low rates of fire incidents. The 2007 Burnley Tunnel collision and fire also resulted in emergency evacuation to the non-incident tube.
FUTURE DATA COLLECTION

A key learning from this exercise is the need for a consistent method of reporting on fire incidents using pre-determined terminology. While AS2577 is acknowledged as the Australian standard process, it is deemed to be too complex for this purpose. A simplified fire incident questionnaire has been prepared and has been circulated to ATOG and major road tunnel concession owners [14]. The fire incident questionnaire is included as Attachment A. It is proposed that the fire incident data base is held by the ATTF and is updated annually. Furthermore, it is proposed that ATTF publish updated output form the revised database on a three year cycle.

ACKNOWLEDGMENTS

This work has been a successful collaboration between the ATTF, ATOG, tunnel concession owners and tunnel operators. Particular thanks to Leena Thavasin who collected and processed the fire incident data for all Transurban tunnels. The resultant set of fire incident data provides evidence of the fire safety performance of Australian road tunnels.

REFERENCES


ATTACHMENT A: FIRE INCIDENT QUESTIONNAIRE
Development of a Risk-based Framework for Road Tunnel Design & Operations

Robin Hall\(^1\) & Iain Bowman\(^2\)

\(^1\) Mott MacDonald, Croydon, United Kingdom
\(^2\) Mott MacDonald, Vancouver, Canada

ABSTRACT

The principal aim of this study was to develop a risk-based framework to support decision-making for UK tunnels operated by Highways England. Road tunnels typically have a large number of systems installed, and their operational effectiveness and availability are important for design and operations. The framework is intended to support decisions during all phases of the life cycle, through the planning and design stages to traffic operations and subsequent refurbishment or renewal of systems.

The development of the framework has taken into account the following important factors:

- There are a large number of potential safety measures, but there is little quantitative data on the effectiveness of many of these measures. Notably, there is very little data available on the casualties that might occur in tunnel fires with or without such safety measures.
- These measures are deployed in a wide range of different combinations, together or sequentially, sometimes automatically but often manually and in an ad-hoc manner in the case of fire emergency responses. The contribution of each measure should be addressed.
- Human behaviour plays a key role when considering the effectiveness of some safety measures. Human behaviour introduces substantial uncertainty.

High level operational safety objectives are firstly defined, together with possible associated tunnel systems and safety measures. For a given tunnel configuration, estimates are derived of the probabilities that these objectives will be satisfied by the associated tunnel systems. This takes account of the effectiveness and availability of each system. The effectiveness of each system is judged from experience. Generic event trees are defined, both for non-fire and fire incidents, combining the effects of different systems to obtain overall mitigation probabilities. Risk calculations are carried out for the different incident scenarios, using derived incident and casualty rates together with the estimated mitigation probabilities. Different tunnel configurations can be compared in terms of operational and safety performance indicators, converted into monetary estimates to allow cost-benefit comparisons. Application examples are presented of how the framework can be used to support decisions concerning tunnel upgrades and operational decisions relating to minimum operating requirements (MORs).

KEYWORDS: road tunnels, risk analysis, safety measures

INTRODUCTION

Road tunnels typically have a large number of systems installed. The proposed framework takes the effectiveness and availability of each of these systems into account and is intended to support decision making through the design stages to operations and subsequent refurbishment of the tunnel or renewal of specific systems, as illustrated in Figure 1.
Figure 1  Context for a risk framework to support road tunnel design and operations

Key Operational Scenarios and Incident Rates

The most significant tunnel safety risks typically include traffic accidents and vehicle fires. Incidents involving dangerous goods have the potential to cause more casualties, but their likelihood is usually very low. In addition to such safety risks, the disruption and traffic delays caused by broken down vehicles can also be a key performance concern.

Whereas detailed statistics are usually available for vehicle breakdowns and traffic accidents, statistics are limited for tunnel fires and other types of ‘major’ incident due to the small number of events and data collection processes. Authorities and operators may record the occurrence of vehicle fires, but not the details of the number and types of vehicles involved and whether the fire became fully-developed (consuming the whole vehicle and its contents). For risk analysis purposes, reference is therefore commonly made to a handful of publications with tunnel fire statistics, such as those produced by CETU [1] and the European DARTS project [2]. Datasets are relatively small. For example, the more recent reviews presented by Kim et al [3], Naevestad and Meyer [4] and Rattei et al [5] considered only 69, 135 and 67 events respectively, compared to the thousands of traffic incidents on highways each year. A key issue is that incident rates can vary widely between tunnels depending on country, location, geometry, traffic modes and volumes, tunnel safety systems and management procedures.

Tunnel Safety Systems

A range of control measures are typically implemented to reduce the risks to an acceptable level. Over the last 15 or so years, additional safety measures have been introduced in response to serious tunnel fires that have occurred, subsequent regulations, research programmes, new technologies and commercial products. Such additional measures include, for example, average speed enforcement systems, automatic incident detection systems (video, radar and acoustic technologies), evacuation wayfinding systems, loudspeaker public address systems, and fixed fire-fighting systems (deluge and water mist types). The contributions of different systems to meeting operational safety objectives tend to be handled subjectively and not systematically.
Minimum Operating Requirements

Safety measures may become unavailable due to equipment failure or because of maintenance activities. Depending on jurisdiction, a set of Minimum Operating Requirements (MORs) may be defined, with minimum equipment levels below which additional compensatory measures may be required to allow the tunnel to be operated in a degraded mode or below which the tunnel may have to be closed. The methodology used to define MORs varies between authorities, operators and practitioners. The approach taken for some UK tunnels is broadly in line with the guidance published by CETU [6]. Consideration may be given to whether the loss of a system can be compensated by use of a different type of system. For example, ‘loss’ of an automatic fire detection system would be compensated to a degree by CCTV (closed circuit television), emergency telephones and mobile phone coverage. An example of a system loss that cannot be compensated for is failure of the tunnel lighting system. For the present purposes, a key issue is that threshold levels are usually established on a subjective basis and not directly linked to risk analysis.

LEGAL PERSPECTIVES ON MINIMUM SAFETY REQUIREMENTS

For UK road tunnels, safety-related decisions are generally based on the requirements of BD 78/99 [7] and the Road Tunnel Safety Regulations [8], which enact the European Directive 2004/54/EC [9] into UK law, supported by reference to practices at other tunnels. Reference is also commonly made to reducing risks to a level that is ‘As Low As Reasonably Practicable’ (ALARP). The concept of ‘reasonably practicable’ lies at the heart of the UK’s health and safety system, and involves weighing a risk against the effort, time and money needed to control it. In general, this involves a comparison between the control measures a duty-holder has in place or is proposing and the measures that would normally be expected in such circumstances (‘good practice’). Where there is recognised good practice, duty-holders would be expected to follow it. If they want to propose an alternative approach, they must be able to demonstrate that the measures they propose to use are at least as effective in controlling the risk. In practice, there is no consensus on when risks are ALARP. Interpretations about ALARP should reflect the following key points (for example, see [10]):

1. Deciding whether the risk is reduced ALARP is a separate exercise from seeking a continual improvement in standards. As technology develops, new and better methods of controlling tunnel risks become available. That does not mean that the best risk controls are necessarily reasonably practicable. It is only if the cost of implementing these controls is not grossly disproportionate to the risk reduction they achieve that their implementation is reasonably practicable.

2. Decisions about what is ALARP will also be affected by changes in knowledge about the size or nature of the risk presented by a hazard. If there is sound evidence to show that a tunnel hazard presents significantly lesser risks than previously thought, then a relaxation in control should be acceptable provided the new arrangements ensure the risks are ALARP.

3. Some tunnel operators may implement standards of risk control that are more stringent than good practice. It does not follow that these risk control standards are reasonably practicable, just because a few operators have adopted them. It is also acceptable for an operator to choose to relax from a self-imposed higher standard to one which is accepted as ALARP.

4. ALARP does not mean that every measure that could possibly be taken to reduce risk must be taken. Sometimes, there is more than one way of controlling a risk. These controls can be thought of as barriers that prevent the risk being realised and there is a temptation to require more and more of these barriers, to reduce the risk as low as possible. ALARP means that a measure can be required only if its introduction does not involve grossly disproportionate cost.

5. ALARP does not represent zero risk. It has to be expected that the risk arising from a hazard will be realised sometimes, even though the risk is ALARP.
‘Good practice’

For UK road tunnels, the standard BD 78/99 has represented ‘good practice’ since its publication in 1999. The European Directive 2004/54/EC is now also relevant, given the large number of European tunnels that use this as the key safety benchmark. Some requirements can be interpreted in a variety of ways and this has led to uncertainty about what constitutes ‘good practice’. Additional safety measures have been introduced in many tunnels in response to lessons learned from serious tunnel incidents that have occurred worldwide, research programmes, and new technologies and products. Benchmarking between tunnels has also led to increases in equipment levels.

Some authorities choose a ‘do minimum’ approach to compliance, whilst others go much further and implement higher performance and more sophisticated systems than is strictly necessary. The ‘do minimum’ approach should align with ‘good practice’ whereas the latter approach reflects a move towards ‘best practice’.

RISK ANALYSIS

Analysis of the risks associated with road tunnel operations involves identification of hazard scenarios and possible outcomes, assessment of the likelihood and consequences of each outcome, calculation of the risks (likelihood × consequence), and summation to determine the total risk. There are significant variations between countries, authorities, operators, designers and practitioners in how risk analysis techniques are applied, as documented by the World Road Association (PIARC) [11, 12].

The scope of risk analysis is typically limited to a small number of ‘representative’ traffic and incident scenarios. The choice of scenarios tends to vary between practitioners, which leads to inconsistency between tunnels and projects. The safety measures that are considered explicitly are often limited to traffic-related factors (such as speed limit), tunnel ventilation, the locations of emergency exits, and the response times associated with detection, warning and control systems.

In practice, there are major uncertainties associated with the following aspects in particular:

- incident rates for tunnel fires and events involving dangerous goods;
- the outcomes can depend on the full range of systems, some of which may not be available when the demand arises;
- the effectiveness of each individual system (and sub-system) installed for detection, warning, communications and evacuation wayfinding, noting that human behaviour is a key area of uncertainty;
- casualty rates, which depend on the characteristics of the population exposed and on complex physiological factors (such as smoke toxicity).

RISK FRAMEWORK

The proposed approach involves evaluating tunnel safety using simple quantitative risk analysis (QRA) techniques tailored to reflect the issues identified above and the availability of data. The analysis can be carried out for different tunnel configurations and equipment options, considering the impacts on a representative set of incidents comprising: breakdowns; road traffic collisions with injuries; road traffic collisions without injuries; and vehicle fires.

Incident rates

Incident data for the UK’s South-East region was used to derive incident rates for the risk framework, as summarised in Table 1. Over a period of 6 years, 23698 breakdowns, 4413 collisions without injuries, 1589 collisions with injuries and 348 vehicle fires were recorded. Although this data is not tunnel-specific, it provides a representative picture of incidents. It is interesting to note that the vehicle fire statistics show significant reductions compared to older published datasets [1, 2].
Table 1 Incident rates and traffic delays

<table>
<thead>
<tr>
<th>Incident type</th>
<th>Incident rate per billion veh.km</th>
<th>of which, traffic delays ≤ 15min</th>
<th>&gt; 15min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-fire incidents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breakdowns</td>
<td>710.1</td>
<td>89.2%</td>
<td>10.8%</td>
</tr>
<tr>
<td>Road Traffic Collisions – no injury</td>
<td>132.2</td>
<td>63.9%</td>
<td>36.1%</td>
</tr>
<tr>
<td>Road Traffic Collisions – injury</td>
<td>47.6</td>
<td>27.2%</td>
<td>72.8%</td>
</tr>
<tr>
<td>Vehicle fires</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cars/LGVs</td>
<td>6.6</td>
<td>53.8%</td>
<td>46.2%</td>
</tr>
<tr>
<td>HGVs/buses</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Categorisation of tunnel systems

A set of ‘function groups’ and associated high level operational safety objectives are defined in Table 2. These objectives are intended to be generally applicable to tunnels and independent of which systems are actually installed in a tunnel.

Table 2 Operational safety objectives

<table>
<thead>
<tr>
<th>Function group</th>
<th>Operational safety objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Backbone' services</td>
<td>• Tunnel systems are powered</td>
</tr>
<tr>
<td></td>
<td>• Tunnel can be monitored and controlled</td>
</tr>
<tr>
<td>Tunnel environment</td>
<td>• Tunnel users are not affected by unsuitable lighting levels</td>
</tr>
<tr>
<td></td>
<td>• Tunnel users are not affected by vehicle fumes</td>
</tr>
<tr>
<td></td>
<td>• Tunnel users are not affected by flooding or other environmental hazards</td>
</tr>
<tr>
<td>Traffic management</td>
<td>• Operator can warn drivers if the road ahead is obstructed or closed</td>
</tr>
<tr>
<td></td>
<td>• Operator can readily close the tunnel</td>
</tr>
<tr>
<td>Monitoring and incident detection</td>
<td>• Operator can monitor tunnel operations and become quickly aware of potential hazards and incidents</td>
</tr>
<tr>
<td>Communication with tunnel users</td>
<td>• Tunnel users can be informed what to do in the event of breakdown, accident or fire emergency</td>
</tr>
<tr>
<td>Mitigation of fire hazards</td>
<td>• Tunnel users are not affected by fire and smoke effects</td>
</tr>
<tr>
<td></td>
<td>• Fires are extinguished promptly</td>
</tr>
</tbody>
</table>

The operational safety objectives can be translated into a set of safety functions, which define the required functionality of the associated tunnel systems. There may be situations where the objective can be achieved naturally without installing a system, in which case the safety function(s) and associated system(s) may not be relevant. For example, the objective “Tunnel users are not affected by flooding” could be satisfied naturally if the tunnel lies on a constant slope such that all excess water and spillages drain out of the tunnel.

A set of operational safety objectives, safety functions and associated tunnel systems is defined in Table 3. This is intended as a generic starting point. The adoption of different systems can be tailored for the specific tunnel in question.
<table>
<thead>
<tr>
<th>Function / System Group</th>
<th>Safety Functions (for Systems)</th>
<th>Associated Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>mechanic’ safety services</td>
<td>0.1 Tunnel systems are powered</td>
<td>0.1 Power supply and distribution system</td>
</tr>
<tr>
<td></td>
<td>0.2 Tunnel can be monitored and controlled</td>
<td>0.2 Tunnel control system</td>
</tr>
<tr>
<td></td>
<td>1.1 Tunnel users are not affected by poor lighting</td>
<td>1.1 Tunnel lighting system</td>
</tr>
<tr>
<td></td>
<td>1.2 Tunnel users are not affected by flooding</td>
<td>1.2 Tunnel drainage system</td>
</tr>
<tr>
<td></td>
<td>1.3 Tunnel users are not affected by vehicle pollution</td>
<td>1.3 Tunnel ventilation system</td>
</tr>
<tr>
<td></td>
<td>1.4 Tunnel users react appropriately in the event of breakdown, accident, or fire emergency</td>
<td>1.4 Emergency telephones</td>
</tr>
<tr>
<td></td>
<td>2.1 Operator can monitor tunnel operations and become quickly aware of hazards &amp; traffic conditions</td>
<td>2.1 Automatic Incident Detection (AID)</td>
</tr>
<tr>
<td></td>
<td>2.2 Operator can readily close the tunnel</td>
<td>2.2 Variable message signs</td>
</tr>
<tr>
<td></td>
<td>3.1 Operator can monitor tunnel operations</td>
<td>3.1 CCTV system</td>
</tr>
<tr>
<td></td>
<td>3.2 Tunnel users are not affected by vehicle pollution</td>
<td>3.2 Automatic Incident Detection (AID)</td>
</tr>
<tr>
<td></td>
<td>3.3 Tunnel users are not affected by flooding</td>
<td>3.3 Fire detection system</td>
</tr>
<tr>
<td></td>
<td>3.4 Tunnel users are not affected by poor lighting</td>
<td>3.4 Re-broadcast - mobiles &amp; maintenance radios</td>
</tr>
<tr>
<td></td>
<td>3.5 Tunnel users are not affected by vehicle pollution</td>
<td>3.5 Re-broadcast - mobiles &amp; maintenance radios</td>
</tr>
<tr>
<td></td>
<td>3.6 Tunnel users are not affected by vehicle pollution</td>
<td>3.6 Re-broadcast - mobiles &amp; maintenance radios</td>
</tr>
<tr>
<td></td>
<td>4.1 Tunnel users are not affected by fire and smoke effects</td>
<td>4.1 Re-broadcast - domestic radio</td>
</tr>
<tr>
<td></td>
<td>4.2 Tunnel users are not affected by fire and smoke effects</td>
<td>4.2 Public Address Voice Alarm (PAVA)</td>
</tr>
<tr>
<td></td>
<td>4.3 Tunnel users are not affected by fire and smoke effects</td>
<td>4.3 Evacuation route signs</td>
</tr>
<tr>
<td></td>
<td>4.4 Tunnel users are not affected by fire and smoke effects</td>
<td>4.4 Evacuation marker lights</td>
</tr>
<tr>
<td></td>
<td>4.5 Tunnel users are not affected by fire and smoke effects</td>
<td>4.5 Evacuation Sound Evacuation System</td>
</tr>
<tr>
<td></td>
<td>5.1 Tunnel users are not affected by fire and smoke effects</td>
<td>5.1 Tunnel ventilation system</td>
</tr>
<tr>
<td></td>
<td>5.2 Tunnel users are not affected by fire and smoke effects</td>
<td>5.2 Cross-connections between bores</td>
</tr>
<tr>
<td></td>
<td>5.3 Tunnel users are not affected by fire and smoke effects</td>
<td>5.3 Fixed fire fighting system</td>
</tr>
<tr>
<td></td>
<td>5.4 Tunnel users are not affected by fire and smoke effects</td>
<td>5.4 Manual fire extinguishers</td>
</tr>
<tr>
<td></td>
<td>5.5 Tunnel users are not affected by fire and smoke effects</td>
<td>5.5 Re-broadcast - emergency services radios</td>
</tr>
<tr>
<td></td>
<td>5.6 Tunnel users are not affected by fire and smoke effects</td>
<td>5.6 Fire mains and hydrant system</td>
</tr>
</tbody>
</table>
Probability of successful mitigation

Ideally, the operational safety objectives will be fully achieved by using various tunnel systems to mitigate the hazards. In practice, the probability of successful mitigation depends on the effectiveness and availability of each system:

\[ \text{Probability of Successful Mitigation} = \text{System effectiveness} \times \text{System availability} \]

The effectiveness of a system can depend on several factors, such as the basis of its design and performance specifications, traffic conditions, the nature of vehicles involved in an incident, and human factors. Availability is a measure of whether a system is ready for use when the demand arises, taking account both of possible failure and outages for maintenance reasons. Availability may be assessed on the basis of past experience and operations and maintenance records at existing tunnels.

Judging how effectiveness varies with the availability of a system can be complicated because of the lack of information on how each individual system (and sub-system) contributes to the overall level of safety. Whilst there is a good understanding about the effectiveness of tunnel ventilation systems and certain other systems, the actual contribution of most systems is far from clear, in particular wherever human factors are involved. This problem is key to defining MORs, and is usually handled in a subjective way, typically involving a group of relevant ‘experts’ discussing and agreeing how the loss of certain equipment should be treated. Sometimes, non-technical considerations are also incorporated into MORs, for example, associated with the availability of the transport network.

A systematic approach is proposed here to characterise the relationship between the availability of a system and its effectiveness. This involves identifying lower and upper limits for effectiveness, corresponding to 0% and 100% availability respectively, and defining the relationship between these two points. This relationship acts as a weighting when the contributions of different systems are examined together. Simplification is necessary. A provisional set of lower and upper limits is proposed in Table 4 for each of the tunnel systems.

<table>
<thead>
<tr>
<th>Systems</th>
<th>Success probability when system availability is …</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0% or not used</td>
<td>100%</td>
</tr>
<tr>
<td>0.1 Power supply system</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.2 Tunnel control system</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1.1 Tunnel lighting system</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1.2 Tunnel ventilation system – pollution control</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>1.3 Drainage system</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>2.1 Tunnel lane control signs</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>2.2 Portal message signs</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>2.4 Portal barriers</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Systems</td>
<td>Success probability when system availability is 100%</td>
<td>Comments</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>3.1 CCTV system</td>
<td>0.0 0.6</td>
<td>Operator attention may be focused elsewhere, even if system availability is 100%.</td>
</tr>
<tr>
<td>3.2 Automatic Incident Detection (AID)</td>
<td>0.0 0.9</td>
<td>The system detects stopped vehicles, debris, pedestrians, smoke. Generally, an effective means of detection.</td>
</tr>
<tr>
<td>3.3 Fire detection system</td>
<td>0.0 0.7</td>
<td>Most common type is Linear Heat Detection. Detection may be relatively slow for small, growing fires.</td>
</tr>
<tr>
<td>3.4 Emergency telephones</td>
<td>0.0 0.5</td>
<td>Motorists can raise alarm directly and explain nature of event. This may take several minutes.</td>
</tr>
<tr>
<td>3.5 Re-broadcast - mobiles and maintenance radios</td>
<td>0.0 0.5</td>
<td>Mobiles may be used sometimes. Depends on mobile coverage.</td>
</tr>
<tr>
<td>3.6 Monitoring of extinguishers, doors, …</td>
<td>0.0 0.1</td>
<td>Indirect alert only. Actual nature of event would be uncertain (even for extinguisher alerts).</td>
</tr>
<tr>
<td>4.1 Re-broadcast - domestic radio (with Voice Break-In)</td>
<td>0.2 0.6</td>
<td>Some motorists will not be listening to their radios.</td>
</tr>
<tr>
<td>4.2 Public Address Voice Alarm (PAVA) system</td>
<td>0.2 0.9</td>
<td>Some people will evacuate when they see fire or smoke, whether or not there is an announcement.</td>
</tr>
<tr>
<td>4.3 Evacuation route signs</td>
<td>0.2 0.9</td>
<td>Familiar means of indicating escape routes. Near portals, tunnel users may disregard. Some users will behave appropriately even if signs are unavailable.</td>
</tr>
<tr>
<td>4.4 Low level evacuation route illumination</td>
<td>0.2 0.5</td>
<td>Principal contribution would be when smoke obscures the lighting system along the tunnel soffit. These systems may be less important near portals.</td>
</tr>
<tr>
<td>4.5 Directional Sound Evacuation System</td>
<td>0.2 0.8</td>
<td></td>
</tr>
<tr>
<td>5.1 Tunnel ventilation system – smoke control</td>
<td>0.2 Depends on design fire scenario, e.g. 30MW =&gt; 0.3 100MW =&gt; 0.8</td>
<td>Effective means of controlling smoke, up to the design fire size. Effectiveness depends on several factors. For incidents close to the portals, smoke will tend to vent naturally.</td>
</tr>
<tr>
<td>5.2 Emergency exits, such as cross-passages</td>
<td>0.2 0.5</td>
<td>Some people will use the cross-passages to evacuate, but most people will probably walk directly to the portals.</td>
</tr>
<tr>
<td>5.3 Fixed fire-fighting systems</td>
<td>0.0 0.8</td>
<td>Means of suppressing fires and limiting fire spread between vehicles. Effectiveness depends on when the system is activated.</td>
</tr>
<tr>
<td>5.4 Manual fire extinguishers</td>
<td>0.0 0.1</td>
<td>Most people do not have training to use extinguishers successfully and safely on vehicle fires.</td>
</tr>
<tr>
<td>5.5 Re-broadcast - emergency services radios</td>
<td>0.2 1.0</td>
<td>Aids effective fire-fighting operations. If this system is unavailable, radio repeaters may be deployed by the fire brigade.</td>
</tr>
<tr>
<td>5.6 Fire mains and hydrant systems</td>
<td>0.2 1.0</td>
<td>Used by fire-fighters to fight fires. If this system is unavailable, fire brigade will use their own resources.</td>
</tr>
</tbody>
</table>

These limits could be used with simple linear relationships. Alternatively, more refined relationships can be derived as illustrated in Figure 2, reflecting a variety of factors:

- For tunnel lighting, the situation depends on where luminaire failures occur. The loss of a few luminaires that are widely spaced may have little impact on overall effectiveness, however as more luminaires fail then dark zones could occur and spread in extent, having a greater impact on overall effectiveness. Illustrative ‘best’ and ‘worst’ cases are shown in Figure 2a.

- In some cases, even if a system is 100% available, the safety objective may be only partially satisfied. An example of this is the CCTV system, shown in Figure 2b. Even if 100% available, there would be no guarantee that an operator at a road network control centre would see and be able to respond quickly, given attention might be focused on events happening elsewhere on the road network.
• In some cases, even if a system is completely unavailable, the safety objective may still be achieved to some extent. Tunnel ventilation is an example of this, since pollution levels would generally be limited naturally by the traffic-induced airflows through the tunnel. Regarding fires, when an incident occurs near the portals, smoke would generally vent naturally to atmosphere. This is illustrated in Figure 2c.

• For the power supplies and LV (low voltage) distribution systems, there would be ‘step’ changes in effectiveness associated with the availability of key elements such as an individual transformer, LV switchboard, etc. This is illustrated in Figure 2d.

Any assumptions would need to be tailored, reviewed and confirmed for each tunnel, by a suitable group of ‘experts’.

![Graphs](image)

**Figure 2**  Examples of possible relationships between Availability and Effectiveness

**Combinations of systems**

The performance of tunnel systems could be evaluated simply in terms of the function groups (listed in Table 2). However, when considering monitoring and incident detection, communication with tunnel users, traffic management and mitigation of hazards, it is helpful to evaluate these systems in the context of incidents, both for non-fire incidents (such as road traffic collisions) and vehicle fires.
The following system groups and scenarios are considered:

- Backbone systems
- Mitigation of hazards associated with the tunnel environment
- Mitigation of non-fire incidents
- Mitigation of vehicle fires

In safety and risk analyses, it is common practice to consider failure probabilities, such as the probability of failure on demand of a safety system. Failure probabilities are used here in the risk analysis, with failure defined as ‘unsuccessful mitigation’, i.e. a failure to satisfy the relevant safety objectives. Similarly, success is here defined as ‘successful mitigation’ i.e. the relevant safety objectives are satisfied. Thus, probabilities of ‘failure’ and ‘success’ for a system are simply linked:

\[
\text{Probability of Unsuccessful Mitigation, } P = 1 - \text{Probability of Successful Mitigation} = 1 - (\text{Availability } \times \text{Effectiveness})
\]

Backbone services – The probability of losing the ‘backbone’ services concerns loss of the power supply and/or power distribution system OR loss of the tunnel control system. Following standard failure logic principles, this can be expressed by:

\[
P_{\text{No_Backbone}} = P_{\text{No_Power}} + P_{\text{No_Control}}
\]

Tunnel environment – Loss (partial or in full) of the capability to mitigate tunnel environment hazards refers to loss of the tunnel lighting system OR loss of the tunnel ventilation system OR loss of the drainage system. This can be expressed by:

\[
P_{\text{No_EnvControl}} = P_{\text{No_Lighting}} + P_{\text{No_Ventilation}} + P_{\text{No_Drainage}}
\]

Non-fire incidents – The situation is more complex for non-fire incidents because systems contribute in different ways as an incident develops. The development and possible outcomes of a non-fire incident are characterised in terms of a simple event tree with the following sequence of events:

- Initial trigger event – This could a breakdown, debris or an animal in the carriageway, etc.
- Time available to avoid? – A driver may have adequate time to respond safely to the initial hazard, for example by changing lanes or slowing down or stopping. This concerns human behaviour rather than tunnel systems. Without information on such behaviour, a subjective assumption of 50% has been made for the chance that drivers would not respond safely.
- Detected (by an operator)? – This depends on CCTV, Automatic Incident Detection (AID), emergency telephones or mobile phones. These are compensatory systems. Detection would be unsuccessful if all of these systems were unavailable. This can be expressed by:

\[
P_{\text{No_Detect}} = P_{\text{No_CCTV}} \times P_{\text{No_AID}} \times P_{\text{No_Telephones}} \times P_{\text{No_Mobiles}}
\]

- Drivers alerted? – This generally depends on lane control signs (LCS) and variable message signs (VMS), but some tunnels are also equipped with traffic signals and barriers at the portals. Loss or failure of all of these systems would result in failure of this function. This combination can be expressed by:

\[
P_{\text{No_Driver alert}} = P_{\text{No_LCS}} \times P_{\text{No_VMS}} \times P_{\text{No_Signals}} \times P_{\text{No_Barriers}}
\]

- Drivers react safely? – Some drivers will ignore warnings. Where a warning is received, it is assumed that 33% (one-third) of drivers would not respond safely. In the situation where no warning is received, it is assumed that 67% (two-thirds) would not respond safely.

For each outcome of the event tree, the probability is multiplied by a mitigation weighting (from 0% to 100%). A simple assumption has been made that if drivers react safely on seeing a hazard, the consequences will be mitigated, otherwise the consequences will be as though there were no safety measures. The probability \(\times\) mitigation products are summed to obtain an overall mitigation probability for input to the risk calculation.
Vehicle fires – This is the most complex situation. The development and possible outcomes of a fire incident are characterised below in terms of a simple event tree with the following sequence of events:

- **Extinguished early?** – Whilst a fire could be extinguished early using a manual fire extinguisher, most people do not have the training to do this effectively.
- **Detected?** – This depends on CCTV, Automatic Incident Detection (AID), fire detection system, emergency telephones, mobile phone coverage and monitoring of doors and extinguishers. Unsuccessful operation could occur because of loss of all detection means, so the probability of failure can be expressed by:
  \[ P_{\text{No Detect}} = P_{\text{No CCTV}} \times P_{\text{No AID}} \times P_{\text{No FireDetect}} \times P_{\text{No Telephones}} \times P_{\text{No Mobiles}} \times P_{\text{No Door alarms}} \]
- **Tunnel users alerted?** – This generally depends on lane control signs (LCS) and variable message signs (VMS), but some tunnels are also equipped with traffic signals and barriers at the portals. Loss or failure of all of these systems would result in failure of this function. The probability of failure can be expressed by:
  \[ P_{\text{No Driver alert}} = P_{\text{No LCS}} \times P_{\text{No VMS}} \times P_{\text{No Signals}} \times P_{\text{No Barriers}} \]
- **Smoke-free escape routes?** – This depends on the tunnel ventilation system (TVS), the presence of intermediate cross-connections between traffic tubes, plus the contribution of a fixed fire-fighting system (FFFS) if installed. Loss or failure of all of these systems would result in failure of this function. The probability of failure can be expressed by:
  \[ P_{\text{No Smoke-free routes}} = P_{\text{No TVS}} \times P_{\text{No Exits}} \times P_{\text{No FFFS}} \]
- **Clear wayfinding?** – This would depend on evacuation route signs, low level evacuation route illumination (e.g. marker lights), and a Directional Sound Evacuation System (DSES), if installed. Loss or failure of all of these systems would result in failure of this function. The probability of failure can be expressed by:
  \[ P_{\text{No Wayfinding}} = P_{\text{No Evac signs}} \times P_{\text{No Escape lighting}} \times P_{\text{No DSES}} \]

The probability of each outcome of the event tree is multiplied by a mitigation weighting (from 0% to 100%). The weighting is estimated on the following subjective basis:

- Smoke free escape route(s) 90% - 100%
- Not smoke-free, but users alerted and wayfinding is effective 50% - 90%
- Not smoke-free and users not alerted, but wayfinding is effective 10% - 50%
- Not smoke-free, users not alerted and wayfinding is not effective 0% - 10%

The probability \times mitigation products are summed to obtain an overall mitigation probability for input to the risk calculation.

**Casualty rates**

Reported casualty rates in road traffic collisions across the UK are published annually by DfT [10]. In comparison, there are no reliable statistics on the casualties that might occur in tunnel fires or dangerous goods incidents, with or without safety measures. Risk analyses often include predictions of casualty numbers, estimated using models of the physical effects of hazards (e.g. smoke spread modelling), evacuation and the physiological effects of exposure to heat, radiation, toxic products, etc. However, such analyses are always subject to substantial uncertainty.

These uncertainties arise due to the huge range of possibilities, of the scenarios considered (e.g. vehicles involved and loads carried), how these scenarios are modelled (e.g. techniques and assumptions), whether the effects of safety measures are taken into account, detection and alarm times, occupancy assumptions, pre-movement times, toxicity effects, etc. Human behaviour is a major source of uncertainty, i.e. how will tunnel users behave in the event of a major fire? Given the uncertainties, there is substantial variability between practitioners.
Rather than trying to model the various complex effects, including human behaviour, it is proposed to define a simple casualty indicator that can be scaled according to the number of lanes in a tunnel tube and some basic traffic and ventilation characteristics. This reflects past tunnel fire incidents, including major incidents that took place in tunnels without modern risk control measures such as fire detection and warning systems, evacuation aids or effective smoke control.

For every fatality that occurs, it has been assumed that there are also 2 serious injuries and 10 slight injuries. The proposed values are presented in Table 5, expressed per occupied lane on each side of the fire, for different representative fire scenarios.

Table 5  Illustrative number of casualties

<table>
<thead>
<tr>
<th>Fatalities + serious injuries + slight injuries per occupied lane on each side of the fire</th>
<th>Car/van fire ≤ 15 MW</th>
<th>HGV/bus fire 30 MW</th>
<th>HGV fire 100MW fire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examples: 2 lane tunnel, uni-directional traffic stopped in both lanes behind fire; OR bi-directional traffic, 1 lane stopped on each side of fire</td>
<td>0.04 + 0.08 + 0.4</td>
<td>0.4 + 0.8 + 4</td>
<td>4 + 8 + 40</td>
</tr>
<tr>
<td>3 lane tunnel, uni-directional traffic stopped in all lanes behind the fire</td>
<td>0.06 + 0.12 + 0.6</td>
<td>0.6 + 1.2 + 6</td>
<td>6 + 12 + 60</td>
</tr>
<tr>
<td>3 lane tunnel, congested traffic trapped on both sides of the fire in all lanes</td>
<td>0.12 + 0.24 + 1.2</td>
<td>1.2 + 2.4 + 12</td>
<td>12 + 24 + 120</td>
</tr>
</tbody>
</table>

Risk analysis

An example of the risk calculation for a tunnel option is shown in Figure 3. The risk of casualties occurring is given by:

\[
\text{Risk} = \text{tunnel traffic} \times \text{incident rate} \times \frac{\text{probability of unsuccessful mitigation}}{\text{casualty rate}}
\]

The following scenarios and consequence outputs are considered:

- **Breakdowns**  Delays (> 15min) per year
- **Collisions without injuries**  Delays (> 15min) per year
- **Collisions with injuries**  Casualties per bvkm; Delays (> 15min) per year
- **Vehicle fires**  Casualties per bvkm

Cost parameters

The results of the risk analysis are used to perform a Cost-Benefit Analysis. Capital (CAPEX) and Operating (OPEX) cost information is used to estimate the Net Present Value of a scheme option. The benefits can be evaluated in monetary terms for reductions of the traffic delays and casualties in traffic incidents and fires. Valuations of the cost per casualty (fatal, serious or slight injury) are taken from DfT data [11]. The Benefit / Cost Ratio can be calculated for each scheme option.
## Figure 3: Example risk calculation

### Tunnel Length (km)
- 0.37

### Number of Lanes
- 2

### Daily Traffic Flow (veh/day)
- 37,200

### Congested Time Fraction
- 5%

### Vehicle Split
- Cars: 70%
- LGVs: 15%
- HGVs, buses/coaches: 15%

### Traffic Accident and Casualty Rates (per bvkm)

<table>
<thead>
<tr>
<th>Incident Type</th>
<th>Traffic Modes</th>
<th>Traffic Peak Fire Size</th>
<th>Traffic bnk/m/yr</th>
<th>Incident Rates without Mitigation per bvkm per year</th>
<th>Mitigation Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdowns</td>
<td></td>
<td></td>
<td></td>
<td>71.0, 3.57, 0.0%</td>
<td></td>
</tr>
<tr>
<td>Accidents without injuries</td>
<td></td>
<td></td>
<td></td>
<td>13.2, 0.66, 27.2%</td>
<td></td>
</tr>
<tr>
<td>Accidents with injuries</td>
<td></td>
<td></td>
<td></td>
<td>47.6, 0.24, 27.2%</td>
<td></td>
</tr>
</tbody>
</table>

### Traffic Delays and Mitigation

<table>
<thead>
<tr>
<th>Traffic Delays</th>
<th>FMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 15min</td>
<td>71.0</td>
</tr>
<tr>
<td>&gt; 15min</td>
<td>13.2</td>
</tr>
</tbody>
</table>

### Traffic Incident Rates (per bvkm)

- Injury accidents: 52.0 RAS30018 (2015, motorways)
- Fatalities: 0.9
- Serious injuries: 6.7
- Slight injuries: 76.4

### Traffic Incident Rates without Mitigation

- Injury accidents: 132.2, 63.9% (per incident type)
- Fatalities: 47.6, 36.1%
- Serious injuries: 6.7, 10.8%
- Slight injuries: 76.4, 27.2%

### Traffic Incident Rates with Mitigation

- Injury accidents: 132.2, 63.9% (per incident type)
- Fatalities: 47.6, 36.1%
- Serious injuries: 6.7, 10.8%
- Slight injuries: 76.4, 27.2%

### Traffic Incident Rates with Mitigation and FMI

- Injury accidents: 132.2, 63.9% (per incident type)
- Fatalities: 47.6, 36.1%
- Serious injuries: 6.7, 10.8%
- Slight injuries: 76.4, 27.2%

### Traffic Incident Rates with Mitigation and FMI and FMI Probability

- Injury accidents: 132.2, 63.9% (per incident type)
- Fatalities: 47.6, 36.1%
- Serious injuries: 6.7, 10.8%
- Slight injuries: 76.4, 27.2%

### Traffic Incident Rates with Mitigation and FMI and FMI Probability and FMI Probability Mitigation

- Injury accidents: 132.2, 63.9% (per incident type)
- Fatalities: 47.6, 36.1%
- Serious injuries: 6.7, 10.8%
- Slight injuries: 76.4, 27.2%

### Traffic Incident Rates with Mitigation and FMI and FMI Probability and FMI Probability Mitigation and FMI Probability Mitigation Probability

- Injury accidents: 132.2, 63.9% (per incident type)
- Fatalities: 47.6, 36.1%
- Serious injuries: 6.7, 10.8%
- Slight injuries: 76.4, 27.2%

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APPLICATION EXAMPLES

Example: Supporting decisions about scheme options

The framework can be used during the planning and development of projects to inform decisions about the provision of safety systems to meet overall objectives and to help ensure that funding is allocated in as efficient a way as possible. This example concerns the comparison of renewal options for an existing tunnel, to illustrate how the framework can be used. The tunnel is 370m long with two tubes, each with two lanes. The traffic characteristics are as follows:

- Average traffic flow is approximately 37,000 vehicles per day;
- Traffic congestion occurs 5% of the time on average;
- Representative split between vehicle types: 70% cars, 15% vans, 10% HGVs and 5% buses and coaches.

The input data matches the existing safety measures in the tunnel, which are broadly in line with BD 78/99. Some systems have exceeded their design lives and their general availability is reduced, including electrical power distribution, tunnel lighting, tunnel ventilation (jet fans), CCTV, and the tunnel control system. Additional measures such as an Automatic Incident Detection (AID) system might also be considered.

The framework can be used to compare the risk levels corresponding to various options (together with their costs). The following options are compared here:

- Do Now – Minimum provision to comply with legal minimum requirements;
- Do Now – Reduced scheme;
- Do Now – Scheme design;
- Delay to next investment period, maintain only until then;
- Delay to next investment period, implement interim mitigation and maintain until then.

The resulting operational and safety performance of each option is measured by the following indicators:

- Delays > 15 minutes, per year
- FWI per bvkm
- ΔFWI per bvkm

Indicative, order of magnitude CAPEX and OPEX costs are used to estimate the benefit /cost ratio for each option. Key inputs and results are summarised in Table 6.

Table 6  Comparison of scheme renewal options

<table>
<thead>
<tr>
<th>Option</th>
<th>Existing, dilapidated</th>
<th>Do Now - Legal minimum</th>
<th>Do Now - Reduced scheme</th>
<th>Do Now - Scheme design</th>
<th>Delay and maintain only</th>
<th>Delay and mitigate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delays &gt; 15min /yr</td>
<td>0.69</td>
<td>0.69</td>
<td>0.68</td>
<td>0.66</td>
<td>0.69</td>
<td>0.69</td>
</tr>
<tr>
<td>FWI /bvkm</td>
<td>1.90</td>
<td>1.87</td>
<td>1.80</td>
<td>1.58</td>
<td>1.90</td>
<td>1.89</td>
</tr>
<tr>
<td>ΔFWI /bvkm</td>
<td>-0.03</td>
<td>-0.10</td>
<td>-0.32</td>
<td>0.00</td>
<td>-0.02</td>
<td></td>
</tr>
<tr>
<td>CAPEX PV</td>
<td>-</td>
<td>£5.9m</td>
<td>£9.2m</td>
<td>£18.9m</td>
<td>£21.4m</td>
<td>£21.4m</td>
</tr>
<tr>
<td>OPEX PV</td>
<td>-</td>
<td>£13.0m</td>
<td>£13.0m</td>
<td>£13.0m</td>
<td>£15.4m</td>
<td>£15.4m</td>
</tr>
<tr>
<td>Cost PV</td>
<td>-</td>
<td>£18.9m</td>
<td>£22.2m</td>
<td>£31.9m</td>
<td>£34.4m</td>
<td>£36.8m</td>
</tr>
<tr>
<td>Benefit PV</td>
<td>-</td>
<td>£0.006m</td>
<td>£0.016m</td>
<td>£0.02m</td>
<td>£0.026m</td>
<td>£0.027m</td>
</tr>
<tr>
<td>Benefit/Cost Ratio</td>
<td>-</td>
<td>7E-06</td>
<td>7E-04</td>
<td>1E-03</td>
<td>2E-03</td>
<td>2E-03</td>
</tr>
</tbody>
</table>
Having estimated the costs and benefits, the various options can be assessed against the scheme objectives. In this case, the analysis indicates that the Present Value of the benefits and the Benefit/Cost Ratio would be negligible for all of options. It might therefore be concluded that the focus should be on compliance with the legal minimum requirements, e.g. to reflect the basic good practice defined in the RTSR [8] together with applicable health and safety regulations.

The framework can also be used to assess the contributions of systems which are commonly associated with ‘good’ or ‘best’ practice, and could be used to support a case to be made for departures from such practices.

**Example: Supporting decisions about MORs**

To illustrate how the risk framework might support MOR decisions, an illustrative range of reduced availability scenarios are compared, for the same tunnel example as outlined above:

- **‘Full’ availability** – All systems are taken to be 99% available.
- **Reduced availability** – All systems are taken to be 80% available.
- **No detection systems** – Other systems are 99% available.
- **No communications** – Other systems are 99% available.
- **No ventilation** – Other systems are 99% available.
- **No wayfinding** – Other systems are 99% available.

The results are shown in Figure 4. They provide an objective view of the impact of reduced availability or complete failure of different systems on the overall level of risk for tunnel users.

![Figure 4](image.png)

*Figure 4  Example of reduced availability impacts on safety risk*

Although the example is rather artificial, it shows how the framework can highlight key points. The importance of incident detection systems is highlighted here. If an incident is not detected, ‘active’ safety systems cannot be used to mitigate the risks. In practice, realistic availability values would need to be used of course.

The framework also enables the MOR thresholds to be considered with reference to route risk levels. Thus, the risk levels to which tunnel users are exposed could be ‘matched’ to the risk levels on the wider network or along the route on which the tunnel lies.
CONCLUDING REMARKS

The ability to make informed decisions regarding tunnel assets is a key requirement both for tunnel operators and for those planning the future of the wider highway network. A practical assessment of the effectiveness of safety measures within road tunnels would facilitate robust decision making at all stages of the asset’s life-cycle. A risk-based framework has been developed that offers the potential of satisfy this need. Initial application to specific examples shows promise in the methodology. Further refinement would improve the predictions and applicability of the tool.

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14. Health & Safety Executive. ‘Principles and guidelines to assist HSE in its judgements that duty-holders have reduced risk as low as reasonably practicable’ http://www.hse.gov.uk/risk/theory/alarp1.htm
17. PIARC. ‘Risk analysis for road tunnels’. World Road Association (PIARC) Technical Committee C3.3 Road tunnel operation, 2008.
A Quantitative Estimate of the Probability of Train Fire in an Urban Light Rail Tunnel

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ABSTRACT
As part of a safety audit of its operations, a US Light Rail Transit (LRT) operator required that a quantitative estimate of the probability of fire occurrence, with a qualitative estimate of consequences, be developed for a specific ventilation section within one of its operational tunnels. Operational data and statistics from the US National Transportation Database and other sources were used to construct a robust estimate of the probability. The analysis found that probability varies significantly with the expected severity of the fire event. Small nuisance fires that do not threaten life safety were found to have a relatively significant probability, estimated at 0.33 incidents/Million Train Revenue Miles (MTRM) for the whole LRT system. Serious fires that could threaten life safety were estimated to be extremely rare. It was found that for the ventilation section under investigation the probability of a serious fire resulting in casualties was in all estimates below 1x10^-6 incidents/year.

KEYWORDS: Quantitative risk assessment, operational safety, safety audit, safety levels, transit tunnels, train fire, probability estimates

INTRODUCTION
Quantitative Risk Assessment (QRA) can be a powerful tool and is useful in assessing safety levels of operational systems. As part of a safety audit of its current light rail operations, a North American transit operator wished to develop a QRA to estimate the probability of fire for a particular section of the line. Their light rail corridor has been operating for less than ten years. In that time it has not experienced a single fire on the network. Consequently, it was necessary to look further than their own operational history in order to develop a realistic estimate of the probability of fire on a train. Using data from the US National Transportation Database and other sources, a set of estimates for the probability of train fire within a single ventilation section of the line were developed.

OBJECTIVES
The objectives were to estimate the probability of fire occurring within a single ventilation section of the light rail line. The section under investigation has a signal at midpoint, which allows for two trains to occupy the ventilation section. Hence the probabilities to be estimated included that of (i) a fire between the midpoint signal and the station to the south (subsection 1), (ii) a fire between the midpoint signal and the station to the north (subsection 2), (iii) a fire in the whole ventilation section, and (iv) a fire occurring with two trains in the ventilation section. An estimate for the probability of a train fire developing to the full design Heat Release Rate (HRR) was also required, as was the probability of fire occurring due to a fault in the train’s systems.

METHODOLOGY
To estimate the required probabilities, historical operational data was sourced from a variety of reporting bodies. The primary data source was the United States’ National Transportation Database (NTD), which reports incidents, including fires, for the whole US transit network. Additional transit operation data was sourced from the Transportation Safety Board (TSB) of Canada, the United Kingdom’s Railway Safety and Standards Board (RSSB), and the New South Wales (Australia) Transport Safety Regulator (TSR). Data on lithium ion battery incidents, as a potential ignition
source, was sourced from the Federal Aviation Authority (FAA) database. This data was used to estimate the probabilities of in-car train fires, including all fires, ‘major’ fires according to the NTD definition of ‘major’ fires, and serious fires that could result in fatalities and/or serious injuries (FSI). The estimates were normalised and comparisons made between estimates derived from independent datasets to improve confidence in the estimates.

Data was also used to develop an estimate of the probability of a train fire developing to the full design HRR. This estimate was used in conjunction with the available operational fire occurrence data.

In a separate exercise, vehicle specifications for systems reliability were used to develop an estimate of the probability of a fire resulting from train malfunction. These would be mainly under-car type fires that present less hazard to the passengers.

The consequences of the fire event were assessed qualitatively, in terms of the expected severity of the fire and its qualitative impact on the train occupants. Hence, the estimated probabilities were classified according to the expected severity of the train fire.

SYSTEM DESCRIPTION

Network Description
The network in question is a modern, urban low-floor Light Rail Transit (LRT) system serving a major US city. It has been running for approximately a decade and has a mix of at-grade, elevated and tunnelled sections. One of the tunnels has multiple sub-surface stations and ventilation sections. Between two of these stations there is a ventilation section that contains a mid-point signal that subdivides the section into two sub-sections and allows for the possibility of two trains on a single track to occupy the section.

This LRT system operates on a dedicated right-of-way, using modern low-floor type rolling stock in multiple units coupled to form a train that is lower capacity and lower speed than a long heavy passenger train or metro/subway system. It is conceptually similar to a European tram-type system but runs on a completely segregated right-of-way and does not operate on public streets.

Vehicle description
The current fleet of vehicles on the network are all modern LRT consists that are compliant with the requirements of NFPA 130-2000 [1]. Additional vehicles are due to be procured as the network expands. Comparison of NFPA 130-2000 requirements with those of the current revision, NFPA 130-2017[2], reveal no significant differences in material fire performance requirements. Hence, the fleet can be stated to meet, with minor exceptions, the present-day requirements for material fire performance.

RISK METHODOLOGY
Risk is defined by the Oxford English Dictionary as “Exposure to the possibility of loss, injury, or other adverse or unwelcome circumstance; a chance or situation involving such a possibility.” Risk in engineering arises from the presence of various hazards, each of which may have consequences in the event that the hazard occurs. In some cases, risk can be quantified, while in others only a qualitative assessment may be possible.

Quantitative Risk Assessment
Quantitative risk assessment assesses the level of residual risk by representing the risk as a numerical quantity. A typical use for a full QRA result is in cost-benefit analysis. The calculation may be summarised as:

\[
\text{Risk} = (\text{Probability of hazard}) \times (\text{Consequences})
\]

Consequences are usually casualties and/or fatalities. The outcomes may be expressed in a f-N plot,
where \( f \) = probability (frequency) of the event and \( N \) = number of casualties from the event. Summing all \( f-N \) pairs yields the risk integral, or Expectation Value (EV), which is formulated as:

\[
EV = \sum [f \times N]
\]

The EV can be used directly in cost benefit analysis to assist in determining the value of risk mitigation measures, for example. It can also be expressed via an F-N (F-N is the sum of all \( f-N \) pairs) plot, often with agreed risk tolerance thresholds shown, giving a concise assessment of the acceptability of the estimated risk. Acceptability may be determined by comparison with an agreed acceptance criteria. One example is the UK HSE’s ‘tolerable if ALARP’ threshold of \( 1 \times 10^{-6} \) probability (irrespective of number of casualties).

Quantitative risk assessment uses statistical data to assess the probability and consequences of a particular hazard, resulting in a numerical estimation of the level of risk. The data set can either be generated by utilising a statistical method such as Monte Carlo simulation, or historical incident data from various reporting bodies can be used. In this assessment, the latter method is used as there are a number of applicable data sets for LRT safety that are readily available.

Numerous guidance documents for assessing risk are available. References [3]-[7] are just a few of the relevant documents.

In this assessment, the focus is on the probability of occurrence of fire events, specifically train fire events. Detailed assessment of the consequences of a fire event is not within the scope of this work. Hence, a full QRA is not being undertaken. In strict risk assessment terms, the probability of occurrence is to be estimated for a number of operational situations, since the consequences are assessed qualitatively. Technically, this is a semi-quantitative risk assessment.

The consequences are qualitatively assessed in terms of the severity of the fire and whether it is expected to lead to casualties. Fire events are classified according to the expected consequences. Table 1 gives a matrix of the estimated approximate level of consequences for vehicle occupants. Outside of a ‘minor’ fire, the consequences could be at a variety of levels of severity. The intensity of colour is an indicator of the general probability of consequences for a specific fire classification. The overlaps indicate the uncertainty in the qualitative estimation.

Table 1 Fire type classification by estimated level of consequences for vehicle occupants

<table>
<thead>
<tr>
<th>Fire Classification</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-1 minor injuries</td>
</tr>
<tr>
<td>Minor</td>
<td></td>
</tr>
<tr>
<td>NTD ‘Major’</td>
<td></td>
</tr>
<tr>
<td>Flashed-over</td>
<td></td>
</tr>
<tr>
<td>FSI</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. NTD ‘Major’ = Definition of a ‘Major’ fire according to US NTD reporting guidelines [8].
2. Flashed-over = Train car experiences fire growth and spread leading to flashover, assumed equivalent to peak HRR fire.
3. FSI = Fatalities and/or serious injuries.

Issues of working with sparse data
When carrying out a quantitative risk assessment, it is necessary to be aware of the quality and extent of the data that is being used. While there are numerous data sets covering LRT incidents during operations, it is common that fires are not recorded separately, or if so, then the data set may not cover the fire occurrences in depth. Furthermore, LRT train fires are in general a low probability event compared with breakdowns and accidents involving customers and/or bystanders (e.g. track crossing incidents).
Thus, while a data set may contain statistically significant data on incidents in general, it may contain statistically sparse data regarding fire occurrence. The difficulty with sparse data is that, while accurate, so far as it exists, there is potentially a large degree of uncertainty. To illustrate, if there is a system that has had only one major fire in its history, the estimated probability of a major fire will be low. However a second fire would double the estimated probability.

A number of options are available to improve the estimation quality in this case. One method, that is useful when updating an estimate, is to use a Bayesian approach, whereby an earlier estimate, the “prior” estimate, is revised by new data to reach a revised estimate, the “posterior” estimate. Another possibility is to utilise additional data sets to refine the estimation. The additional data sets must be sufficiently similar to the baseline data to allow comparison and/or conflation of the two sets. In the analysis reported here, the latter method has been utilised in estimating the most serious of fire occurrences, to improve confidence in the probability estimates.

At all times, the quality of the data must be kept in mind, and any conclusions drawn from the analysis need to be cognizant of the data quality.

INCIDENT DATA

United States National Transit Database (NTD)

The primary source for transit data within the USA is the database maintained by the US Federal Transit Administration (FTA): the US National Transit Database. All transit authorities within the USA are required to report data for operations to the NTD, including data on incidents, including fire events [9],[10]. All incidents are reported in the data. The period covered is from 2002 to 2016 and all modes of transit are covered.

The NTD reporting requirements for major incidents need to be noted. Under the NTD reporting guidance, an incident must be reported as ‘major’ if any one of the four following criteria are satisfied:

- Total property damage exceeds $25000
- One or more fatalities are recorded
- One or more injuries requiring immediate medical transport are recorded
- An evacuation is required for life-safety reasons

These criteria are considerably broader than some other authorities’ definitions of ‘major’, or ‘serious’ incidents, which only certify an incident as serious if major injuries and/or fatalities occur. It should also be noted that differing reporting bodies use different terminology to denote a serious incident: e.g. ‘major,’ ‘serious,’ ‘potentially high risk’ are examples of the differing terminology used. These differences between reporting bodies need to be considered when comparing data from other sources with the NTD data.

It should be noted that the NTD data does not explicitly record fires on trains, only all fires on the LRT network. This includes not only train fires, but also trackside fires, station/stop fires, and fires at depots. Hence some estimation needs to be made as to what proportion of the recorded ‘LRT’ fires are fires on trains. First, fires constitute a small percentage of the total incidents on a rail network. Figure 1 summarises reported events on the US light rail network between 2002-2016, per the NTD. Fires of all types (including station and lineside fires) constitute 5.1% of all events reported to the NTD in the reporting period.
Figure 1. US NTD light rail events breakdown by type 2002-2016

Figure 2 - Figure 3 show the incident rates for all types and ‘major’ incidents on the US LRT network, while Figure 4 shows the incident rate for ‘major’ fires on the US LRT network. The percentage of ‘major’/all incidents was 39.5%.

Figure 2. US NTD All incidents data, US LRT network 2002-2016

Figure 3. US NTD ‘major’ incidents data, US LRT network 2002-2016
LRT Operator data
The LRT Operator has not experienced any fires during its period of operations. They have however experienced incidents, including some ‘major’ incidents. These are shown in Figure 5 and Figure 6. The LRT Operator’s rate of all incidents was 62.7% of the rate for the US LRT network as a whole. The LRT Operator’s rate of ‘major’ incidents was 48.8% of the rate for the US LRT network as a whole. These rates likely reflect the relative newness of the system, which thus benefits from the latest safety features and is in a good state of maintenance.
European Union Rail Safety Performance data
Figure 7 summarises the normalised incident rates in the European Union between 2012-2014, reproduced from [11]. The EU data is qualitatively similar to the NTD data in that it demonstrates that fires in rolling stock form a small percentage of the overall incident rate. It can be seen that the vast majority of rail incidents arise from person-train interactions.

Transport Canada data
The Transport Safety Board of Canada publishes safety data on the Canadian rail network[12]. The most recent annual data covers the period 2001-2015, and is presented in Figure 8. This data is of interest as, at least up to 2010, fire was recorded as a specific cause of fatalities and serious injuries, information which is not available from the US NTD data. The Canadian data captures all fires, similar to the NTD data, but also does not break down by type of fire. Note that MMTTM (millions main track train miles) is equivalent to MTRM (millions train revenue miles).

Subsequent to 2010, the rate of serious injuries and fatalities due to fire has not been recorded. This is presumably because between 2001-2010 the total number of rail fire fatalities was 1 (0.11% of all fatalities), and the total number of rail fire serious injuries was 5 (0.69% of all serious injuries). It is assumed that these numbers were deemed by TSB to be insignificant and that it was no longer necessary to track these specifically after 2010.
The TSB data is not used explicitly in the subsequent probability estimate. It does however provide qualitative corroboration that casualties due to fires form a small proportion of the total casualties.

![Figure 8](image)

**Figure 8** Canada TSB data, all fires per million main-track train miles (MMTTM), 2001-2015

**United Kingdom Railway Safety and Standards Board (RSSB) data**
The UK RSSB data [13], [14] captures train fires, but does not report lineside or station fires. See Figure 9. Note that PMTM (passenger millions train miles) is equivalent to MTRM (millions train revenue miles).

![Figure 9](image)

**Figure 9** UK RSSB data, all fires per passenger million train miles (PMTM), 2001-2016

**New South Wales (Australia) Transport Safety Regulator (TSR)**
The Transport Safety Regulator for New South Wales has data on the breakdown of fire types. Figure 10 reproduces Figure 24 from Reference[15]. For the reporting period, there were 350 fires of all types on the network, of which 167 were train fires. Thus, from this data, the rate of train fire occurrence as a percentage of all fires was 47.7%.

![Figure 10](image)
This is the only data that was found that breaks down the relative frequency of train fires, lineside and station fires. It is assumed that this relative frequency may be applied, with caution, to the NTD data, thus yielding an estimate of the frequency of train fires on the US LRT network, as shown in Figure 11.

Federal Aviation Administration (FAA) data on Li-ion battery fires and World Bank data on global flight departures

The above cited data sources focus on rail fires in general. They include therefore train fires (both in-car and under-car), trackside fires, and station fires, both major and minor in size. To estimate the rate of occurrence of fires that could be serious to passengers i.e. fires that have a reasonable probability of causing harm to vehicle occupants, it is necessary to look into causes of fires, and to look at potential sources of in-car fires that could be expected to grow undetected for a sufficient time that progress to flashover is feasible.

It is assumed that overt acts of vandalism and/or terrorism should be excluded. Vandalism should be controllable by housekeeping and operational and security measures. Terrorism is statistically extremely rare, and the probability can be significantly controlled by effective security measures by those charged with monitoring known terrorist groups and sympathisers. Other causes of in-car train fires need to be examined. For modern rolling stock constructed from materials that satisfy current vehicle materials fire-performance standards (as used by the LRT Operator), ignition sources lower than 100-150kW may be discounted as, once the ignition source fuel has been consumed, fires of this size will tend to self-extinguish rather than spread.
A typically cited cause of in-car train fires is “luggage fires”. Luggage fires have been shown to be able to reach peak HRR of approximately 250kW [16, 17]. This is larger than the 100-150kW initiating fire sizes which vehicle design standards such as NFPA 130, ISO EN 45545 and DIN 5510 require train materials to be able to withstand. Therefore there is a reasonable probability that a luggage fire could cause a fire to spread and potentially flash over within a train car.

However, as the other data sources indicate, serious in-car fires on trains are rare. So the question arises: how would a piece of luggage on a train catch fire? One potential ignition source would be one of the numerous personal electronic devices that use lithium-ion (Li-ion) batteries for their electrical power source. Recent press stories covering incidents from e-cigarettes, cellphones, tablets, etc suggest this happens at a statistically significant frequency.

Data is available from the aviation industry on the frequency of Li-ion battery incidents. The US FAA records Li-ion incidents, dating from 1991 to 2016 [18], that have occurred globally on both cargo and passenger flights. The World Bank has data on passenger flight departures over the same period [19]. Thus from the two sources it is possible to estimate a probability of occurrence for a Li-ion battery incident, as shown in Figure 12.

![Li-ion fire rate - passenger flights](image)

**Figure 12** Li-ion battery incidents, global passenger aviation data 1991-2016. Source: [18], [19].

This data is assumed to be transferable to rail transit, since the hazard derives from the personal electronic device, not the mode of transportation. It is also assumed that persons using rail transit carry a normalised population of personal electronic devices (i.e. number of devices per person) that is comparable to that carried on passenger flights. Hence it is reasonable to assume that the risk of a Li-ion battery incident on rail transit is not dissimilar to that on passenger flights.

**PROBABILITY ANALYSIS**

**Probability of fire resulting in casualties (FSI type fire)**

This section documents the analysis carried out to estimate the probability of a fire occurring in the ventilation section in question. To get to the probabilities of interest, it is first necessary to work through the available data, starting with incidents, both ‘all’ and ‘major’, in general, working through the data on all fires, then to ‘major’ fires, then to train fires specifically. From these a probability of fire on the overall system can be estimated. Subsequently, data on section and route length, and on train movements, can be used to estimate the specific probabilities for the ventilation section of interest and the two ventilation sub-sections created by the signal location midway through the ventilation section.
The data summarised in the previous section was employed to create a series of estimates for the probability of fire. The probability of any type of train fire on the system was estimated, as was the probability of an NTD ‘major’ type fire on the system.

Then, two independent data sources, the RSSB data [13],[14] and the Li-ion data [18],[19] were used to estimate the probability of a fire that could result in fatalities and/or serious injuries (FSI). These are tabulated in Table 2 and Table 3. The RSSB data estimated that the probability of a fire on the UK network over the period 1992-2000 was 4 out of 2911, or 1.37x10^{-3} fires/MTRM. Applying this rate to the estimate of ‘major’ fire for the LRT Operator yields an estimated probability of a FSI fire equal to 3.97x10^{-5} FSI fires/MTRM.

It should be noted that during the reporting period for the RSSB data, the UK rail network had a serious problem with arson fires, none of which resulted in FSIs. In contrast, the LRT Operator has had zero arson fires since it started operations. So, if arson fires are discounted from the RSSB data, the resulting rate of FSI fires would be 2.45x10^{-3}. Applying this rate to the estimate of ‘major’ fire for the LRT Operator yields an estimated probability of a FSI fire equal to 7.08x10^{-5} FSI fires/MTRM. This is assumed to be the upper bound for the estimate of FSI train fire probability by using the RSSB data.

It was assumed that Li-ion batteries are a reasonable ignition source for the commonly cited ‘luggage’ fire that is frequently cited as an initiating event for an in-car train fire. A Li-ion battery incident has the potential to lead to a large in-car fire that could flash-over, due to the possibility that such a fire could grow undetected for a significant period of time. It is assumed that all Li-ion battery incidents lead to a flashed-over fire. This is known to be conservative since Reference [16] cited earlier FAA data which showed that out of 35 such incidents, only three resulted in minor injuries and only one resulted in major injuries, with no fatalities reported. However it is here assumed that any Li-ion battery incident could lead to a flashed-over fire. It is further, conservatively, assumed in this case that a flashed-over fire will result in serious injury and/or fatalities i.e. would be classified as a FSI fire. In reality, prompt and effective emergency response could prevent casualties even in a flashed-over fire.

Two incident rates are used. The 25 year average rate is 1.68x10^{-8} incidents/passenger flight departure (1.68x10^{-2} incidents/million passenger flight departures). However in 2015-2016 there was a highly publicized issue with a particular brand of mobile device. The data for 2016 reflects this, with a single year rate of 9.29x10^{-8} incidents/passenger flight departure (9.29x10^{-2} incidents/million passenger flight departures). Since the manufacturer of the faulty devices removed them from the marketplace at the end of 2016, it would be expected that data for 2017 and onwards, when available, would show a lower rate of incidents than seen in 2016. Assuming that this would be the case, the 2016 data is assumed to be a reasonable estimate of the upper bound for the probability by using the Li-ion data.

<table>
<thead>
<tr>
<th>Probability Parameter</th>
<th>incidents/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>'major' train fire/MTRM</td>
<td>2.892E-02</td>
</tr>
<tr>
<td>(probability of 'major' train fire in full vent section)/year</td>
<td>3.663E-03</td>
</tr>
<tr>
<td>(probability of FSI fire in full vent section)/year</td>
<td>1.456E-07</td>
</tr>
<tr>
<td>(probability of FSI fire in full vent section)/year^1</td>
<td>2.595E-07</td>
</tr>
<tr>
<td>(probability of 'major' train fire in vent sub-section 1)/year</td>
<td>2.168E-03</td>
</tr>
<tr>
<td>(probability of FSI fire in vent sub-section 1)/year</td>
<td>8.615E-08</td>
</tr>
<tr>
<td>(probability of FSI fire in vent sub-section 1)/year^1</td>
<td>1.536E-07</td>
</tr>
<tr>
<td>(probability of 'major' train fire in vent sub-section 2)/year</td>
<td>1.495E-03</td>
</tr>
<tr>
<td>(probability of FSI fire in vent sub-section 2)/year</td>
<td>5.942E-08</td>
</tr>
<tr>
<td>(probability of FSI fire in vent sub-section 2)/year^1</td>
<td>1.059E-07</td>
</tr>
</tbody>
</table>

^1- arson fires are discounted (i.e. upper bound on estimate)
Table 3  Annualised probability of fire in ventilation section, using FAA and World Bank Data for Li-ion battery incidents

<table>
<thead>
<tr>
<th>Probability Parameter</th>
<th>Probability Parameter incidents/year</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of Li-ion incident (2016)</td>
<td>9.286E-08 incidents/pass flt deps</td>
<td></td>
</tr>
<tr>
<td>Probability of Li-ion incident (25 year average)</td>
<td>1.678E-08 incidents/pass flt deps</td>
<td></td>
</tr>
<tr>
<td>Probability of Li-ion incident on LRT system (2016)</td>
<td>8.995E-03 incidents/yr for 2016</td>
<td></td>
</tr>
<tr>
<td>Probability of Li-ion incident on LRT system (25 year average)</td>
<td>1.578E-03 incidents/yr (25 yr avg)</td>
<td></td>
</tr>
<tr>
<td>Probability of FSI fire (2016)</td>
<td>2.601E-04</td>
<td></td>
</tr>
<tr>
<td>Probability of FSI fire (25 year average)</td>
<td>4.564E-05</td>
<td></td>
</tr>
<tr>
<td>Probability of ‘major’ train fire/MTRM</td>
<td>2.892E-02</td>
<td></td>
</tr>
<tr>
<td>(probability of ‘major’ train fire in full vent section)/year</td>
<td>3.663E-03</td>
<td></td>
</tr>
<tr>
<td>(probability of FSI fire in full vent section)/year (25 yr avg)</td>
<td>1.672E-07</td>
<td></td>
</tr>
<tr>
<td>(probability of FSI fire in full vent section)/year (2016)</td>
<td>9.529E-07</td>
<td></td>
</tr>
<tr>
<td>(probability of ‘major’ train fire in vent sub-section 1)/year</td>
<td>2.168E-03</td>
<td></td>
</tr>
<tr>
<td>(probability of FSI fire in vent sub-section 1)/year (25 yr avg)</td>
<td>9.895E-08</td>
<td></td>
</tr>
<tr>
<td>(probability of FSI fire in vent sub-section 1)/year (2016)</td>
<td>5.640E-07</td>
<td></td>
</tr>
<tr>
<td>(probability of ‘major’ train fire in vent sub-section 2)/year</td>
<td>1.495E-03</td>
<td></td>
</tr>
<tr>
<td>(probability of FSI fire in vent sub-section 2)/year (25 yr avg)</td>
<td>6.824E-08</td>
<td></td>
</tr>
<tr>
<td>(probability of FSI fire in vent sub-section 2)/year (2016)</td>
<td>3.890E-07</td>
<td></td>
</tr>
</tbody>
</table>

Comparison of the estimates in Table 2 and Table 3 reveals that the figures are similar in order of magnitude. The estimates derived using the Li-ion battery incident data are slightly higher than those derived from the RSSB data, however it must be remembered that the assumption that all Li-ion battery incidents lead to a flashed-over, FSI type fire is conservative. The probability of a train fire reaching flashover is discussed below.

The estimates are summarised and compared in Figure 13. The upper bound of the estimate using the Li-ion battery data reflects the special circumstances of the 2016 data where there was a major issue with a particular brand of mobile device.

![Figure 13: Annualised probability estimate of FSI type fire in ventilation section](image)

**Figure 13  Annualised probability estimate of FSI type fire in ventilation section**

**Probability of FSI fire with two trains in the ventilation section**

The frequency of occurrence of two trains occupying the ventilation section was estimated from operational data (Table 4). The intent of the midpoint signal is to assist with recovery from congestion...
and the section is near the north terminus of the line. Hence the frequency of two trains in the section
is higher for the northbound track than for the southbound track.

Table 4  Data for two trains in ventilation section, sample day, 1st quarter, 2017

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of train movements NB =</td>
<td>144</td>
</tr>
<tr>
<td>2 trains in section count =</td>
<td>32</td>
</tr>
<tr>
<td>Cumulative time 2 trains =</td>
<td>0:52:12</td>
</tr>
<tr>
<td>Operational time =</td>
<td>20:00:00</td>
</tr>
<tr>
<td>% time 2 trains =</td>
<td>4.35%</td>
</tr>
<tr>
<td>No. of train movements SB =</td>
<td>144</td>
</tr>
<tr>
<td>2 trains in section count =</td>
<td>3</td>
</tr>
<tr>
<td>Cumulative time 2 trains =</td>
<td>0:00:48</td>
</tr>
<tr>
<td>Operational time =</td>
<td>20:00:00</td>
</tr>
<tr>
<td>% time 2 trains =</td>
<td>0.07%</td>
</tr>
</tbody>
</table>

From this data, the estimated probability of a fire occurring with two trains in the ventilation section
on the same track was calculated.

Table 5 Annualised probability of train fire in vent section with two trains on a single track

<table>
<thead>
<tr>
<th>Probability Parameter - 2 trains in vent section</th>
<th>incidents/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>(probability of ‘major’ train fire)/year</td>
<td>9.576E-05</td>
</tr>
<tr>
<td>RSSB (probability of FSI fire)/year</td>
<td>6.429E-09</td>
</tr>
<tr>
<td>RSSB no arson (upper bound) (probability of FSI fire)/year</td>
<td>1.146E-08</td>
</tr>
<tr>
<td>(probability of ‘major’ train fire)/year</td>
<td>9.576E-05</td>
</tr>
<tr>
<td>Li-ion 25 yr avg (probability of FSI fire)/year</td>
<td>7.384E-09</td>
</tr>
<tr>
<td>Li-ion 2016 (upper bound) (probability of FSI fire)/year</td>
<td>4.209E-08</td>
</tr>
<tr>
<td>(probability of flashover fire) / year</td>
<td>1.712E-06</td>
</tr>
</tbody>
</table>

Probability of fire reaching full design Heat Release Rate (HRR)

Estimating the risk of a train fire progressing to the full design HRR is non-trivial. A full design HRR,
following current hazard analysis practice, is typically based on an estimate of the HRR resulting
from a flashed-over, fully involved single car train fire. Modern train car materials must have strong
fire resistance performance. The probability of a train fire progressing to flashover and consequently
to full design HRR is very low.

One approach to estimate the probability could be to use a Monte Carlo simulation to simulate a large
number of initiating fires and tally the count of events where a flashed-over, fully involved train fire is
the result. However such an approach is outside the scope of this work. Alternatively, historical
operational statistics could be used. In general, the data does not record the severity of the fire, merely
that a fire was reported. The Li-ion battery incident data could be used to make a first order estimate
of fire severity, however this requires a number of assumptions.

The UK RSSB data may be used to make a first order estimate of fire severity, despite the data
generally presenting consequences as the severity, rather than presenting the severity of the fire itself.
[13], [14] do however classify fires as (i) “significant events” [13] where the severity of the fire is
described, and (ii) “potentially high risk” or “not potentially high risk” [14]. Since 2001 all fires
reported in the data were “not potentially high risk”. It is reasonable to assume that this description
excludes a flashed-over fire. Out of all fires reported, there were 6 “significant events” where the
description of the incident appears to be correspond to a flashed-over fire. The significant events total
6 over a 24-year period, out of a total of 3985 fires reported. On the basis of this data, the probability of a train fire that could be described as reaching full design HRR is $1.51 \times 10^{-3}$ incidents/year, with the proviso that none of these fires have occurred in the past 16 years. An alternative normalisation, based on 'passenger million train miles' (equivalent to MTRM) is $9.28 \times 10^{-4}$ incidents/PMTM.

This probability can be combined with the overall probability of a train fire on the LRT system to estimate the probability of a flashed-over fire on the system. For the whole system, the probability is estimated to be $0.33 \times 9.28 \times 10^{-4} = 3.06 \times 10^{-4}$ incidents/MTRM. The probability of a flashed-over fire is summarised in Table 6. The estimated probabilities by this method are higher than those calculated for FSI fires earlier. This could be due to a variety of factors, including:

- While flashed-over fires present a risk of fatalities and/or serious injuries, it is not certain that they will result in such outcomes, since operational response can mitigate the consequences of such a fire;
- The data for the specific occurrences of flashed-over fires (i.e. the “significant events”) is older data, and from a time when rolling stock on the UK network was considerably less resistant to fire than it has become in the past decade.

### Table 6  Annualised probability of a flashed-over (peak HRR) fire in vent section

<table>
<thead>
<tr>
<th>Probability Parameter</th>
<th>incidents/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flashover fire/MTRM</td>
<td>3.060E-04*1</td>
</tr>
<tr>
<td>(probability of flashover fire in entire vent section) / year</td>
<td>3.876E-05</td>
</tr>
<tr>
<td>(probability of flashover fire in vent sub-section 1) / year</td>
<td>2.294E-05</td>
</tr>
<tr>
<td>(probability of flashover fire in vent sub-section2) / year</td>
<td>1.582E-05</td>
</tr>
<tr>
<td>(probability of flashover fire in entire vent section) / year – 2 trains in section</td>
<td>1.712E-06</td>
</tr>
</tbody>
</table>

1 – Incidents/MTRM

### Probability of train fire due to fault on train

The LRT Operator specified required mean distances between failures as part of the procurement specification for the LRT vehicles. This allows an estimate of any fire due to vehicle fault to be calculated as tabulated in Table 7. An assumption is made (likely conservative) that 1% of all failures could cause ignition.

### Table 7 Probability of fire due to faults on train

<table>
<thead>
<tr>
<th>System</th>
<th>Mean Distance (mi) Between Failures (MDBF)</th>
<th>Failures/MTRM</th>
<th>% of failures that cause ignition</th>
<th>Probability of fire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion system</td>
<td>100,000</td>
<td>1.00E-05</td>
<td>1%</td>
<td>1.00E-07</td>
</tr>
<tr>
<td>Friction brake system</td>
<td>85,000</td>
<td>1.18E-05</td>
<td>1%</td>
<td>1.18E-07</td>
</tr>
<tr>
<td>Communications, except radio</td>
<td>200,000</td>
<td>5.00E-06</td>
<td>1%</td>
<td>5.00E-08</td>
</tr>
<tr>
<td>Cab signal system</td>
<td>200,000</td>
<td>5.00E-06</td>
<td>1%</td>
<td>5.00E-08</td>
</tr>
<tr>
<td>TWC system</td>
<td>200,000</td>
<td>5.00E-06</td>
<td>1%</td>
<td>5.00E-08</td>
</tr>
<tr>
<td>Car body &amp; appointments</td>
<td>1,000,000</td>
<td>1.00E-06</td>
<td>1%</td>
<td>1.00E-08</td>
</tr>
<tr>
<td>Side doors &amp; controls</td>
<td>85,000</td>
<td>1.18E-05</td>
<td>1%</td>
<td>1.18E-07</td>
</tr>
<tr>
<td>Lighting (except light bulbs)</td>
<td>500,000</td>
<td>2.00E-06</td>
<td>1%</td>
<td>2.00E-08</td>
</tr>
<tr>
<td>General electrical apparatus</td>
<td>100,000</td>
<td>1.00E-05</td>
<td>1%</td>
<td>1.00E-07</td>
</tr>
<tr>
<td>HVAC equipment &amp; controls</td>
<td>150,000</td>
<td>6.67E-06</td>
<td>1%</td>
<td>6.67E-08</td>
</tr>
<tr>
<td>Couplers &amp; draft gear</td>
<td>250,000</td>
<td>4.00E-06</td>
<td>1%</td>
<td>4.00E-08</td>
</tr>
<tr>
<td>Trucks &amp; suspension</td>
<td>250,000</td>
<td>4.00E-06</td>
<td>1%</td>
<td>4.00E-08</td>
</tr>
<tr>
<td>Wheel truing</td>
<td>30,000</td>
<td>3.33E-05</td>
<td>1%</td>
<td>3.33E-07</td>
</tr>
<tr>
<td>Aggregate probability of train fire</td>
<td>1.10E-06</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CONCLUSIONS
A set of probability estimates for fire occurrence have been calculated for a safety audit for a US LRT Operator. Drawing on a variety of sets of historical source data, estimates have been calculated for differing fires, classified qualitatively by probable consequences i.e. NTD ‘major’ type fires, flashed-over (peak HRR) type fires, fires resulting in fatalities and/or serious injuries (FSI). These have been calculated for the entire system, for a specific ventilation section and for the two sub-sections within that section created by a mid-point signal. Probabilities for fires occurring with two trains on a single track within the section were also calculated. These are summarised in Figure 14.

The probability of any fire due to a train fault is estimated to be 1.1x10^{-6}. The probability of serious fire is low, and the probability of a FSI-type fire occurring within the specified ventilation section is less than 1x10^{-6}. The probability of a FSI-type fire occurring when there are two trains on the same track in the ventilation section is estimated to be below 1x10^{-7}. These compare favourably to a ‘tolerable if ALARP’ threshold of 1x10^{-6}. The probability of a flashed-over fire in the ventilation section is somewhat higher with a maximum probability of 3.9x10^{-5}, however this may be due to (i) conservative assumptions made in the calculation and (ii) the age of the data used in assessing the probability of flash-over.

![Figure 14: Summary of estimated probabilities of fire occurrence](image-url)
REFERENCES


Rail System Ventilation Rehabilitation

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ABSTRACT

Ventilation systems form an integral part of the fire-life safety systems for underground rail or metro systems. For older systems there is a need to assess the condition of equipment and assess options for rehabilitating or upgrading performance to try and meet modern present day standards. This paper outlines a comprehensive approach to rail system ventilation rehabilitation considering fire potential, ventilation performance, and overall fire-life safety risk.

KEYWORD: rehabilitation, design fire, CFD, ventilation, rail, metro, risk

INTRODUCTION

Ventilation systems form an integral part of the fire-life safety (FLS) features in underground rail and metro systems. As these facilities age there is a need to rehabilitate the fans and associated equipment. Many of the world’s rail and metro networks predate modern FLS design standards such as NFPA 130 [1]. Although most standards have “grandfather” clauses for FLS, it is good practice to not only rehabilitate the ventilation system, but where possible to upgrade the performance.

The first goal of a ventilation rehabilitation project is typically to bring the system to a state of good repair. Older systems were not typically designed with the same level of FLS analysis, such as computational fluid dynamics (CFD) modelling and egress analysis, as modern systems. Rolling stock fire characteristics may also have been based on limited information at the original design phase. These considerations mean that bringing an existing system to a state of good repair may or may not result in better FLS outcomes. It is therefore helpful to characterize the system’s current performance as part of a rehabilitation project. This paper covers a three-step approach to rehabilitating a metro ventilation system that combines railcar fire testing and simulation, CFD and egress analysis, and risk analysis. This approach is already being applied to an existing metro system in the United States, where NFPA 130 is the applicable design standard.

BACKGROUND

In order to better understand the need for rehabilitation some background material is presented, considering three main themes: previous underground rail fire incidents, current US experience with rehabilitation projects, design fire development, and risk assessment and acceptance.

Underground Rail Incidents

A thorough review of previous rail fire incidents (metro and heavy rail) is provided in literature dedicated to the subject [2]. This review helps to understand the societal need for FLS features in an underground rail facility. From that literature there is an emerging theme to the nature of fire incidents, which is that the most common fire incidents are small events in terms of the fire heat release rate (FHRR) and impact on life safety, but that large FHRR events can occur, with devastating loss of life. Small fire events are noted to be far from insignificant, particularly with respect to disruptions, injuries and sometimes loss of life.
In terms of major events, involving multiple casualties, there have been in the order of 10 to 15 such events globally over the past 100 years [2], which is a very small number considering the vast number of rail and metro systems operating. Many of these major events, where a railcar experiences a flashover, are a result of arson rather than a vehicle fault. As an example, a subway fire of 2003 in Daegu, South Korea, killed 198 people and injured 146 people. The fire started in one train car through an arson attack. The fire later spread to a second train that came from the opposite direction and stopped alongside the incident train. Post-incident analysis revealed that response procedures played a major part in this event because the second train should never have entered the station. The situation was exacerbated when the automatic fire detection and response system shut down the power supply to the trains, causing doors to remain closed, trapping 79 passengers inside the train. It is also noted that there was a lack of emergency equipment to be used for firefighting, which made the situation worse.

Small FHRR fire events due to vehicle faults, track fires or power system faults tend to be common. Some recent examples include the following:

- New York City, June 2017: A subway train derailed and a small fire started, possibly due to trash [3]. Around 800 people in the train were evacuated, a process which took over one hour. Occupants forced doors open during the evacuation, and people were exposed to smoke. No major injuries were reported.
- Atlanta, May 2017: Smoke filled a railcar traveling through a tunnel. There were no injuries reported but stations were closed for around two hours while passengers were evacuated. People on a train nearby also had to be evacuated. Passengers interviewed after the evacuation iterated that there was initial confusion about the appropriate course of action [4, 5]. The smoke that filled the train was caused by an arc of high voltage electricity [5]. The metro agency noted in statements that regular training is provided for their staff, and that a post-incident review was conducted to determine any corrective actions.
- Washington, DC, January 2015: Severe electrical arcing was found to be the cause of a smoke event that filled a tunnel and station with smoke on the Washington Metropolitan Area Transit Authority (WMATA) network [6]. The tunnel ventilation fan operation was not optimal in this event and as result all railcars filled with smoke, and in addition, passengers waited at least 35 minutes to evacuate because the train was stalled in the tunnel. As a result of smoke inhalation, there was one fatality from this incident and 90 people were injured [6]. Investigations by the National Transportation Safety Board (NTSB) found that although efforts were being made toward operational safety, that there were many areas for improvement, particularly related to equipment operability, and training and testing of operational personnel [7]. Work to update ventilation modes and improve operational responses is underway as a result of this incident and investigation [8]. Recognizing the risk, the NTSB also issued a directive to all transit agencies in the United States, recommending that all rail transit agencies conduct an audit of their systems to identify the state of repair of the tunnel ventilation, emergency procedures, training programs, and compliance with best practice such as NFPA 130 [9].

The minor incidents discussed above are examples of incidents that occur with reasonable frequency. This review shows that although the FHRR is quite small, typically at around 1 MW, the consequences in terms of human impact and disruption are serious. The review also highlights that the NTSB takes these incidents very seriously and also the need for a widespread check of current transit systems.

**Current US Experience**

A survey of 30 transit agencies in the United States was recently undertaken [10]. Six of the agencies were singled out for more in depth reporting. Five of the six agencies cited emergency ventilation systems being used as a part of their response to fire. NFPA 130 [1] specifies the requirements for a
modern rail tunnel system. However, several agencies acknowledge that their aging systems are often impeded by physical constraints that limit the ability to meet today’s standards. For existing systems the aspirational goal of rehabilitation projects is to bring them in compliance with NFPA 130 [9]. However, given that this is not always feasible, it is necessary for agencies to at least assess the performance of their existing system and bring it to a state of good repair.

Considering the existing system performance can reveal potential for improvement. For example, the Greater Cleveland Regional Transit Authority (GCRTA) found that although their system had an emergency ventilation system in place, the operations (always operated in exhaust) did little for smoke management if the fire location and egress path of passengers were not also considered [10]. Sound Transit in Seattle further stressed that making sure to blow the smoke away from passengers should always come first, even if this means going against the optimal direction for ventilation. It is noted that smoke is emphasized as being responsible for more harm than heat from a fire [10].

Beyond the use of emergency ventilation systems, passenger evacuation and safety are also dependent on the emergency response procedures set forth by the agencies that operate each tunnel system. Agencies such as Massachusetts Bay Transportation Authority (MBTA) and GCRTA that manage a mixture of transit options (heavy, light, commuter rail), also face the challenge of needing to customize procedures based on the type and location of incident train involved. Systems with heavy rail trains must factor the slowdown that occurs when passengers must descend from ladders to reach the track level for evacuation. As a result, rather than waiting to deal with the complexities involved during a fire emergency, these agencies focus on taking the proactive measure of preventing fires by vigilantly clearing the tracks of litter that can serve as ignition sources for fires. Reducing the potential of combustibles, and security considerations, led the Port Authority Trans-Hudson Corporation (PATH) to eliminate trash cans on its platforms so that trash would not be blown onto the tracks, and they replaced wood ties on the tracks with a non-combustible material [10]. Additionally, the PATH, GCRTA, and Sound Transit agencies all maintain close relationships with local fire departments and frequently conduct drills to train staff. WMATA tries to reduce passenger panic in its operational response by incorporating a delay before alarm announcements to allow time for an operator to verify that a fire emergency exists.

Transit agencies in the United States are following through on the NTSB recommendations following the WMATA incident [10]. Ventilation definitely plays a major role in FLS but the review here highlights that there are many other facets to achieving the best possible level of FLS in an existing system. In particular, the preventative and operational actions, which are relatively inexpensive compared with major ventilation upgrades, are seen as having potential for significant safety improvements.

Approaches to Developing System Design Fires

The design FHRR is a key input to a ventilation system design and the magnitude of the FHRR, the soot yield and the growth rate, all have major impacts on the outcomes during a fire in an underground facility. Ventilation systems for many existing facilities have been designed based on heuristics for the railcar FHRR, which do not fully take into account the fire potential of materials on board the railcar. Each rail system is unique in design, from the geometry to the interior materials lining the railcars. As such, the combustibility and potential FHRR vary from one system to another, and these factors should be considered when looking at a system ventilation rehabilitation.

Rail system fires can be classified into three categories: track fires (fires initiated in the undercarriage of a rail car), interior vehicle fires (fires initiated inside a train car), and station fires. Track fires are mostly caused by electrical issues or debris on the tracks and rarely escalate to include the entire railcar (refer above). Station fires can be due to a variety of reasons, not always controllable nor preventable, such as arson. Interior vehicle fires are the most likely to threaten passenger safety and smoke can spread out of the train car and into the tunnel, thereby impeding evacuation.
The interaction of an ignition source and interior materials of a train car dictate whether fire will spread beyond the ignition point and potentially involve the entire train to flashover or self-extinguish. With the advancement of computational technology, testing, and understanding of material properties, it is possible to approximate a custom design fire size for a given rail system based on rail car interior material testing and composition. Multiple studies have investigated the use of computer models, based on small-scale testing, to simulate fire in a system that would otherwise require large-scale testing. Results compared to historically established physical tests show that while it is possible to replicate the fire curve of individual materials, obtaining accuracy for the fire spread of a system involving many materials continues to be an area of further research and development.

The National Institute of Standards and Technology (NIST), in a series of studies conducted between the late 1990s and early 2000s, investigated the difference between basing fire growth and passenger evacuation on small-scale material testing, mockup testing of partial vehicle assemblies, and full-scale fire testing of an Amtrak coach rail car. The focus of these studies was the time it took to reach untenable conditions for passenger evacuation. On average, 13% agreement was achieved between the physical tests and computational model predictions. NIST determined that ignition source sizes of 25 kW to 200 kW were needed to propel flame spread [11].

NFPA 130 discusses conducting tests with a cone calorimeter [12] to obtain material properties for fire situations. Practical demonstrations of this, including use of the test results in CFD models are available [13]. It was found that a further calibration was necessary for a realistic model, thereby reaffirming the importance of physical testing on at least a scale model [13]. The method was applied to the Singapore Circle Line metro system, for the design of its emergency tunnel ventilation system. The ignition source used for the full-scale model was 200 kW and the analysis resulted in recommending a 5 MW design fire for the station and 10 MW design fire for the tunnels [13].

One method of categorizing fire hazard is to use a flame spread parameter, calculated based on outputs from cone calorimeter testing [14]. This is suggested as a screening tool to estimate whether materials on an interior of a rail car will support fire growth. The approach emphasizes the possibility, practicality, and benefits of performing small-scale fire testing via cone calorimetry to obtain material properties, in favor over the more costly, highly-customized, and complicated large-scale fire testing. Material properties are then used in pyrolysis computational models, which involve the interactions of multiple types of materials of the entire train car to predict flame spread over the system. The expectation is that once this approach is calibrated, it can be implemented to supplement the design fire development for a given system.

Risk Assessment and Acceptance

In much of the United States, transit systems were built prior to the current edition of NFPA 130, and therefore in some respects do not meet the criteria set forth by the standard. The aspirational long term goal of each rail system is to comply with NFPA 130, however, the standard recognizes that full compliance might not be achievable, and that maintenance of the existing performance should be sustained at a minimum [1].

Ventilation upgrades are not always cost-effective to develop, nor are they always acceptable to the community, particularly in built-up areas. For instance, a project to retrofit a ventilation plant in New York City was recently shelved due to community opposition to the neighborhood disruption it would have caused [15]. The project was noted to have been “on the shelf” for over 20 years and this made the safety aspect questionable to the community. In addition to community opposition, that project had an estimated cost in the order of $80 million to $96 million. Balancing out these requirements, the fact that limited resources (funding) might be available, the need to maintain the existing system, and that the level of safety is different throughout the network, requires an ongoing (live) risk-based approach to assess where to best allocate resources. The American Public Transport Association (APTA) has developed guidelines for fire safety analysis of existing passenger rail equipment [16]. This document identifies a method that stakeholders can
use to address four crucial elements; identification and prioritization of risks, development of action plans to reduce risk, measuring, monitoring and documenting, as well as maintenance of the action plan [16]. APTA provides a method to identify risks unique to a rail system based on fire location, train location, and the equipment being run during the fire scenario. Each fire scenario is scored based on frequency of the event occurring, and the consequence of the risk. The scores agreed upon for each risk are used to set priority for necessary action to alleviate or eliminate each hazard [16].

Though some risks may be mitigated to reduce the spread of fire or smoke, decrease ignition sources or improve the probability of early detection, APTA recognizes that there will always be an amount of residual risk [16]. Residual risk cannot be completely eliminated for a system, and some level must be accepted. APTA does not quantify how much risk is deemed tolerable, however, it notes that all stakeholders must agree upon the necessary actions to be taken to reduce risk as much as possible.

APTA does not stipulate the timeframe at which such countermeasures to mitigate risk should be implemented, however, proper maintenance and tracking is expected to ensure risks are tended to in a timely manner [16]. For example, in the instance of the ventilation plant proposed in New York City [15], agencies must take into consideration not only the consequence of each countermeasure and where it stands relative to other risks, but public perception of such countermeasures. Though specific construction measures may not rank as high as other improvements, the public perception of heavy construction is that major improvements are being made. Therefore, strategies that require a heavy construction effort, and impose the most adverse effects on communities and businesses, need to be properly timed. Risk assessments are a delicate balance between agencies, passengers, crew and the surrounding communities. Timely identification and mitigation is necessary to assure that rail systems maintain a level of operation that is acceptable by standards, regulators and stakeholders.

INTEGRATED APPROACH TO RAIL SYSTEM VENTILATION REHABILITATION

An integrated approach to rail system ventilation rehabilitation is demonstrated in this paper. The framework and following sections demonstrate the application of this framework via a case study. Some points about each step include the following:

1. The first step involves characterizing the existing system in terms of current performance. It is unlikely that an aging system will satisfy modern equivalents, however, this provides a baseline that informs further considerations.
2. The second step involved considering options for improvement. This could include extra ventilation capacity, egress improvement, operational changes or fire prevention measures.
3. Step three advocates using risk assessment to provide a framework for informed decision making.
4. Finally, step four is a continuous improvement initiative whereby the first three steps are periodically repeated in order to keep decisions made relevant with respect to equipment condition, available funding and community expectations.

CASE STUDY

A case study is provided in the following sections to illustrate the integrated approach to rail system ventilation rehabilitation. The case study is assumed to be an existing US tunnel that was designed and built prior to release of modern fire safety standards such as NFPA 130. The geometry and main fire safety parameters of the existing system are described in Table 1 with key features shown as Figure 1. It should be noted that the case study is based on a fictitious tunnel that is not representative of any existing or planned infrastructure. For the case study it is assumed that the segment being investigated is in an urbanized environment which limits options for large-scale change to the tunnel envelope or surface connections. The tunnel segment is also considered crucial to business continuity and cannot be taken out of service for extended periods for construction purposes.
Table 1  Case study parameters

<table>
<thead>
<tr>
<th>Tunnel Geometry</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>600 m</td>
</tr>
<tr>
<td>Width</td>
<td>10.8 m</td>
</tr>
<tr>
<td>Height</td>
<td>4.8 m</td>
</tr>
<tr>
<td>Tracks</td>
<td>2 tracks with solid dividing wall between tracks, see Figure 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Railcar</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Subway, predates modern standards such as NFPA 130</td>
</tr>
<tr>
<td>Consist</td>
<td>6 cars, total length of 140 m</td>
</tr>
<tr>
<td>Occupant load</td>
<td>40 people per car, 240 people total, population mix of male, female, child and elderly</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Evacuation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy</td>
<td>Portals using an elevated walkway</td>
</tr>
<tr>
<td>Walkway</td>
<td>0.9 m wide, constrained by tunnel/track geometry</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ventilation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-point ventilation</td>
<td>66 m³/s supply or 66 m³/s exhaust, depending on location of train and fire</td>
</tr>
<tr>
<td>Activation</td>
<td>Manual activation by centralized control room</td>
</tr>
</tbody>
</table>

![Figure 1  Case study geometry](image)

CHARACTERIZE THE EXISTING SYSTEM

The first step in the analysis is to characterize the existing system in terms of the likely hazards and the existing performance of the fire safety systems. Aside from the geometry discussed above, the design FHRR and ventilation performance are typically the main elements when it comes to characterizing the existing system.

Design Fire Methodology

A key component for FLS design is the design fire. Modern versions of NFPA 130 place strict requirements on the materials used and their fire performance under standardized tests, however, for older rolling stock there may be less information regarding fire potential. Methods to predict the design fire vary from educated guessing (fire load divided by assumed, non-scientific, burn time based on previous experience), to cone calorimeter informed analysis (such as Duggan’s method), to CFD assessment, to full scale testing.

Fire testing on a full railcar is the most accurate method for determining fire behavior, but it is an expensive option that is rarely implemented. Small scale testing using the cone calorimeter, refer to Figure 2, has been used to characterize fire behavior of individual materials [17]. The simplest cone calorimeter based methods tend to overestimate the fire heat release rate because they assume all materials burn instantaneously, with the heat release rate informed by the cone calorimeter test. More
advanced methods improve on this, but still have a tendency to overestimate the fire growth rate and flashover potential.

Scale models of a railcar interior can be used to understand the interaction of materials during a fire and to help calibrate larger scale models such as a CFD model of a full railcar [13]. A CFD model can never replace a full scale railcar fire test, however, the calibrated model can help to understand the response of the materials to different kinds of ignition sources. NFPA 130 Annex D outlines the following steps to consider when developing a model to predict railcar fire profiles:

1) quantity and properties of accelerants;
2) fire characteristic of car interior materials measured according to ASTM E1354;
3) layout of the car interiors, including seating layouts, orientations, and dimensions;
4) bags and luggage carried by passengers;
5) overall thermal transmission value for vehicle body;
6) openings, including windows and doors;
7) oxygen levels; and
8) mechanical and natural ventilation.

CFD is the most advanced method available short of conducting full scale testing. It can predict a more realistic fire growth rate. Note that a critical input to a CFD analysis is the ignition source; with any railcar it is possible to reach a flashover condition (>10 MW) if a large enough ignition source is used, and key here will be stakeholder agreement to an appropriate level of ignition. Note that this discussion also assumes that the most critical scenario is a fire originating internal to the vehicle and that external fires are minor (1 MW) because of external material fire rating and hardening (i.e. floor can withstand ASTM E 119 test for 30 minutes or more). The interior scenario is assumed to be a deliberate event such as a minor arson event (newspaper) to more serious event (luggage or worse).

The methodology described above was used on a recent project to characterize the railcar fire potential. Railcar interior materials were understood to have been NFPA 130 compliant following a rehabilitation several years earlier. Tests of materials in the cone calorimeter were conducted, along with three mock-up scale railcar fire tests (using seats, flooring and wall panels). The tests were used to calibrate a full-scale CFD model of a railcar. The work included the following:

- Railcar seat materials (fiberglass reinforced polymers) were exposed to various ignition sources and did not burn in an uncontrolled way. Ignition sources included burning newspaper, gasoline, a blow torch, and a backpack. In all of the tests the seat material did not continue to burn once the primary ignition source was depleted.
- Tests on interior mock-ups (seats, flooring, walls), refer Figure 3, which showed that the fire did not readily spread, unless the ignition source was sufficiently large and located to concentrate heat through a more constrained fire plume. The FHRR was measured as part of the test to assist in calibration of a CFD model.
- Cone calorimeter tests were used to derive material properties of individual materials (ignition temperature, conductivity, heat capacity, density, heat of combustion, soot yield) and to derive heat release rate profiles of individual materials (i.e. heat release rate per unit area). The data were then used in CFD models of the mock-up. These models were used to help refine the material properties as part of a calibration process.
- Parameters from the final mock-up scale CFD models were used in a full-scale railcar model to estimate the worst-case (flashover) fire potential (growth rate and peak FHRR).
The outcome of this analysis was an understanding of the railcar fire potential; including the worst-case growth rate and peak FHRR, soot yield, heat of combustion, as well as the response of the system to common ignition sources. The tests showed that, in general, the railcar interior materials were unlikely to burn when exposed to minor arson fires, such as a burning newspaper or a small gasoline pool. These results were used to inform a characterization of fire scenarios for further analysis in CFD models and risk assessments. A key aspect of the definition of a fire scenario for risk assessment is that there is not one type of fire, but rather a spectrum of fires ranging from low to high hazard. Fires were characterized in terms of FHRR, growth rate and likelihood as described in Table 2 with fire hazard types (FHTs) of low, medium and high defined and carried forward into the rest of the analysis. Fire likelihoods were based on observation and assumptions, partly informed by testing and operational experience.

<table>
<thead>
<tr>
<th>Hazard severity (FHT)</th>
<th>Relative likelihood</th>
<th>FHRR range</th>
<th>Growth rate</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (L)</td>
<td>95%</td>
<td>&lt; 1 MW</td>
<td>T-squared, fast</td>
<td>Trash fire, electrical arcing event, minor arson</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>4.99%</td>
<td>&gt;1 MW to 5 MW</td>
<td>T-squared, medium</td>
<td>Major arson or equipment fault</td>
</tr>
<tr>
<td>High (H)</td>
<td>0.01%</td>
<td>&gt;20 MW</td>
<td>Profile, from CFD</td>
<td>Worst-case event</td>
</tr>
</tbody>
</table>

**Table 2** FHRR ranges informed by testing and analysis

**Figure 3** Mock-up of a railcar interior for fire testing

**Ventilation System Performance**

The first step in characterizing the existing ventilation system performance is gathering information about the installed equipment, and making assessments about the state of this equipment and how it is operated. This is likely to require gathering of design documents and commissioning results, if they exist, and undertaking site assessments of the components that make up the ventilation system. Site assessments could include taking airflow measurements in the tunnel to determine the actual performance of the existing, and aging, ventilation system [18]. This initial step is a key step in a rehabilitation project if details about the installed equipment and their condition are not well defined, and could also help to inform costs associated with bringing the existing system into a good state of repair.

The actual performance of the existing system prior to rehabilitation could be difficult to quantify with a level of certainty that can be carried forward into a reasonable future service life. The current condition of the equipment and any future deterioration might mean that the performance has or will become degraded compared to the as-designed performance. With this in mind, the existing system is characterized in terms of its designed performance rather than the performance as it stands prior to any rehabilitation being undertaken. This means that the analysis of the ventilation system performance is in terms of bringing the existing system into a good state of repair, thus providing a
baseline that can be used to inform alternative design options. Deterioration or operational deficiencies are accounted for when comparing alternatives in the risk assessment based on the site visit assessments undertaken to assess the condition of the existing equipment.

It is likely that a rail system requiring rehabilitation was designed without the use of modern analysis tools such as CFD and egress modelling. However, when it comes to characterizing ventilation system performance these tools are now readily available and relatively inexpensive. Using CFD models coupled with egress modeling, along with Subway Ventilation Simulation (SVS) analysis [19], provides a detailed understanding of the system performance taking into account the various fire scenarios, ventilation modes, timing, and evacuation characteristics.

For the case study in this paper, Fire Dynamics Simulator (FDS) version 6.5.3 [20] was used for the CFD modelling and this was coupled with FDS+Evac [21] to perform the evacuation analysis. The main inputs to the modelling are defined by Table 1 and Figure 1. FDS+Evac is particularly useful as it is intrinsically coupled to FDS, which means that the setup, execution and post-processing of the models can be scripted. This is advantageous when many models need to be run to inform the analysis of multiple alternatives. Different ventilation conditions were considered in the analysis including natural ventilation (zero pressure boundary in the FDS model), mid-point exhaust or supply (modeled with a fixed volume flow boundary in the FDS model) and longitudinal ventilation with jet fans (modeled using a fixed velocity boundary at the tunnel inlet).

Table 3 summaries the outcomes from the ventilation system analysis of the existing system. For each scenario a score was calculated that is an indication of fire safety acceptability of that scenario. This metric could be based on multiple factors, however, for this case study the fractional effective dose (FED) was used. The calculation of the FED is as described in the FDS+Evac user manual [21] and it is output for each of the 240 agents in the model. As defined by ISO 13571 [22], an accumulated FED of 1.0 corresponds to a log-normal distribution of responses, with statistically 50% of the population expected to experience compromised tenability. A threshold criteria of accumulated FED > 0.3 translates to approximately 11% of the population being statistically susceptible to compromised tenability.

The maximum FED from each model was recorded and a score computed on a log scale basis:

\[
Score = S_{ij} = \left[\log_{10}(\text{max FED})\right] \times 100/3
\]  

If the maximum FED was less than 0.001 then it was automatically set to 0.001. With this scale, a low FED (0.001) would give a system ventilation score of 100 (best possible) and with an FED of 1, the score would be calculated to 0 (worst possible). A log scale was used for computing the scoring because it enabled a better reflection of the scenario outcomes compared with a linear scale which did not show up any major differences. The denominator of 3 is necessary to normalize the log of the FED (which can be between 0 and 3). Given that the maximum FED is based on a single person, it is a reasonable approach to use a log scale this way; the system will give a good ventilation score if just one person is exposed to a little smoke, but it will give a poor score if one person has an FED of 1.0. This is appropriate because an FED of 1.0, even if it is only for one person, indicates a situation where it is likely that more people are exposed to smoke. The inverse applies for very low FED values.

From the outcomes in Table 3 it is seen that the existing system performance is reasonable for some of the low and medium hazards, but this is somewhat dependent on the fire location. These low and medium fire hazards are more probable and a good level of performance is expected for these hazard types. The performance is quite poor for the high hazard fire, but it should also be remembered that this hazard is less probable, which is not accounted for in the scoring. The scoring provides an indication only of the performance for each hazard type and it is the risk assessment that factors probability of these events to provide an overall performance appraisal.

When characterizing the ventilation system performance it could also be the case that it was not
originally designed for the fire scenarios being considered. This highlights the benefit of characterizing the design fire into a range of scenarios (low, medium, high). If a single design fire was applied, the system may be under- or over-designed relative to the FHRR, and this may distort the overall system appraisal.

However, note that an assessment where every possible fire scenario is analyzed was not conducted because the risk assessment methodology, discussed further below, does not require it. The risk assessment methodology, which assigns a score in proportion to ventilation system performance, is designed to allow the score to be assigned by the engineer, supported by as little or as much quantitative analysis as their judgement deems necessary. The advantage of this approach over an approach that analyzes all possible scenarios is that the engineer can run a few scenarios and then screen the system and the alternative concepts, thus allowing an efficient identification of the more attractive concepts for further development.

Table 3 Ventilation system performance with equipment in a good state of repair

<table>
<thead>
<tr>
<th>ID</th>
<th>FHT</th>
<th>Train / fire location</th>
<th>Ventilation</th>
<th>Score</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>71</td>
<td>Smoke to W and people move E in clear air</td>
</tr>
<tr>
<td>2</td>
<td>L</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>59</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>3</td>
<td>L</td>
<td>Mid tunnel / W side of shaft</td>
<td>EV, smoke to E</td>
<td>23</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>4</td>
<td>L</td>
<td>Mid tunnel / E side of shaft</td>
<td>EV, smoke to W</td>
<td>46</td>
<td>Smoke to W, captured at shaft</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>91</td>
<td>Smoke to W and people move E in clear air, some late BL to E</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>65</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>Mid tunnel / W side of shaft</td>
<td>EV, smoke to E</td>
<td>14</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>Mid tunnel / E side of shaft</td>
<td>EV, smoke to W</td>
<td>52</td>
<td>Smoke to W and BL to E</td>
</tr>
<tr>
<td>9</td>
<td>H</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>70</td>
<td>Smoke to W, people move E in clear air, some late BL to E</td>
</tr>
<tr>
<td>10</td>
<td>H</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>1</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>11</td>
<td>H</td>
<td>Mid tunnel / W side of shaft</td>
<td>EV, smoke to E</td>
<td>0</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>12</td>
<td>H</td>
<td>Mid tunnel / E side of shaft</td>
<td>EV, smoke to W</td>
<td>0</td>
<td>Smoke to W and BL to E</td>
</tr>
</tbody>
</table>

Abbreviations:
- FHT = fire hazard type
- L: <1 MW fast growth
- M: ≤ 5 MW medium growth
- H: ≥ 20 MW arson fire
- W = west
- E = east
- EV = Exhaust (66 m³/s)
- SV = Supply (60 m³/s)

Remarks:
- Column “Ventilation” notes the design basis behavior of smoke, column “Outcomes” notes the actual behavior.
- Column “Score” is computed as noted by equation 1.

OPPORTUNITIES FOR IMPROVEMENT

Developing Alternatives

Opportunities for improvement as part of a rehabilitation project are likely to be system-dependent. However, a few items that require consideration are (1) the existing performance, (2) the operational strategy, (3) physical limitations (4) budgetary constraints (5) business continuity requirements and (6) mandatory regulatory requirements. The weight that is applied to each of these considerations is also going to be system-dependent, but this at least provides prompts of some key items to consider.

In terms of the case study, the as-designed performance of the existing system has been characterized in the previous section. However, this does not necessarily reflect the current condition of the equipment or other operational deficiencies. The opportunity here lies in bringing this equipment into a good state of repair to reinstate the original ventilation performance. There is also an opportunity to adjust the operational strategy and see if this provides a benefit. The later could be as simple as improving operator training or reconfiguring the operational modes to achieve a better outcome.

In developing the case study example it was defined that large-scale structural works were not...
possible due to the urban environment above and that business continuity needed to be considered as the system could not be out of service for long periods. These would be likely constraints on an actual rail system. With this in mind, major changes to the ventilation arrangement are not considered further, neither are changes to the evacuation strategy such as widening the walkway. While this does limit some of the alternatives that could be considered, there are other opportunities worth considering and the focus here is on ventilation alternatives.

There is a solid dividing wall between the tracks that has a break at the mid-point ventilation station. This dividing wall may be beneficial in terms of limiting smoke spread for certain scenarios, but may reduce the efficacy of the ventilation system as the railcars act as a pinch point within the tunnel, affecting the system aerodynamics. Assuming the dividing wall is only partially load-bearing, openings could be added to make a porous wall with an open area of 12%. This may reduce smoke spread because it effectively opens the tunnel (removes the rail vehicle pinch point) and the system may be more effective for some scenarios.

Longitudinal ventilation is also a possible alternative. Assuming there is sufficient headroom for jet fans to be installed, the fans would provide good ventilation performance, albeit at a significant cost. This alternative might be representative of an NFPA 130 design where the longitudinal ventilation provides a clear evacuation path on one side of the fire and the direction of operation is dependent on the fire location in the train.

Given the tunnel is relatively short at 600 m, there might also be an opportunity to utilize a natural ventilation solution. This would be operationally simple with reduced ongoing maintenance and capital costs. From an operator’s point-of-view this may be preferred, but external wind effects need to be considered, as well as any requirements for intervention and post-incident recovery.

Analysis of Selected Alternatives

Bringing the system into a good state of repair has already been characterized and this is carried forward into the risk assessment where the state of equipment and operational considerations are factored into the performance of the system prior to rehabilitation. The system prior to rehabilitation is denoted Alternative 1 and the system being bought into a good state of repair is denoted Alternative 2.

The other alternatives selected for further analysis include the porous center wall (Alternative 3), longitudinal ventilation with jet fans (Alternative 4) and natural ventilation (Alternative 5). These alternatives were subjected to the same analysis methodology as the existing system, with specific scenario selection suitable for these alternatives. Fire scenarios for analysis were selected using a small subset of all the possible combinations of fire severity and location.

Table 4 provides results for the porous center wall. The improvement in smoke management and egress outcomes for the scenarios tested is negligible. Analysis for the longitudinal ventilation with jet fans is provided in Table 5. The scores based on FED are improved to a moderate extent, except for one scenario, associated with the high severity fire hazard, where there is a large improvement in the outcome. Finally, for the natural ventilation solution a range of winds were also considered given that this alternative is more susceptible to external wind conditions. The analysis for this alternative is given as Table 6. Results show a general drop in performance compared with ventilated cases, especially for unfavorable wind directions.

Final results, refer to Table 7, are obtained from Table 3, Table 4, Table 5 and Table 6 by averaging the data obtained from analysis. It is noted that the data are not comprehensive in terms of the scenarios; alternative ventilation approaches were considered only for a train located west of the vent plant. However, assuming that the results would trend the same way for different locations, the results from Table 3 are used to inform judgement on adjustments to performance scores. In general, when a train was located toward the center of the tunnel risk scores are poorer by around 30 to 40
points, and considering that the “mid tunnel” region represents no more than one third of the tunnel length, an average point reduction of 10 to 15 points was observed and applied to all the results.

Table 4  Alternative 3 – porous center wall

<table>
<thead>
<tr>
<th>ID</th>
<th>FHT</th>
<th>Train / fire location</th>
<th>Ventilation</th>
<th>Score</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>L</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>78</td>
<td>Smoke to W and people move E in clear air</td>
</tr>
<tr>
<td>14</td>
<td>L</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>79</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>15</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>89</td>
<td>Smoke to W and people move E in clear air, some late BL to E</td>
</tr>
<tr>
<td>16</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>86</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>17</td>
<td>H</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>86</td>
<td>Smoke to W and people move E in clear air, some late BL to E</td>
</tr>
<tr>
<td>18</td>
<td>H</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>1</td>
<td>Smoke to E and BL to W</td>
</tr>
</tbody>
</table>

See Table 3 for abbreviations and notes

Table 5  Alternative 4 – longitudinal ventilation with jet fans

<table>
<thead>
<tr>
<th>ID</th>
<th>FHT</th>
<th>Train / fire location</th>
<th>Ventilation</th>
<th>Score</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>L</td>
<td>W tunnel / W end train fire</td>
<td>JFV, smoke to W</td>
<td>85</td>
<td>Smoke to W and people move E in clear air</td>
</tr>
<tr>
<td>20</td>
<td>L</td>
<td>W tunnel / E end train fire</td>
<td>JFV, smoke to E</td>
<td>92</td>
<td>BL to W reduced</td>
</tr>
<tr>
<td>21</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>JFV, smoke to W</td>
<td>79</td>
<td>BL to E reduced</td>
</tr>
<tr>
<td>22</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>JFV, smoke to E</td>
<td>97</td>
<td>BL to W reduced, more smoke to E</td>
</tr>
<tr>
<td>23</td>
<td>H</td>
<td>W tunnel / W end train fire</td>
<td>JFV, smoke to W</td>
<td>86</td>
<td>BL to W reduced</td>
</tr>
<tr>
<td>24</td>
<td>H</td>
<td>W tunnel / E end train fire</td>
<td>JFV, smoke to E</td>
<td>82</td>
<td>BL to W reduced, more smoke to E</td>
</tr>
</tbody>
</table>

See Table 3 for abbreviations and notes, JFV = jet fan ventilation, sized to achieve critical velocity for >20 MW fire

Table 6  Alternative 5 – natural ventilation

<table>
<thead>
<tr>
<th>ID</th>
<th>FHT</th>
<th>Train / fire location</th>
<th>Ventilation</th>
<th>Score</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>NV, no wind</td>
<td>66</td>
<td>Smoke moves to E, beyond vent plant</td>
</tr>
<tr>
<td>26</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>NV, no wind</td>
<td>15</td>
<td>Smoke moves to W, does not move to E</td>
</tr>
<tr>
<td>27</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>NV, wind to E</td>
<td>11</td>
<td>Smoke moves to E</td>
</tr>
<tr>
<td>28</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>NV, wind to E</td>
<td>91</td>
<td>Smoke moves to E</td>
</tr>
<tr>
<td>29</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>NV, wind to W</td>
<td>97</td>
<td>Smoke moves to W</td>
</tr>
<tr>
<td>30</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>NV, wind to W</td>
<td>18</td>
<td>Smoke moves to W</td>
</tr>
</tbody>
</table>

See Table 3 for abbreviations and notes

Table 7  Final averaged risk scores for each ventilation option (rounded to nearest 10)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>50</td>
<td>70</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>M</td>
<td>60</td>
<td>70</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>H</td>
<td>20</td>
<td>30</td>
<td>70</td>
<td>10</td>
</tr>
</tbody>
</table>

Simulations were not run for these cases, but given generally observed poor performance this scheme was given a score 10 points worse than the worst result from Alternative 2 simulations.

INFORMED DECISION MAKING

Risk Assessment

The analysis for each alternative gives an indication of the performance for each hazard type, but does not factor in the probability of these hazards occurring. This could be misleading for a rehabilitation project where hard constraints limit the practical improvements that can be made. For instance,
aspirational goals around achieving NFPA 130 equivalent performance may not be realistic and there needs to be a framework to demonstrate that the rehabilitated project has achieved a reasonable balance between practicality, cost and performance, and that the residual risk is acknowledged and monitored.

A risk framework has been developed for rehabilitation projects that provides this framework by comparing the benefits and costs associated with a range of alternatives (Alternatives 3 to 5), and comparing these to doing nothing (Alternative 1) and bringing the system into a state of good repair (Alternative 2). This allows aspirational goals such as NFPA 130 to be included and assessed, but also other incremental improvements that could be staged over time when budgets and other opportunities permit.

An important aspect of the risk framework is the semi-quantitative nature of the assessment. While the inputs could be informed by detailed analysis, they could also be developed through stakeholder workshops with expert judgement. Ultimately the framework could incorporate detailed or qualitative inputs depending on the stage, complexity or requirements of a rehabilitation project. This flexibility also enables operators to carry the risk assessment forward, monitor the residual risk and identify opportunities for improvement.

The risk framework consists of a range of score-cards that can be tailored to a particular project. These score-cards could be based on elements such as ventilation performance, evacuation provisions, or any other element that impacts fire safety. A weighting can then be applied to each score-card if a particular element is deemed to have more influence on the outcome (e.g. smoke management can be given a greater weighting). When these score cards are combined they provide an overall indication of the FLS performance of an alternative that can be compared to other alternatives.

A simplified version of the risk framework is provided below in order to illustrate the scoring as applied to the case study herein, which was based solely on ventilation performance. For the analysis of the different alternatives a score was given out of 100 for the low, medium and high hazards (refer to Table 7). The higher the score, the better the alternative was in term of FLS. This score, however, does not take into account the state of the equipment or operational assumptions.

A fire hazard score (FHS) is defined where a higher number denotes a potentially higher consequence and vice-versa. This takes into account the consequences of an unmitigated hazard. That is, without any fire safety provisions what an order of magnitude consequence could be for each hazard type. The score for an alternative reduces the unmitigated hazard taking into account the operation and condition of the equipment. The FHS used for the case study is calculated by Equation 2. This equation factors the unmitigated hazard score ($H_j$) by accounting for the relative hazard associated with the alternative (i.e. $(100 - S_{i,j} \alpha_i \beta_i)/100$). This means that if an alternative achieves a near perfect score (e.g. $S_{i,j} \alpha_i \beta_i \rightarrow 100$), then the alternative is successful at mitigating the hazard. Conversely, if the alternative has little effect on the outcome (e.g. $S_{i,j} \alpha_i \beta_i \rightarrow 0$), then the unmitigated hazard remains largely unchanged.

$$FHS_{i,j} = \frac{H_j}{100} \left(100 - S_{i,j} \alpha_i \beta_i\right), \hspace{1cm} (2)$$

where,

- $FHS_{i,j}$ FHS for alternative $i$ applied to hazard $j$ (mitigated hazard; low, medium and high hazards),
- $H_j$ FHS before the scoring is applied to hazard $j$ (unmitigated hazard), for the case study $H_l=10$, $H_m=100$, and $H_h=1000$,
- $S_{i,j}$ score for alternative $i$ as applied to hazard $j$ (value between 0 and 100) (for the case study, this is based on the analysis in the previous sections),
operation factor to account for operational considerations associated with alternative \(i\) (e.g. procedural, training, etc.) (value between 0 and 1) (for example, well-defined procedures and well-trained staff would be 1), and

condition factor to account for the condition of equipment associated with alternative \(i\) (value between 0 and 1) (for example, new equipment would be 1, faulty equipment would be closer to 0).

Once the FHS is computed for each hazard, the overall fire risk score can be calculated. Risk is typically defined as the product of consequence and likelihood. The order of magnitude consequences are defined by the FHS for each hazard type. The likelihood of each hazard type occurring (\(P_L\), \(P_M\), \(P_H\)) can be informed by system fire statistics or some other relevant source. For the purposes of the case study the probability was informed by design fire considerations (refer to Table 2). The following equation gives the overall fire risk score (FRS) for the alternative:

\[
FRS_i = FHS_L P_L + FHS_M P_M + FHS_H P_H
\]  

For each alternative a cost is also assigned. This cost could be based on detailed quantity surveying of the alternatives or an order of magnitude cost calculation. For the case study, order of magnitude cost estimates have been used. This cost for each alternative is then calculated as millions of dollars per fire by taking into account the frequency of each FHT.

Figure 4 shows an example of the risk assessment output as applied to the case study example. In this example the current condition assumes that the equipment is always operated appropriately and that 80% of the time the aged equipment will function. The FRS has been normalized by the results for Alternative 4 as this alternative represents an NFPA 130 compliant option. While the risk is lowest for the NFPA 130 design it has the worst outcome in terms of the cost versus benefit, which needs to be considered when there are only finite resources available. The natural ventilation option has the best cost versus benefit score, but this option is least compliant with NFPA 130 since there is now no ventilation where previously ventilation was provided. This option would not be acceptable from a community perspective, where there would be an expectation to at least keep the FLS ventilation equipment in good repair. The result that therefore is most acceptable is a rehabilitation effort to bring the equipment to a state of good repair (Alternative 2).

**Decision Making**

The result of the risk analysis shows the cost/benefit performance of the different options relative to a benchmark tunnel or station. It may not be possible to achieve NFPA 130 compliance and there is a need to accept and manage some level of residual risk, a situation that is acknowledged in guidelines published by the American Public Transport Association (APTA) [16]. Ranking of options relative to a benchmark is helpful because it allows the risk analysis to become a live analysis that can help to look ahead and plan for allocation of resources in the future in the most cost and safety effective ways possible.

It is noteworthy that risk analysis should never be based on cost versus benefit alone. This point was highlighted in the case study above where the best option for cost versus benefit was the least safe and would not be acceptable to the community because: 1) It is reducing safety relative to the current situation, and 2) It could be perceived as “rolling the dice” with respect to public commuter safety. That said, a decision also should not be made on the safest option alone because this is potentially a very inefficient allocation of resources. The approach shown here needs balanced risk decisions to be made based on cost, community requirements (such as NFPA 130), and overall level of safety.
SUMMARY / CONTINUOUS IMPROVEMENT

Ventilation systems form an integral part of the fire-life safety systems for underground rail or metro systems. For older systems there is a need to assess the condition of equipment and assess options for rehabilitating or upgrading performance to try to meet present day standards. It is not always possible to meet present-day standards in an existing system and therefore an approach to determination of the best option for rehabilitating a metro ventilation system needs to combine railcar fire characteristics, CFD and egress analysis, and risk analysis. Existing rail systems are large and complex systems, and a full quantitative assessment of all the factors would be a very significant undertaking. A method was therefore developed with the objective of simplifying the process while still providing meaningful data for making informed decisions. The method includes the following steps:

1. Characterise the existing system performance (design fire and ventilation system effectiveness).
2. Consider options for improvement. This could include extra ventilation capacity, egress improvement, operational changes or fire prevention measures.
3. Conduct risk assessment to provide a framework for informed decision making.

The key part of the method is that it is semi-quantitative; a scoring system is developed which is informed by a mix of analysis (CFD and egress) and judgement. This score-based approach to risk assessment introduces the potential to not rely on massive amounts of analysis to generate or update a risk assessment; an owner can use as little or as much analysis as the situation requires. In contrast to a full quantitative risk assessment method, this method allows for efficient early phase screening of concepts and more refined analysis of options further along in a project, if necessary. A short tunnel with ventilation was analysed to demonstrate application, and it was seen that it is possible to develop an assessment that provides sufficient detail to inform an upgrade/rehabilitation design decision, with minimal quantitative analysis.

In conclusion, the method of assessment demonstrated herein, and the flexibility of analysis input can
enable an effective assessment of ventilation system performance, costs and risks. The method’s efficiency also makes it possible to adjust the risk assessment as years advance, adjusting the input parameters related to training, condition of equipment and observed events, and costs as the system ages and is improved, thus allowing prioritization of resources between maintenance, rehabilitation and upgrades related to FLS.

REFERENCES

Risk Analysis for Road Tunnels – A Metamodel to Efficiently Integrate Complex Fire Scenarios

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¹Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Germany
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ABSTRACT
Fires in road tunnels constitute complex scenarios with interactions between the fire, tunnel users and safety measures. More and more methodologies for risk analysis quantify the consequences of these scenarios with complex models. Examples for complex models are the computational fluid dynamics model Fire Dynamics Simulator (FDS) and the microscopic evacuation model FDS+Evac. However, the high computational effort of complex models often limits the number of scenarios in practice. To balance this drawback, the scenarios are often simplified. Accordingly, there is a challenge to consider complex scenarios in risk analysis.

To face this challenge, we improved the metamodel used in the methodology for risk analysis presented on ISTSS 2016. In general, a metamodel quickly interpolates the consequences of few scenarios simulated with the complex models to a large number of arbitrary scenarios used in risk analysis. Now, our metamodel consists of the projection array-based design, the moving least squares method, and the prediction interval to quantify the metamodel uncertainty. Additionally, we adapted the projection array-based design in two ways: the focus of the sequential refinement on regions with high metamodel uncertainties; and the combination of two experimental designs for FDS and FDS+Evac.

To scrutinise the metamodel, we analysed the effects of three sequential refinement steps on the metamodel itself and on the results of risk analysis. We observed convergence in both after the second step (ten scenarios in FDS, 192 scenarios in FDS+Evac). In comparison to ISTSS 2016, we then ran 20 scenarios in FDS and 800 scenarios in FDS+Evac. Thus, we reduced the number of scenarios remarkably with the improved metamodel. In conclusion, we can now efficiently integrate complex scenarios in risk analysis. We further emphasise that the metamodel is broadly applicable on various experimental or modelling issues in fire safety engineering.

KEYWORD: risk, tunnel, fire, evacuation, CFD, metamodel, uncertainty, adaptivity

NOMENCLATURE
Bold notation of $\xi$ or $s^2$ signal vectors for results of multiple scenarios.

Roman and Greek letters

$d$ number of risk indicators (dimensions) in $\bar{x}$

$fa = [F\bar{A}, FA]$ failure of tunnel alarm [no, yes]

$HRR_{max}$ maximum heat release rate /MW

$N_u$ number of tunnel users

$n$ number of scenarios

$P_{stretch}$ stretching factor

$q_{90}(s)$ 90% quantile of $s$

$s^2 = s^2(\xi)$ variance of $\xi$ (prediction interval)

$\bar{t}_\alpha$ random realisation of the Student’s t-distribution

$t_{crit,\alpha}$ critical value of the Student’s t-distribution
**INTRODUCTION**

Fires in road tunnels constitute complex scenarios with interactions between the fire, tunnel users and safety measures like fire detection, tunnel alarm or emergency ventilation. Thus, many risk indicators, which are factors with effects on risks for tunnel users, describe the scenario. Several methodologies for risk analysis in road tunnels evolved during the last 15 years [1] to determine the risks and to evaluate the effects of safety measures. To take the complex scenarios into account, more and more of these methodologies now apply complex models to quantify the consequences. Complex models can be either: fire models like computational fluid dynamics models which simulate the spread of heat and smoke in a fire scenario; and, microscopic evacuation models which simulate the movement of individual tunnel users as well as their interactions in an evacuation scenario.

But complex models cause high computational effort that often limits the number of scenarios in practical applications. Furthermore, risk analysis requires consequences of an ‘infinite’ number of scenarios on the entire domain of risk indicators (‘global objective’), e.g. from low to high heat release rates. In contrast, the ‘local objective’ focuses on specific regions of the domain, e.g. only on high heat release rates [2]. Thus, the global objective requires an increased number of scenarios. In case of restricted computational resources, a common compensation is to reduce the number of risk indicators leading to simplifications in the scenarios, e.g. in [3]. In conclusion, there is a challenge for risk analysis to integrate complex scenarios considering several risk indicators with complex models. To face this challenge, we improved the metamodel used in our methodology for risk analysis published on ISTSS 2016 [4].

In general, the metamodel consists of three different parts. First, the experimental design defines the parameters of risk indicators for a small number of scenarios. Second, the consequences of these scenarios are quantified with the complex models and saved in a permanent data base. Third, the response surface model interpolates the consequences from the data base to any arbitrary scenario. The interpolation enables the quick analysis of ‘infinite’ scenarios for the global objective but causes uncertainties called metamodel uncertainty.

Different methods for the first and the third part of the metamodel exist. With view on experimental designs, several methods address global objectives with good space-filling properties. Space-filling means the evenness of spread of a small number of scenarios on the entire domain. For this purpose, Latin hypercube designs are very common [5], in particular with some optimisations in space-filling [6]. The projection array-based design [7] improves the space-filling properties of Latin Hypercube designs in particular for high-dimensional problems. Furthermore, it is possible to append new scenarios to an existing projection array-based design in sequential refinement steps. With view on the response surface model, first- or second-order models are typical for local objectives [5]. Instead, the moving least squares method focuses on the global objective [8]. Additionally, the prediction interval...
[9] quantifies the metamodel uncertainties of the moving least squares method. In brief, we adapted the experimental design and the response surface model correspondingly in order to improve the metamodel. Consequently, this paper outlines the metamodel in Section ‘Methodology’ and Section ‘Results and discussion’ focuses on proving its efficiency. In detail, we organised the paper as follows. Section ‘Methodology’ consists of four subsections. First, the Subsection ‘Risk analysis with complex models’ describes the complex scenario, the risk indicators [4], the computational fluid dynamics model Fire Dynamics Simulator (FDS) [10] and the microscopic evacuation model FDS+Evac [11]. Second, the Subsection ‘Experimental design’ deals with the projection array-based design [7]. There, we also outline our adaptions: the focus on particular regions of the domain during sequential refinement; and the combination of two experimental designs for FDS and FDS+Evac. Third, the Subsection ‘Response Surface Model’ provides the background to the moving least squares method [8]. The subsection also addresses our implementation of the metamodel uncertainty based on the prediction interval [9]. Fourth, we shortly summarise the setup of the metamodel and outline the optimisation of the moving least squares models in the Subsection ‘Setup of the metamodel’. Then, Section ‘Results and discussion’ shows the different refinement steps. The Subsection ‘Metamodel’ highlights their effects on the moving least squares model and the metamodel uncertainty. The Subsection ‘Risk analysis’ shows the effects on risk measures and discusses the advantages to the metamodel used in ISTSS 2016 [4]. Finally, Section ‘Conclusions’ concludes that first, the metamodel efficiently integrates complex scenarios and second, emphasises that the metamodel is not only limited to risk analysis but also applicable on various issues in fire safety engineering.

METHODOLOGY

We put the focus of this paper on the improved metamodel, which is now used within the same methodology for risk analysis presented on ISTSS 2016 [4]. Thus, we only provide the essential information of the methodology for risk analysis in the first Subsection and refer to [4] for further information. Then, Subsections ‘Experimental design’ and ‘Response surface model’ describe in detail the adapted parts of the metamodel. Finally, we summarise how to setup the metamodel in Subsection ‘Setup of the metamodel’.

Risk analysis with complex models

The methodology for risk analysis [4] comprises twelve risk indicators, which define the scenario and the initial frequency of the fire. Risk indicators are factors affecting the risks in the road tunnel and rely on probabilistic, empirical or analytical models. We chose the risk indicators based on a literature review described in [4,12] and quantify the results of risk analysis with the two risk measures [13]: first, the individual risk $R_{\text{ind}}$ is the annual frequency that a person being permanently in the tunnel will die due to a fire scenario; second, the societal risk, often presented in societal risk curves, is the annual frequency that a specified minimum number of persons dies in a fire scenario. In summary, the risk measures depend on the consequences and on the initial frequency of fire in an ‘infinite’ number of arbitrary scenarios.

In case of a fire, five risk indicators define the fire and the evacuation scenario (see Table 1). Two of these risk indicators affect the spread of heat and smoke in the fire scenario $x_i^f = [HRR_{\text{max},i}, t_{\text{max},i}]$. The evacuation scenario, the evacuation of tunnel users during the fire scenario, considers three additional risk indicators $x_j^e = [x_i^f, t_{\text{pre},j}, N_{\text{tu},j}, f_{\text{aj}}]$. The maximum pre-evacuation time $t_{\text{pre}}$ is the maximum duration between the alarm of a tunnel user and the beginning of its movement. The individual pre-evacuation time of a tunnel user is governed by a uniform probability distribution between zero and $t_{\text{pre}}$. The risk indicators $t_{\text{max}}$ and $t_{\text{pre}}$ use uniform probability distributions because of scarce statistical basis (see Table 1). For the risk indicators $HRR_{\text{max}}$ and $N_{\text{tu}}$ the probability distributions are twofold: for the evaluation of the metamodel we apply uniform probability distributions (Table 1) and for risk analysis we use specific probability models (Table 2).
Table 1: risk indicators with uniform probability distribution (white background: fire scenario, grey background: evacuation scenario;

<table>
<thead>
<tr>
<th>risk indicator</th>
<th>term</th>
<th>min</th>
<th>max</th>
<th>references / remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum heat release rate</td>
<td>$H_{RR\max}/MW$</td>
<td>25</td>
<td>200</td>
<td>[14]</td>
</tr>
<tr>
<td>time to maximum heat release</td>
<td>$t_{max}/s$</td>
<td>600</td>
<td>1200</td>
<td>[15,16]</td>
</tr>
<tr>
<td>maximum pre-evacuation time</td>
<td>$t_{pre}/s$</td>
<td>100</td>
<td>300</td>
<td>[17–19]</td>
</tr>
<tr>
<td>number of tunnel users</td>
<td>$N_{tu}$</td>
<td>30</td>
<td>180</td>
<td>30 vehicles in the evacuation area</td>
</tr>
<tr>
<td>failure of tunnel alarm</td>
<td>$f_a$ (Boolean)</td>
<td>no</td>
<td>yes</td>
<td>$p(F_A) = 0.01; p(\overline{F_A}) = 0.99$ [20]</td>
</tr>
</tbody>
</table>

Table 2: risk indicators with specific probability models used for risk analysis (white background: fire scenario, grey background: evacuation scenario)

<table>
<thead>
<tr>
<th>risk indicator</th>
<th>term</th>
<th>remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum heat release rate</td>
<td>$H_{RR\max}/MW$</td>
<td>discrete distribution from 5 MW to 100 MW according to [20]; assumption: no fatalities for $H_{RR\max} &lt; 25 MW$</td>
</tr>
<tr>
<td>number of tunnel users</td>
<td>$N_{tu}$</td>
<td>depending on the numbers of vehicles and vehicle types according to [20]</td>
</tr>
</tbody>
</table>

The fire and evacuation scenarios include the following interactions in the bi-directional road tunnel shown in Figure 1. After the ignition, the heat release rate of the fire develops with an exponential curve with the risk indicators $H_{RR\max}$ and $t_{max}$ [21]. Accordingly, heat and smoke spread within the tunnel. Following the fire detection triggered by the heat release rate, the longitudinal emergency ventilation starts and the tunnel alarm alerts all tunnel users at the same time ($\overline{F_A}$). But in case of a failure of tunnel alarm ($F_A$), each tunnel user individually gets alerted by smoke depending on its initial position in the evacuation area. A tunnel user starts to move towards the emergency exit after its alarm and its individual pre-evacuation time which is less than $t_{pre}$. Thereby, smoke can impede the individual movement speed. Also, the tunnel users might interact, in particular close to the emergency exit and in scenarios with high number of tunnel users $N_{tu}$. A tunnel user is added to the number of fatalities if its individual fractional effective dose reaches the fatal limit [11]. Finally, the evacuation scenario leads to the fraction of fatalities which is the number of fatalities per number of tunnel users $N_{tu}$.

![Figure 1](tunnel_geometry.png)

Figure 1  tunnel geometry of the scenario focussing on the upper evacuation area next to the fire source;

We use two complex models to determine the fraction of fatalities $\xi^C$ in the fire and evacuation scenarios. Therefore, we combine the computational fluid dynamics model Fire Dynamics Simulator (FDS) [10] and the microscopic evacuation model FDS+Evac [11]. The fire model FDS simulates the spread of heat and smoke in the fire scenarios. The evacuation model FDS+Evac simulates the evacuation scenario and therefore adopts the spread of heat and smoke of a fire scenario simulated with FDS. FDS+Evac considers individual tunnel users with random initial positions in the evacuation area and random characteristics like walking speed [11]. To take the randomness into account, we run
100 replications of one evacuation scenario. We then calculate the deterministic mean fraction of fatalities $\xi^e$ among these replications. Due to the high computational effort of FDS, we analyse less fire scenarios than evacuation scenarios with the complex models. Thus, multiple evacuation scenarios base on the same fire scenario.

To conclude this Subsection, we built the definition of risk indicators and the scenario on an extended literature review [4,12]. The scenario covers the fire growth, important safety measures including the failure of tunnel alarm as well as the individual reaction and evacuation of tunnel users. Thus, the scenario with five risk indicators in total is complex with view on other common methodologies for risk analysis, e.g. [3].

**Experimental design**

The experimental design defines the set of $n$ scenarios to be simulated with the complex models. We denote the experimental design in general with $X = [\vec{x}_1, \vec{x}_2, ..., \vec{x}_n]^T$ with $d$ risk indicators defining a scenario $\vec{x}_i$. Fire scenarios and evacuation scenarios depend on different risk indicators and thus have two separate experimental designs. The experimental designs for $n_f$ fire scenarios and $n_s$ evacuation scenarios are:

$$X^f = \left[ HRR_{\text{max},i}, t_{\text{max},i}, ..., t_{\text{pre},i}, N_{\text{tul}}, \right]^T$$

$$X^e = \left[ HRR_{\text{max},i}, t_{\text{max},i}, t_{\text{pre},i}, N_{\text{tul}}, N_{\text{tu}}, \right]^T.$$

It has to be mentioned that $X^e$ considers $d_e = 4$ risk indicators neglecting the failure of tunnel alarm $fa$. The failure of tunnel alarm is a Boolean which cannot be interpolated in the response surface method. Thus, there are two separate data bases for the evacuation scenarios with $\overline{FA}$ and $FA$. Both data bases use the same experimental design $X^e$. For the sake of simplicity, we use the same notation $X^e$ for both cases and only specify the failure of tunnel alarm if required. Finally, FDS+Evac determines the fraction of fatalities for both data bases $\xi^e = \xi^e_k = [\xi^e_1, ..., \xi^e_n]$ with $\overline{FA}$ and $FA$.

We setup separate initial experimental designs $X_0$ for the fire scenarios and the evacuation scenarios and subsequently add scenarios with the projection array-based design [7] (see Figure 2). The initial experimental design has only scenarios at the outer vertices of the domain, which is the minimum requirement for the response surface model. We then use the projection array-based design for its improved space-filling properties and the option for sequential refinement.

The projection array-based design extends the Latin hypercube design [22] with an additional underlying structure of projection arrays. The Latin hypercube design consists of $n$ substrata with exactly one scenario in each dimension, named here with ‘lhd-condition’. The projection arrays base on a fractional factorial design with $\left\lceil \frac{n^2}{d} \right\rceil$ number of strata in each dimension where $\left\lceil \cdot \right\rceil$ denotes the ceiling function. Hence, the number of projection arrays is always equal or higher than the number of scenarios $n$. The projection array-based design demands maximum one scenario per projection array, named here with ‘pa-condition’, as well as the lhd-condition. The pa-condition improves the space-filling properties compared to common Latin hypercube designs and thus meets the global objective of risk analysis.

During the sequential refinement of the experimental design, we have to make an exception for the lhd-condition. The initial experimental design has more than one scenario in the substrata at the outer edges. Therefore, all initial scenarios at the outer edges of each dimension count only as one scenario, e.g. leading to eight substrata for ten scenarios in Figure 2. For the sequential refinement of the projection array-based design, we augment the existing experimental design $X_{i-1}$ with new scenarios $X_{\text{new}}$ in sequential refinement steps: $X_i = [X^f_{i-1}, X^e_{\text{new}}]^T$. The sequential refinement maintains both lhd- and pa-condition.
We adapted the projection array-based design according to the requirements for risk analysis. First, to put focus on particular regions of the domain in each refinement step, we stretch the strata and substrata with the stretching parameter $p_{\text{stretch}}$, e.g. more to its centre with $p_{\text{stretch}} > 1$ or more to its outer edges with $p_{\text{stretch}} < 1$ (Figure 2). The procedure allows to maintain the pa- and lhd-condition. Second, we combine the fire and evacuation scenarios of the two separate experimental designs $X^f$ and $X^e$ to reduce the number of fire scenarios ($n_e > n_f$). For this, the evacuation scenario $\vec{x}_c^{s} = [H_{\text{max},i}, t_{\text{max},i}, N_{\text{tu},i}, f_{a_i}]$ adopts parameters of a fire scenario $\vec{x}_f^j = [H_{\text{max},j}, t_{\text{max},j}]$ leading to $\vec{x}_c^{s} = [\vec{x}_f^j, t_{\text{pre},i}, N_{\text{tu},i}, f_{a_i}]$. Thus, different evacuation scenarios can use the same fire scenario which obviously leads to the loss of lhd-condition in $\vec{x}_f^j$ whereas the pa-condition is not affected. To sum up, the focus on particular regions of the domain and the combination of experimental designs can reduce the number of scenarios in the experimental designs.

**Response surface model**

The response surface model nearly interpolates $\xi_{X^e}$ for any arbitrary scenario $\tilde{x}$ to $\xi = \xi_X(\tilde{x})$. Therefore, we use the moving least squares method [8] because it accounts for the global objective of risk analysis. The moving least squares method is based on a local weighted least squares fit of a linear or quadratic polynomial. The fit is local because of the distance-dependent weighting, based on a weighting function, of each $\xi_c^{s} \in \xi_{X^e}$ to the local scenario $\tilde{x}$. Thus, there are other fits for different scenarios $\tilde{x}$ and hence the moving least squares method interpolates better to local $\xi_c^{s}$ than fits of global first- or second-order models. We apply linear polynomials for $X^e$ with $n_e^{1/d_e} \leq 3$ and else quadratic polynomials in the moving least squares method. We furthermore implemented three different function types each having one weighting parameter [9,23] for the weighting function. With this response surface model, the metamodel can quickly interpolate the fraction of fatalities $\xi = \xi_X = \xi_X(\tilde{x})$ for many arbitrary scenarios $\tilde{x}$.

Obviously, the interpolation causes uncertainties called metamodel uncertainties. The metamodel uncertainty $\Delta \xi = |\xi - \xi_c|$ is the uncertain difference $\Delta \xi(\tilde{x})$ between $\xi(\tilde{x})$ to the unknown fraction of fatalities $\xi_c(\tilde{x})$ at any arbitrary scenario $\tilde{x} \in X^e$. We use the prediction interval [9] to quantify the metamodel uncertainty. The prediction interval was developed ‘for predicting the interval of "the value of a single future observation" at a point’ [9]. The prediction interval, denoted with $\Delta \xi$ (or the vector $\Delta \xi$) is linearly proportional to the root of the variance $s^2(\xi)$ [9, eq. 21] at $\tilde{x}$ (see equation 1).

$$\Delta \xi = \Delta \xi(\alpha) = t_{\text{crit},\alpha} \cdot s(\xi)$$ (1)
The variance $s^2(\xi)$ underlies a Student’s t-distribution with the two sided confidence interval $\alpha$ and $t_{\text{crit}, \alpha}$ as the critical value of the Student’s t-distribution with $n_e - d_e$ degrees of freedom. We derive the following probabilistic metamodel uncertainty from the prediction interval: $\Delta \xi = t_{\alpha} \cdot s(\xi)$ (or $\Delta \tilde{\xi}$) with $t_{\alpha}$ as random realisation of the Student’s t-distribution from equation 1. As a result, the metamodel of the uncertain fraction of fatalities $\tilde{\xi}$ (or $\tilde{\xi}$) is given in equation 2.

$$\tilde{\xi} = \xi + \Delta \tilde{\xi} = \xi + t_{\alpha} \cdot s(\xi)$$ (2)

Setup of the metamodel
We used the following procedure to setup a metamodel. First, we built the experimental designs $X^f_i$ and $X^e_i$ (Subsection ‘Experimental design’). Second, we ran simulations with the complex models to yield $\xi_{X^f_i}$ and saved them in a data base. Third, we optimised the weighting function of the moving least squares method to $\xi_{X^f_i}$. The aim of the optimisation is to reduce the 90% quantile $q_{90}(s)$ of the variance (root) with $s = s(\xi) = [s(\xi(x^f_i)), ...]$ for scenarios $x^f_i$ evenly distributed on the entire domain. As result of the optimisation, the response surface model $\xi_{X^f_i}$ of the metamodel uses one of the three function types with the weighting parameter. Finally, we used the metamodel for two purposes in the Section ‘Results and discussion’: first, to evaluate the effects of refinement steps on the metamodel and to define $p_{\text{stretch}}$ for the subsequent refinement step (Subsection ‘Metamodel’); second, to determine $\tilde{\xi}$ of arbitrary scenarios $\tilde{X}$ for the use in risk analysis (Subsection ‘Risk analysis’).

RESULTS AND DISCUSSION
In a first step, we setup two separate initial experimental designs $X^f_0$ and $X^e_0$ to analyse the effects of the refinement steps on the metamodel as well as on the risk analysis. Subsequently, we ran three additional refinement steps $i$ with the procedure described in Subsection ‘Setup of the metamodel’ of Section ‘Methodology’ with the parameters shown in Table 3. For each experimental design $X^f_i$, we found the highest values of the variance $s^2(\xi)$ at the outer vertices and edges of the domain. Accordingly, we focused the refinement steps for $X_2$ and $X_3$ on these regions with $p_{\text{stretch}} < 1.0$. As a result, we obtained the experimental designs shown in Figure 3. Finally, we scrutinised the effects of the refinement steps on: first, the metamodel (Subsection ‘Metamodel’) using risk indicators shown in Table 1; second, results of risk analysis (Subsection ‘Risk analysis’) with risk indicators from Table 2.

Table 3: overview on the sequential refinement steps:

| refinement step | $n_f$ | $n_e$ | $p_{\text{stretch}}$ | $q_{90}(s|FA)$ | $q_{90}(s|FA)$ |
|----------------|------|------|----------------------|----------------|----------------|
| $X_0$          | 4    | 16   | ---                  | 0.157          | 0.147          |
| $X_1$          | 6    | 48   | 1.0                  | 0.059          | 0.052          |
| $X_2$          | 10   | 96   | 0.1                  | 0.029          | 0.029          |
| $X_3$          | 14   | 144  | 0.01                 | 0.028          | 0.035          |
Figures 3 fire scenarios of all sequential refinement steps with the underlying strata (solid lines) and substrata (dashed lines) for $X_3$ with $p_{stretch} = 0.01$.

**Metamodel**

Table 3 shows the global effects of refinement steps on the variance (root) $s(\xi)$ with $q_{90}(s)$. The variance steadily decreased until refinement step $X_2$. The results of refinement step $X_3$ were twofold: for no failure of tunnel alarm ($F_{FA}$) the variance was nearly constant but for failure of tunnel alarm ($FA$) the variance even increased. Thus, the refinement step $X_2$ led to converging global variances with $n_{e}^{1/d_x} < 3.2$ evacuation scenarios along one dimension. Due to the combination of the experimental designs, we required only ten instead of 96 fire scenarios for each evacuation scenario. In conclusion, the sequential refinement focussing on regions of the domain together with the combination of two experimental designs can lead to small numbers of simulations with the complex models and hence reduce the computational effort.

The refinement steps had also local effects on the variance $s^2(\xi)$. Exemplarily, Figure 4 shows the root of the variance of the refinement steps $X_1$ and $X_2$. Refinement step $X_1$ had increased variances in the centre of the domain. With four new fire scenarios and 48 new evacuation scenarios, refinement step $X_2$ clearly decreased the variance not only globally but also locally in this region. From this result, we draw two conclusions: first, no additional scenarios were required in the centre of the domain; second, the sequential refinement with focus on regions with high metamodel uncertainty can lead to an efficient decrease of the metamodel uncertainty.

In general, the moving least squares models $\xi_{X_2}$ and $\xi_{X_3}$ led to mostly similar results whereas $\xi_{X_1}$ revealed larger differences (see Figure 5). The similarity between $\xi_{X_2}$ and $\xi_{X_3}$ was in particular true for scenarios with failure of tunnel alarm ($FA$). In these scenarios, the optimisation of the weighting function led to rather global polynomials according to $\xi_{X_2}$. Thus, $\xi_{X_3}$ did not adapt much to the new scenarios of $\xi_{X_3}$ which reasons the increased variance of $X_3$ (Table 3). In case of no failure of tunnel alarm ($FA$) the moving least squares model $\xi_{X_3}$ was more flexible and adapted to new scenarios $\xi_{X_3}$ (e.g. arrow in Figure 5). Summing up, the results show the sophistication of moving least squares method compared to global first- or second-order models in case of global objectives as well as the convergence between $\xi_{X_2}$ and $\xi_{X_3}$.
evacuation scenarios with $t_{pre}=124$ s and $N_u=48$ and no failure of tunnel alarm

**Figure 4** root of the variance $s(\xi)$ for $X_1$ (left) and $X_2$ (right); the variance for $X_1$ is globally higher than for $X_2$; the locally elevated variance in the centre for $X_1$ vanishes after the refinement step;

evacuation scenarios with $t_{pre}=241$ s and $N_u=118$ and no failure of tunnel alarm

**Figure 5** moving least squares models $\xi_{X_1}, \xi_{X_2}, \xi_{X_3}$; the arrow highlights the flexibility of $\xi_{X_3}$ to new scenarios;

After a thorough scrutiny of the global and local effects on the prediction interval as well as the convergence of the response surface model, we concluded that the metamodel $\xi_{X_2}$ is a sufficient representation of the complex model. For this reason, we applied the metamodel on risk analysis in the next Subsection.

**Risk analysis**

Subsequently, we analysed the effects of the experimental designs $X_0, X_1, X_2, X_3$ on the risk measures. Therefore, we ran a risk analysis with $10^6$ random scenarios $\bar{X}$ and yielded the metamodel $\xi_{X_1}$ considering the metamodel uncertainty. In summary, Table 4 and Figure 6 show the individual risk and the societal risk curve.

**Table 4**: relative individual risk based on the metamodels of all refinement steps to the last refinement step $\xi_{X_3}$:

<table>
<thead>
<tr>
<th>metamodel</th>
<th>$\xi_{X_0}$</th>
<th>$\xi_{X_1}$</th>
<th>$\xi_{X_2}$</th>
<th>$\xi_{X_3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{ind}(\xi_{X_1})/R_{ind}(\xi_{X_3})$</td>
<td>7.91</td>
<td>2.36</td>
<td>1.09</td>
<td>1.00</td>
</tr>
</tbody>
</table>
We can see from Table 4 that the individual risk converged to a difference of less than 10% between $\xi_{X_2}$ and $\xi_{X_3}$. The societal risk curves in Figure 6 showed similar behaviour. On the one hand, $\xi_{X_1}$ still led to differences to $\xi_{X_3}$ for small number of fatalities which can be directly linked to the different results of the metamodels. On the other hand, $\xi_{X_2}$ only deviated from $\xi_{X_3}$ for high number of fatalities in scenarios subjected to small initial frequencies. Thus, statistical uncertainties are the major reason for these differences. Concluding, together with the results shown in Table 3, $\xi_{X_2}$ with ten fire scenarios and two times 96 evacuation scenarios ($FAFA$) lead to a sufficient precise risk analysis.

In comparison, the methodology for risk analysis published in ISTSS 2016 [4] rests on a metamodel with 20 fire scenarios and two times 400 evacuation scenarios. At this time, we had no option for sequential refinement in the experimental design. Thus, we simply made a very conservative guess of the required number of scenarios to get definite results. Thus, the conservative guess causes the large discrepancy between the numbers of scenarios. From this experience we derive that the sequential refinement is favourable since it allows to get rough results quickly and then more accurate results step by step until sufficient accuracy is reached.

CONCLUSIONS
We developed a metamodel to consider complex scenarios in risk analysis including interactions between fire, tunnel users and safety measures. To model the interactions, we use the complex models FDS [10] and FDS+Evac [11]. The metamodel now consists of the projection array-based design [7] and the moving least squares method [8]. A probabilistic model based on the prediction interval [9] quantifies the metamodel uncertainty. Additionally, we implemented: first, the sequential refinement of the projection array-based design with focus on regions of the domain; and second, the combination of the experimental designs for fire and evacuation scenarios. As a result, the sequential refinement led to convergence of the metamodel uncertainty and in risk measures with ten fire scenarios and two times 96 evacuation scenarios.

The metamodel efficiently integrates the complex models for two reasons: first, the sequential refinement; and second, the combination of experimental designs. First, in comparison to our conservative guess of the required number of scenarios published on ISTSS 2016, we highlight that the use of the sequential refinement avoids conservatively large numbers of scenarios without knowledge on the accuracy of the results. Furthermore, we expect an efficient decrease of the metamodel uncertainty because of the local effects of the focussed sequential refinement. Second, the combination of both experimental designs reduces the number of simulations with the computationally expensive fire model. Hence, our metamodel now allows considering complex scenarios with various risk indicators and interactions for risk analysis. This is an important characteristic with focus on future increasing sophistication in scenarios due to growing use of e.g. fixed fire-fighting systems or new energy carriers.
We finally emphasize that the metamodel is not limited to risk analysis but in general applicable on various experimental or modelling issues related to: (time) expensive procedures; various variables (high dimensional problems); and a global objective. To conclude, the metamodel is in particular interesting for many practical applications in fire safety.

ACKNOWLEDGEMENTS
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Safety Related Challenges when Designing Sustainable Cities – A Practical Example with an Underground CNG Bus Terminal

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ABSTRACT
The transition towards sustainable city planning is challenging from many perspectives, e.g. the speed of development towards fossil free fuels and updating of regulations for controlling risk in the transport infrastructure do not manage to keep an even pace. This applies both at the detailed level regarding technical design requirements and on a more comprehensive performance level of safety objectives that can be verified to confirm compliance with society's safety objectives. This paper presents challenges, experiences and results in connection with the analysis of the risks associated with an underground bus terminal operated with gas-powered buses. A risk analysis approach used in an ongoing project in the final stage of the planning process, which makes it possible to discuss experiences and difficulties based on work in practice. Two main types of injury are studied; fire and explosion, where people can be exposed to both high temperatures, toxic smoke, radiation, pressure waves and impact by flying debris. Fire, may occur with ignition of combustible gas mixture (in air). It can be noted that an underground bus terminal operated by gas powered buses constitutes a complex facility from a risk perspective and that the risk level without special consideration for additional safety measures is expected to be high. Therefore a safety concept is required that is balanced between different types of measures, such as supervision, control and safety enhancing installations as well as inherent passive protection.

KEYWORDS: compressed natural gas, risk analysis, explosion, jet flame, fossil free.

INTRODUCTION
The transition towards sustainable city planning is challenging from many perspectives. Earlier we were heavily relying on transportation using fossil fuels but a trend is that quite rapidly renewable fuels, for example compressed natural gas (CNG), are introduced in a large scale, e.g. in bus fleets. Risks associated with some types of renewable fuels differ quite substantially compared to traditional fuels, which must be taken into account and appropriate risk reducing measures applied. This does not only concern the busses themselves, especially not since a trend is to place transport infrastructure in underground facilities to avoid creating barriers in society and reducing environmental impact such as noise. This adds additional complexity and this changed risk picture needs to be considered when safety concepts are developed for facilities, such as underground bus terminals to ensure compliance with society's safety ambitions [1]. To emphasise this a number of fires in gas-powered buses have occurred and been reported on, which provides an limited empirical evidence that the risks associated with them need to be taken seriously and that the potential for major damage is available [2] [3].

Another challenge is that the speed of development towards fossil free fuels and the authorities ability updating regulations for controlling risk in the transport infrastructure do not manage to keep an even pace. This applies both at the detailed level regarding technical design requirements and on a more comprehensive performance level of safety objectives that can be verified to confirm compliance with society's safety objectives. Since such national explicit objectives are lacking, explicit safety targets need to be formulated within each specific construction project, then using qualitative and/or quantitative methods to verify that the goals are met in an iterative process. However, both guidelines and underlying research is limited, since the combination of application, underground facilities and
fossil free fuels are relatively new. Therefore the risk assessment itself poses a project risk which can be significant.

In practical terms, this has consequences. Either we may refrain from allowing new types of facilities that go hand in hand with development of sustainable urban development, or further steps need to be taken to derive safety concepts based on risk analysis in a credibly and satisfactorily way. The question therefore needs to be addressed if it is suitable and possible to use an engineering approach to design such a facility and how to address the challenges it entails when knowledge, research and guidance in the field is highly limited. A direct effect of this is that the need for research and development in connection with the project work becomes necessary and comprehensive. Since uncertainties are large, it also calls for extensive uncertainty analysis.

In the bus terminal used as a real case example there is a departure hall occupied by about 2000 persons at high traffic hours. The risk analysis is the basis for the design of the safety concept, as detailed requirements on safety measures directed towards risks associated with the use of CNG are lacking. The risk image is complex to analyze and evaluate by multiple scenarios characterized by potentially large consequences but with very low probabilities, such as jet flame, Unconfined Vapor Cloud Explosion (UCVE), pressure vessel explosion and domino effects. These scenarios are of a type that is not traditionally encountered in the current type of facility, and there is no way to lean against practices or regulations to develop appropriate risk mitigation measures. The prerequisites and risk exposure in some respects correspond to the design of a hazmat industry or a tunnel where transport of dangerous goods occur. However, a big difference is that in a bus terminal a large number of people is in close vicinity to the busses, which poses challenges on the safety concept and questions about the appropriateness of the facility.

PURPOSE AND OBJECTIVES
The purpose of this paper is to present challenges, experiences and results in connection with the analysis of risks associated with an underground bus terminal operated with CNG-powered buses.

The objective of the paper is to present how qualitative and/or quantitative methods can be used to verify that the safety targets are met in an iterative process and how research and development in connection with the project work becomes necessary and comprehensive.

TERMINAL DESCRIPTION
A new bus terminal is planned in the central parts of Stockholm. The bus terminal will be located underground in Katarinaberget. Included in the terminal are large waiting areas, bus areas, boarding areas and a combined single tube exit and entrance road tunnel. The terminal is connected to the Stockholm metro and a large shopping mall area through a mutual arrival hall. The terminal and the complexity of the facility and its surroundings is presented in Figure 1.

Figure 1. Site plan showing location of terminal and surroundings.
The bus terminal is about 280 metres long, 80 metres wide and is divided into three main valves; two valves for buses and one large departure hall in the middle. The terminal is located -4 m below sea level. Figure 2 and Figure 3 illustrate; (A) Northern bus area, (B) Departure hall, (C) Southern bus area, (D) West entrance connected to the shopping mall and the Stockholm metro, (E) East entrance, (F) road tunnel including an emergency exit.

Figure 2. Cross section of bus terminal.

Figure 3. Horizontal view of bus terminal.

Either before departure or after arrival all travelers are passing through the departure hall. It is located between the two bus areas and can be reach from two different entrances. The hall is about 3000 m² and the height of the valve is 8.6 m. The hall is a separate fire compartment.

The entrance hall is connected to a number of different occupancies i.e, commuter train terminal to Saltsjöbanan, the Stockholm metro and a shopping mall. The entrance hall is a three level fire compartment fire separated from the different occupancies.

Buses arrive to the terminal through a road tunnel and stop on the south side of the departure hall. After travelers are disembarked, the buses may either temporarily park in a bus waiting area or drive to the other side of the departure hall to be boarded. The bus area is about 15 000 m² and the height of the northern valve is 8.0 m and the height of the southern valve is 8.5 m.

The width of the road tunnel where the buses enter the terminal is 9 m and the length is 100 m. The construction material of the road tunnel is a mix of rock and concrete. The gradient of the road tunnel is 3.8%.

The construction material in the bus area is mainly of pure rock, spray concrete with steelfibers and pp-fibers, armed concrete and parts with lightweight structures.

**Capacity and loads**

Performed traffic demand analyses verify that the bus traffic differ a lot during the day. In the morning a large number of travelers will arrive and in the afternoon a lot of travelers will departure. The number of arriving buses and departing buses at the most busy hour (in the afternoon and in the morning) are described in Table 1.
Table 1. Number of buses to and from bus terminal in 2030.

<table>
<thead>
<tr>
<th></th>
<th>Arrivals</th>
<th>Departures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning peak hour</td>
<td>227</td>
<td>80</td>
</tr>
<tr>
<td>Afternoon peak hour</td>
<td>90</td>
<td>204</td>
</tr>
</tbody>
</table>

Translated to number of people the maximum occupant load is 11 000 in the morning. Where about 8000 travelers, from 227 buses, are assumed to arrive to the bus terminal during one hour. 84% of them is assumed to transfer to the Metro. About 3000 travelers, 80 buses, are assumed to depart from the bus terminal during the same hour. 84% of them are transferred from the Metro and the remaining 16% are transferred from connecting trains, buses or arriving by foot.

The maximum occupant load is 9 000 in the afternoon. Where about 7000 travelers, to 204 buses, are assumed to depart from the bus terminal during one hour. During the same hour about 3000 travelers, 90 buses, are assumed to arrive. 84% of them is assumed to transfer to the Metro. The remaining 16% is transferred from connecting trains, local buses or arriving by foot.

In the risk analysis a maximum occupant load in the departure hall of 5000 persons is assumed.

CNG-BUSES

Identification and description of hazards

The following hazards have been identified in a fuel system in a gas driven bus, see also Figure 4.

F (Bottles) = Fuel tank (gas bottles)
H (High Pressure) = Piping and associated armature (high pressure)
S (Safety Equipment) = Safety equipment (malfunctioning pressure release valve located on high pressure side or activated fuse due to bus fire)
L (Low pressure) = Piping and associated armature (low pressure, after pressure reduction)

![Figure 4. Schematic overview of bottles, valves and pipes on gas bus. The figure is collected from Volvos vehicle manual for buses but is also representative for other vehicles.](image)

Hazardous events

Hazardous events can occur from a number of different reasons and result in different outcomes. How severe an emission of fuel gas becomes is dependent on several factors e.g. what initiates the emission, what part of the fuel system that the emission is initiated in, the spread of the emission, if the emission is ignited or not and the effect of the emission on humans within the bus and the surroundings.

Two sources resulting in emission of fuel gas are bus fire (where the fire initiates from another reason than due to emission of fuel gas) and malfunctioning equipment in the fuel system.

Figure 5 and Figure 6 shows examples of buses being exposed to fire (Linköping 2005-01-28).
Figure 5. Internal ceiling in fire exposed bus. Soot on the cylinder shaped fuel tanks can be seen through the holes in the ceiling.

Figure 6. Fuel tanks in fire exposed gas bus seen from above (roof of bus) with the cover removed.

Figure 7 shows an example of safety equipment (fuse) in a fuel system in a gas bus. The fuse activates at a temperature of 110-130°C and stays open after being activated. The fuses’ purpose is to depressurize high temperature gas bottles in order to avoid high pressure within the bottles and decrease the risk of explosion.

Figure 7. Example of safety equipment (pressure release device).

Hazards
In this analysis the following hazards are evaluated:

Fire, can occur through ignition of flammable fuel gases within air. Fire can occur as jet-flame depending on the nature of the emission, the extent of the emission and the conditions of the ignition. The spread of the jet-flame and radiation emitted from the jet-flame is evaluated within the analysis. The flame and the radiation from the flame can cause fire spread to other buses and affect people within the terminal.

Explosion, can occur as deflagration when combustion of fuel gases within air. Such an explosion in a contained space can create a pressure wave. Sudden release of chemical energy in the fuel tanks of a gas bus can create a pressure wave. In addition to the pressure wave itself an explosion can spread fragment and fire within it surroundings and increase the damage.

Pressure vessel explosion, see further in section “Example consequences of extreme accident”.

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Dispersion calculations
The refuel-pressure within gas buses in Sweden is limited to 200 bar at a temperature of 15 °C.
Fuel tanks (gas bottles) in referred buses have a capacity to store around 400 Nm³ [4].
The size of an emission from the high-pressure parts of the fuel system is dependent on how filled the tanks are, the area of the point of emission and the geometry of the emission point. If the buses are refuelled with around 200 Nm³ every 24 hours the medium filling capacity is around 75 % (300 Nm³) which results in a medium pressure within the high-pressure parts of the fuel system being 150 bar. Usually, a gas bottle has a volume of 200 litres which equals 30 m³ gas within a bottle. This results in 20 kg methane.
The size of an emission from the low-pressure parts of the fuel system is in the same way dependent on how filled the tanks are, the area of the point of emission and the geometry of the emission point. The pressure within the low-pressure parts of the fuel system is dependent on bus manufacturer and the type of motor. The pressure can reach 15 bar when pressure is high on the gas engine and is around 5 bar when idle speeding. When operating the terminal the pressure on the engine will be low. The pressure within the low-pressure parts of the fuel system will probably be around 5-10 bar.
The diameter of the fuel lines will slightly vary between the different bus manufacturers but is usually around 6 mm. The filling lines are usually within the range of 10-12 mm.

Properties of CNG
Compressed natural gas (CNG) can be both biogas and natural gas (fossil fuel). In both cases the main component is methane. The CNG that is used within commuter buses in Stockholm usually consist of a mixture of biogas and natural gases where most part of the molecules are biogas. Table 2 and Table 3 shows the usual composition of biogas and the physical and chemical properties for biogas [5].

Table 2. Normal composition for biogas

<table>
<thead>
<tr>
<th>Component</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH₄)</td>
<td>&gt; 97 %</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>&lt; 2,0 %</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>&lt; 0,8 %</td>
</tr>
<tr>
<td>Oxygen</td>
<td>&lt; 0,2 %</td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>&lt; 0,00005 %</td>
</tr>
<tr>
<td>Tetrahydrothiophene</td>
<td>&lt; 0,0010 %</td>
</tr>
</tbody>
</table>

Table 3. Typical physical and chemical properties for biogas.

<table>
<thead>
<tr>
<th>Physical condition at 20°C</th>
<th>Compressed gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>No color</td>
</tr>
<tr>
<td>Smell</td>
<td>Distinct and unpleasant if odourised, otherwise odorless. Odourised by Tetrehydrothiophene (THT)</td>
</tr>
<tr>
<td>Relative density (air=1)</td>
<td>Lighter than air &lt;1</td>
</tr>
<tr>
<td>Water solubility [mg/l]</td>
<td>Not known but considered low</td>
</tr>
<tr>
<td>Limit of flammability [vol% in air]</td>
<td>5-15 %</td>
</tr>
<tr>
<td>Self ignition temperature [°C]</td>
<td>&gt; 600 °C in normal pressure</td>
</tr>
<tr>
<td>Minimum ignition energy (MIE)</td>
<td>0,3 mJ</td>
</tr>
</tbody>
</table>
RISK ANALYSIS
From the start of the project it has been discussed whether CNG powered buses are safe to operate in an underground terminal environment. Consequently, the project group conducted a holistic risk identification analysis, where a number of risks where identified, ranging from serious to low consequences. Additionally, low probability scenarios with high consequence where also studied, since these risks could not be dismissed as negligible. Special attention was also placed on bus related accidents, which could lead to a greater risk contribution, hence to the fact that the terminal is located underground compared to a more traditional above ground terminal. CNG-powered buses have been operating for several years in the public transport system. However, during this period, little emphasis has been placed on the fire protection design for these types of terminals related to the inherited risks in using CNG as fuel.

At an early stage, the identified risks were deemed difficult to handle, considering that the risks involved accident scenarios with jet flame, gas cloud explosion and pressure vessel explosion. In addition to these risks, other risks were also identified, such as fire in bus with diesel fuel, etc., but these risks are not included in this paper. The identified accident scenarios combined with high traffic flows of buses (about 8 buses / minutes in peak traffic), high commuter rate (about 2000 people simultaneously in the facility), proximity to other facilities and intersections (subway, commercial galleries, various types infrastructures and buildings) and that the entire facility is located below ground, results in a complex risk analysis.

For this reason, a preliminary safety concept was presented. The basis for the safety concept is to be comprehensive with a combination of administrative measures, a management function, and that the facility is provided with both passive and active systems for dealing with accidents. This is to create a good robustness for the facility, hence that no system malfunction or insufficient reliability could compromise the safety. Furthermore, the operator requested a high demand on the availability and reliability for the facility, as terminal represent an important focal point in public transport in Stockholm. With the safeguards imposed on the safety concept as a basis, a quantitative risk analysis was conducted based on an event-tree analysis. During the analysis, the safety concept has been adjusted and adapted to optimize the protection measures. After that, the risk calculations have been completed.

In Sweden, there are no guidelines for how a risk analysis for these types of underground facilities should be conducted. However, there is a prevailing practice when designing road tunnels or when physical planning are carried out. The methodology include; risk analysis consisting of a quantitative risk analysis and event tree methodology. In this project, which has some similarities with tunnels with high complexity, such as road tunnels with dangerous goods transport, the risk assessment methodology was considered very suitable, since the methodology includes; systematically and transparently implementing, managing and reporting the risks. The method is able to handle many different types of safety barriers and system failures, etc. Nevertheless, the great disadvantage is that the analysis becomes very complex and usually resulting in uncertainties that needs further in depth analysis. This approach is based on the fact that the calculated risk can be estimated in some way to determine whether the risk level is acceptable or if additional risk mitigation measures are necessary. There is no national safety target for acceptable risk in for these types of facilities. Therefore, an important part of the project has been to elaborate a project-specific safety target that could be used in risk evaluation to perform the risk assessment. The development of such a safety target for the bus terminal is presented in more detail in [6].

Method description and event tree
The conducted risk analysis is based on literature studies, computer simulations, hand calculations, experience assessments, statistical evidence, expertise and event-tree methodology. The analysis is thus both qualitative and quantitative by nature.

The event tree methodology provides tools that systematically bring forth and describes the evolution of accidents with its relation to implemented protection barriers and how they work. The barriers can consist of technical and administrative measures, fixed and manual extinguishing systems and fire walls. Event tree gives an illustrative picture of possible accident developments that may arise after an
initial event. In the current case, the vehicle gas involved in accidents where the initial events consist of traffic accidents, arson, technical errors or material defects.

The main features of the analysis follows below overall elements:

- Literature study, collection of statistics, basis for consequences etc.
- Qualitative analysis of the object and its conditions.
- Development of safety concepts.
- Selection of initial events as well as relevant and representative accident scenarios.
- Analyze events and build event trees with its various barriers. Adjusted and adapted to optimize the protection measures.
- Quantitative estimation of frequencies for different initial events occurs in different ways depending on the available data and its applicability.
- Estimate of the consequences of the various accident scenarios. The calculations are based on scenario specific quantitative studies of fire and explosion processes in combination with evacuation possibilities in these processes as well as the various traffic conditions in the facility (high-speed, low-traffic and night traffic).

In order to nuance the risk image, comparisons were also made with a bus terminal that is located above ground. When conducting a literature study the following accidents with buses which were powered by CNG have been identified. In all studied cases the buses have ignited which has led to jet-flames being generated from the fuel system. In all cases the fuses in the fuel system have work as designated.

1. The bus fire at Strandbadsvägen in Helsingborg, Sweden.
2. The bus fire at Ättekullagatan in Helsingborg, Sweden.
3. The bus fire at Tornavägen in Lund, Sweden.
4. The bus fire at Wittenburgerweg, Holland.
5. The bus fire at Gnistängtunneln, Göteborg, Sweden.

For the bus fire at Ättekullavägen in Helsingborg The Swedish Accident Investigation Authority [2] conducted an detailed investigation of the accident. The summary and recommendations of the investigation do not touch upon the CNG system for the buses or the design of the facilities in which such the vehicles are being used.

The investigation consolidates that accidents with biogas as a fuel can lead to fast development and potentially severe damage. Several scenarios with such development have been studied in this report and the mapping of such scenarios are part of the risk identification being conducted. The result of the calculations of these scenarios are similar as in the real cases. The fire development is very rapid and there is a potential for fatalities.

In the conducted analysis, severe accidents related to vehicles with CNG fuel systems which results in jet flames, gas cloud explosion as well as pressure vessel explosion are identified. However when the risk analysis was conducted there was no documented accidents resulting in gas cloud explosion or pressure vessel explosion in tunnels in Sweden. In recent years there has been a few accidents with pressure vessel explosion, for example in Gnistängtunnel [1]. Internationally these types of occurrences have been documented, such as the CNG propelled bus explosion in South Korea. Although the circumstances surrounding the accident are not clear, but documented on film. The conclusion is that the consequences modelled in the risk analysis reflects the potential severe damaged that can occur during unfortunate circumstances exemplified by the real case accidents, for example if an accident occurs adjacent to a bus terminal.
Description of scenarios
Since the problems which are analyzed are complex, inherently the analysis models also become complex.

This section outlines the structure of the event-tree model. In order to create transparency of the calculation process the chapter also includes used conditions and assumptions. Due to the fact, that the event-tree model is extensive, it cannot be subsequently be fully reported in an easy-to-understand manner. For that reason, the section will instead describe the principles for building the event-tree. For detailed information of the event tree model, please review the original project report [7].

The event-tree model consists simply of a number of small event-trees that are inter linked in a network of different event-trees. The in-depth parameters for the event-tree model are described based on the following basic classification:

- Event-tree for fire in a CNG fueled bus.
- Event-tree for technical failure of equipment in a CNG fuel system.

In the following sections, the above-mentioned event-trees are described in more detail. However, the event-trees only pertains to a fire on a CNG fueled bus, other fuel systems are not included.

Event-tree for fire in a CNG powered bus
The event tree assumes that a CNG powered bus starts to burn. The origin of the fire may be due to collision, technical fault, self-ignition or arson. With these fire origins as a starting point, the event tree is built based on the parameters (branches) shown below. Note that some parameters only constitute a specification of other individual parameters, i.e. there are parameters that are only relevant to certain event development and or scenarios.

- Traffic situation (High traffic/Low traffic/Night traffic)
- Accident scene (Entrance to a tunnel/Disembark/Boarding/Crank/Standby)
- Fire event origin (Engine/tire/bus coupé)
- Does the engine sprinklers system work (Yes/No)
- The fire is manually extinguished, at an early stage (Yes/No)
- Fire detection system works (Yes/No)
- The facility sprinkler system works (Yes/No)
- Affected equipment part, (failing pressure release device gives pressure vessel explosion) (Bottle/Pressure release device/None)
- Ignition occurs (Yes/No)
- Type of ignition (Delayed/Direct)
- Direction Jet Flame (Up/Sideways)
- Spreading to adjacent located bus (Yes/No)

As shown above, the event-trees uses a large amount of parameters, which results to an extensive number of outcome combinations, where the risk impact consists of multiple scenarios linked to various sources of fire, different conditions and protective measures that do not work as intended.

Statistical input
According to Swedish and Norwegian statistics [8] 1-2 buses out of a 100 begins to burn each year. The statistics applies to buses regardless of fuel type and it also known that fire in buses evolve rapidly. Specific statistics relating to fire in CNG powered busses could not be located during the literature studies. Below pie chart depicts the origin or cause of a fire in busses according to available statistics, see Figure 8 [8].

It has be assumed that the above statistics are well represented for commuter busses. Although, the proportion of arson might be slightly higher for the Stockholm commuter busses (SL) than buses which are chartered. The fire cause has a crucial role in how quickly an accident evolves, hence the accident development has been weighed into the assumptions in the analysis.

When identifying potential sources of emissions, four different sources of emissions were identified. These are; high-pressure pipes, low-pressure pipes, CNG containers and pressure release device.
There are also other components in the fuel system that could be the source of a CNG leak. However, these components are considered to be included in the above mentioned emission sources.

There are very little statistics for failure rates on equipment for CNG vehicles. Therefore, relevant statistics was used from other types of gas systems as a base-line. For example, failure rate statistics for pressure release devices are rare to find, hence statistics for safety valves was used. For natural gas pipelines there are some statistics for leakage, while more general statistics are available for pressurized containers. This, of course, adds further uncertainty to the analysis, but the uncertainties are well within the framework of how risk analysis are carried out in other areas. All uncertainties are managed in an indepth uncertainty analysis only breifly reported on to illustrate how the results are affected. The failure rate for pressurized containers and safety valves occur $5 \times 10^{-7}$ and $2 \times 10^{-5}$ annually [9]. It is assumed that each bus is equipped with ten containers, where each container is equipped with an individual pressure release device. However, within the normal operational environment of the underground bus terminal, other fuel system designs on commuter busses could be operated. In conclusion, this means that the initial failure rate for technical systems is $2.15 \times 10^{-3}$ annually per bus.

The failure rate calculation for the underground bus terminal is calculated, in the same fashion as for commuter busses. Hence the following calculation argument; the total failure rate for commuter busses in the terminal, is calculated by adding the number of buses moving in the bus terminal per hour and the number of hours each bus is present in the bus terminal. For high traffic there are 216 buses per hour, for 7 h. In a low traffic environment, there are 65 buses per hour for 9 h and for night traffic, there are 12 buses per hour for 8 h. During weekends it is assumed that half of the day is comprised by low-traffic, while the other half is comprised by night traffic. In total the calculation results to an initial frequency of $2.05 \times 10^{-2}$ annually, which can be converted to roughly one fuel system failure in every 49 years. The expected frequency of a fire on bus in underground terminal has been calculated to $7.48 \times 10^{-2}$ annually, i.e. recalculated to a frequency of about one fire for every 13.4 years.

**Consequence calculations**

The impact assessments has investigated the radiation levels that arise from different sizes of jet flames and the pressure levels that occur at different sizes of emissions. The calculations then form the basis to the estimation of expected number of deaths, similar to the traditional ASET-RSET analysis, i.e. number of people that are thought to be killed if exposed to critical conditions. How critical conditions propagate, are modeled differently for the different scenarios, which is then compared to the evacuation evolution of the accident in the corresponding scenarios.

The calculations have been carried out partly as hand calculations and in other cases through computer simulations.

The following scenarios have been calculated:

1. Extreme accident (pressure vessel explosion)
2. Large hole (6 mm) on high pressure line and explosion
3. Large hole (6 mm) on high pressure line and jet flame
4. Medium hole (1.9 mm) on high pressure line and explosion
5. Medium hole (1.9 mm) on high pressure line and jet flame
6. Small hole (0.75 mm) on high pressure line and explosion
7. Small hole (0.75 mm) on high pressure line and jet flame
8. Large hole (6 mm) on low pressure line and explosion
9. Large hole (6 mm) on low pressure line and jet flame
10. Medium hole (1.9 mm) on low pressure line and explosion

*Figure 8. The origin of fires in busses.*
11. Medium hole (1.9 mm) on low pressure line and jet flame
12. Small hole (0.75 mm) on low pressure line and explosion
13. Small hole (0.75 mm) on low pressure line and jet flame
14. Emission pressure release device and explosion
15. Emission pressure release device and jet flame

EXAMPLES OF SCENARIO TYPES
Within the risk analysis for the underground bus terminal, the following failure scenarios have been used, selection of examples, short version. In the risk analysis these types of scenarios are elaborated based on specific conditions combined together into an extensive event tree.

Example consequences of extreme accident (pressure vessel explosion)
If a CNG container with compressed gas bursts or if a larger hole is created on the container, the following consequences will emerge:

1. Emissions of combustible gas. Gas emissions can result in secondary effects such as a so-called fireball, where all gas is burned within a few seconds, accompanying with high heat radiation levels for onto objects located near the fireball.
2. The CNG container bursts, which can result that fragments are shot out. Parts of the gas's compressive energy are transferred to motion energy on to the fragments, creating projectiles that can be transported long ways, hence create significant damage all objects the fragments encounter.
3. The origin of a shock wave, overpressure, due to gas expansion. Parts of the compression energy pass into motion energy of the released gas and cause a shockwave that can destroy or propel objects away.

Usually there are two reasons why a CNG vessel may rupture, either due to overpressure exceeds the design pressure of the container or because the strength of the container has deteriorated, for example due to fatigue.

The most common reason for overriding the design pressure of the vessel is overfilling or because thermal heating causes failure in the pressure release device or malfunction of the pressure regulator.

The most common reason for the strength deterioration is that the bottle is oxidized, rusted, material defect, wear due to vibration or collision with other objects (vehicle collision).

Example shockwave consequence
As the container breaks a part, the gas expands resulting in a shock wave. The strength of the shockwave path at different distances, x, from the center of the explosion, is appreciated by using the TNT method. The pressure has been calculated to 10 kPa at a distance of 12 to 13 meters.

The calculations are made by adopting the TNT equivalent calculation works for the particular case. The calculations are judged very conservative, as no consideration is given to the damping effect of the pressure wave caused by the roof cover on top of the containers.

Example over pressure consequence
Two explosion calculations have been carried out with the CFAC program FLACS [10], one corresponding to the released amount of gas simulated on a large hole approximately 100 g gas, which corresponds to a gas cloud of about 1 m³. The other explosion used a gas cloud of 10 kg gas which corresponds to a gas cloud at 175 m³ (7x5x5 m). The results of the calculations show that the cloud of 100 g of gas produces very small pressure increases without any significant environmental impact, less than 0.5 kPa (5 mbar).

The larger CNG container with 10 kg of gas gives a maximum pressure of about 13 kPa in the zone of combustion, i.e. in the vicinity of buses. Outside this zone, the pressure decreases to 8-10 kPa with an impulse of about 250 ms and is constant throughout the underground terminal's environment.

There are currently no research and data from conducted trials on vehicle gas leakage and ignition of gas clouds, which leads to uncertainties about the size of the gas cloud. Calculations and assessment shows that combustible mix that can lead to explosion cannot be ruled out. Further, in calculations,
conservative assumptions have been made regarding the combustible amount of gas that may participate in an explosion based on the precautionary principle and the lack of input.

**Example jet flame consequence**

Given that an ignition takes place is considered to happen in two different ways, delayed or directly. In the more common occurring scenarios fire starts in some parts of the bus and then spread to the fuel tanks. The pressure vessel explosion is affected and a jetflame occurs, the pressure vessel explosion has low probability to fail. In the scenarios, if this is not the scenario, an explosion can occur when the gas bottle explodes. This, however, after relatively late into the scenario, which means that commuters have had time to evacuate.

The initial length of the jet flame length has been calculated to range from 10 to 12 meters. After approximately 2 minutes, the jet flame length has been reduced to about 7.5 meters and then continues to decrease as pressure drops.

The flames from natural gas do not become optically thick (the emission factor becomes significantly less than 1), which results in the radiation transfer to the environment being less than for heavier hydrocarbons. This is reflected in the fraction of power output emitting natural gas flares, F, being less than for heavier hydrocarbons. Radiation calculations have been performed with an emissivity of 0.2. The distance to the ignition level at which the radiation intensity of a flame will be able to ignite materials such as wood, plastic or rubber (12.5 kW/m² for about 10 minutes) is initially only a few meters around the flame (2–4 meters).

The distance to the level when the radiation intensity from a flame may affect people critically (risk of second degree burns have been afflicted to 4 kW/m²) is initially up to 18 meters (after 2 minutes up to approximately 10 metres).

A major prerequisite for limiting the consequences of the jet flame is that the pressure release device is facing upwards, which causes the jet flame to hit the ceiling and the radiation levels around the flame evolve as described above. In the above scenario, the bus is already on fire, which means that there are already high radiation levels around the bus.

**THE SAFETY CONCEPT**

The preliminary safety concept of the bus terminal is a prerequisite for this analysis [11]. The preliminary safety concept is a description of the safety measures that the facility is assumed to be equipped with as a starting point based on a qualitative risk analysis. The safety concept is based on robustness and have a holistic perspective in which different types of risk mitigation measures, but might need to be complemented after the quantitative risk evaluation.

The bus terminal is designed with the following safety measures, see Figure 9:

1. The evacuation of the facility is designed to ensure satisfactory evacuation. This is based on sufficient capacity in evacuation routes, evacuation routes location, etc.
2. The facility is equipped with fire ventilation, which is automatically started by the automatic fire alarm, but can also be controlled by the emergency service from the fire alarm control unit and by the management function.
3. The entire facility is equipped with automatic extinguishing system. The bus carriageway is equipped with a fixed firefighting system called deluge system with high water flow. A deluge system means that the entire or several sections of sprinkler heads are activated upon detection.
4. The structural system in the bus carriageway area is designed in accordance with the regulations for tunnels. Carrying construction, frame completions and separations, i.e. lightweight construction in the bus carriageway is dimensioned to cope with increased pressure build-up due to a delayed ignition of a vehicle gas. Design value for pressure is calculated in this analysis.
5. The facility is divided into different fire cells to ensure the satisfactory evacuation and to limit the consequences of a possible fire. When dimensioning of the fire separations between bus carriageway and waiting halls, particular consideration is given to the origin of jet flame in buses with vehicle gases and emission of vehicle gases. The bus terminal is equipped with indoor fire hydrants and fire hydrant risers.

6. The facility is provided by a safety management function. The management function has the task of monitoring and controlling the functions in case of fire or other undesired events of the facility. The management function is able to manually control various functions in the bus terminal.

7. The ventilation system in the bus carriageway, as well as the installation vault / roof of the bus carriageway and entrance tunnel are designed with the EX classifications (ATEX).

8. Evacuation routes are provided with systems for pressurizing the compartments in order to prevent spreading of fire gases in to the area.

9. The entire facility is equipped with an automatic fire alarm with full monitoring. Bus carriageway including entrance tunnel is equipped with two different types of fire detection system and a system for detecting vehicle gases.

10. The whole facility is equipped with an evacuation alarm with spoken announcements.

11. The facility is equipped with traffic control systems.

12. The facility is equipped with CCTV.

13. The entire plant is equipped with emergency power and UPS to manage redundancy on safety technology systems and to be self-sufficient. The emergency power lasts 24 hours.

14. The safety valves should be oriented vertically to avoid the risk of extensive fire spread and domino effects.

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**Figure 9. Parts of the safety concept of the bus terminal**

**THE UNCERTAINTY ANALYSIS**

The uncertainties in this quantitative risk analysis have been analyzed and attributed to two fundamental categories; stochastic uncertainties (non-reducible) or knowledge-based uncertainties (reducible). Both categories are represented in this analysis. The following classification of uncertainties is more useful in practice:
• Model uncertainties.
• Completeness uncertainties.
• Parameter uncertainties.

The three classifications are reviewed, motivated, and described for the analysis. When considering the results and presenting the conclusions, it should be taken into account that quantitative risk analyses are to a large extent based on assessments and rough estimates.

CALCULATED RISK LEVEL
The calculated risk for the facility is presented in the form of societal risk with F/N curve (F = frequency, N = number of fatalities).

Figure 10. The societal risk, F/N-curve. Please note that it refers only to accidents with gas-powered buses.

Figure 11. The additional risk contribution from accidents that are estimated to occur only because the facility is located underground.

The presented risk level for the bus terminal for gas-powered buses, includes accident risks within a wide range of accidents with varying degrees of severity where some have potentially major consequences see Figure 10.

These consequences are largely due to the consequences that are created momentarily when parts of the fuel system's components for various reasons fails/malfunction, e.g. so-called pressurized vessel explosion. The severity of the consequences are not due entirely to the fact that the facility is underground. Corresponding accidents can also occur in the facilities above ground and outdoors, and have substantial consequences.

Figure 10 shows the risk contribution from the consequences that are estimated to occur only because the facility is located underground, i.e. this can be seen as a comparison to a bus terminal on the ground (Figure 11). Note that no risk analysis has been conducted for a bus terminal on the ground, so the comparison is just a rough estimation. It can be seen from the figure that mainly scenarios with fewer number of affected persons that can be related to the terminal being placed underground.

SENSITIVITY ANALYSIS
The analysis shows clearly that uncertainties regarding the expected number of technical failures on the fuel systems of vehicle gas-powered buses make a significant contribution to the societal risk, while the uncertainty in other parameters is estimated to have a relatively low impact on the results.

The reason that technical failures that lead to gas emissions affect the result greatly, is that this type of accidents does not give people a warning, but results in an explosion or a jet flame instantaneously. The parameters that have been identified as relevant for the sensitivity analysis and give the greatest impact on the results are presented below.

Frequency of failures on cylinders, according to [9] pressure vessels have a defect rate of 5.0E-07 per
bottle per year. This gives the current facility a probability regarding the part of equipment that is affected with respect to bottles of 0.1%. This parameter significantly affects the results. This is illustrated in Figure 12 and Figure 13 below where the frequency of 30 or more deaths is one-tenth lower if the likelihood of pressurized vessel explosion is 0.01% instead of 0.1%.

Figure 12. The societal risk with 0.01 % likelihood for pressurized vessel explosion.

Figure 13. The societal risk with 0.1 % likelihood for pressurized vessel explosion.

The number of vehicles powered by gas in the operation phase is assumed to be 100% in these analysis.

EXAMPLES OF FURTHER CHALLENGES
Separating walls
Protecting people in the waiting hall and meeting architectural requirements at the same time has been a challenge. There is a desire to have transparency between bus carriageway and waiting hall. The bus terminal architecture should be more like an airport architecture, which places high demands on how technical solutions are designed. In order to meet the requirements, special solutions have been needed to resolve the requirements for separations to handle fire and pressure build-up and to solve evacuations between the areas. A dividing glass wall that have fire resistance cannot be designed durable against dynamic pressure. This has resulted in constructing two different separations. The designed pressure against the separating walls between the bus carriageway and the waiting hall is dimensioned for an explosion that makes a pressure of 10 kPa with an impulse of 250 ms. The fire separations walls is designed to EI90. It was also necessary to install two doors in order to make evacuation between the two areas possible in some places. One door is intended for evacuation in one direction and the other one for the opposite direction. The doors used for everyday use will also consist of sliding doors whereupon the complexity of control is increased etc.

Direction of safety valves on the buses’ fuel system
The conducted risk analysis shows that a side-facing (horizontal) safety valve will create a jet flame that result in high risks of fire spread between buses and fire compartments. This even if the deluge sprinkler system is also activated. Since the jet flame probably occurs after evacuation has been completed, consequences apply mainly to the facility but can also affect the safety for evacuating people. Large domino effects in the form of rapid fire spread between buses as well as a fire that is not expected to be managed by the rescue service, threaten the bus terminal. However, it can be difficult to ensure that all buses that operate in the facility in the future will have an upward safety valve, this makes a major challenge for the operator of the bus terminal.

CONCLUSIONS
The challenge to evaluate risk in a bus terminal where buses are gas-powered is substantial but possible. The risk analysis shows that buses that are gas-powered contribute to high level of risk and different types of risk mitigation systems are necessary. The uncertainties in the area, with a bus terminal under ground, are large but can be managed, by adding different risk mitigation measures and make a robust safety concept. The sensitivity and uncertainty analysis shows that the safety
concept that are introduced is robust and gives the bus terminal good possibilities to handle accidents with gas-powered buses.

The selected methodology with fault- and event tree gives a good overview over the risk analysis and where different risk mitigation measures are needed. Event tree methodology is a tool to systematically develop and illustrate an accident possible course depending on what barriers and conditions there are and how they work. These barriers may consist of both technical and administrative measures. Fixed firefighting system, smoke control system, well placed escape routes are examples of protective barriers.

The systems and the restriction are showing a significant reduction of the risk level in bus terminal. The analysis also shows that huge demands are set on the mitigation systems that are deployed. Among other things, this need creates customized systems and detailed designs and tests of them. This applies, for example, to separations that will handle dynamic pressures and directions of safety valves etc.

In complex projects of this type, it is necessary to take a holistic approach to the safety of the object and find a robust solution based on several risk mitigation systems and safety barriers. With the method used by WSP in the current project, this is achieved in a transparent way which is a key issue to resolve the current project risk that sustainable development can introduce in infrastructure projects.

REFERENCES

Designing Rail Tunnel Fire Safety in Sweden – A Case Study on the Precision of Hand Calculative Methods for Rail Tunnel Safety

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ABSTRACT

This paper shortly describes the process for deriving acceptable evacuation solutions in Swedish rail tunnels. Basically, the acceptable level is derived using a risk analysis approach, analysing the consequences of certain fire scenarios. The method used for evaluating these fire scenarios are complex models for both fire and evacuation calculation, e.g. CFD models for fire and software like STEPS or Pathfinder for evacuation. The complex nature of these models leads to time consuming calculations. Because of time limitations in the projects, early estimations of the results are often valuable in order to get a rough estimation on what measures are needed to design a tunnel that is safe to evacuate in a fire scenario. There are simpler, more time effective hand calculative models that can be applied to give estimates of the fire and evacuation development in a tunnel. To study the precision of these methods, this paper performs two case studies where two different tunnels are evaluated using both hand calculative methods and more complex calculation models.

KEYWORDS: fire safety design, tunnel fire safety, fire modelling, evacuation modelling, CFD, hand calculations

INTRODUCTION

All railway tunnels in Sweden that are connected to the trans-european network have to follow the European regulations set in the Technical Specifications for Interoperability focusing on safety in railway tunnels (SRT TSI) [1]. This TSI describes a set of minimum requirement on fire safety measures such as width of the walkway, emergency exit doors, emergency lighting, distance between emergency exits etc.

As an addition to this, the Swedish Transport Administration has produced their own technical guideline [2] which includes supplementary requirements for their new tunnel projects. The guideline stipulates both minimum requirements on the technical solution and a level of societal risk (expressed as an F/N-curve) that has to be demonstrated using a risk analysis. The requirement on societal risk in earlier versions of the technical guideline published by the Swedish Transport Administration has often led to a higher security level than the TSI with safety measures such as shorter distances between emergency exits, walkways on both sides of a single track tunnel or longitudinal fans to ensure a certain air velocity.

In general, fires in trains constitutes the majority of the total level of risk. Fire and evacuation analysis are therefore performed with the aim of concluding the consequence of certain scenarios identified in earlier steps of the risk analysis. Parameters such as air-velocity, design fires, time to evacuation, number of passengers, and position of the train are varied in the scenarios. The process of choosing design fires for these analyses have previously been described in more detail by Åhnberg & Mossberg, 2016 [3].

When performing these analysis the tools generally used are computational fluid dynamics (CFD)
models for fire and smoke calculations and advanced evacuation models for evacuation. These models are generally very complex by nature which leads to a lot of time consuming calculations. Because of time limitations in the projects, early estimations of the results are often valuable in order to get a rough estimation on what measures are needed to design a tunnel that is safe to evacuate in a fire scenario.

These rough estimations have previously been based on experience and engineering judgement until the calculative results could be obtained. However, there are several empirically developed hand calculation tools that could be used to perform these early estimations [4].

The purpose of this paper is to perform a case study on two different tunnels to investigate how accurate early estimations are if using simple hand calculative models in comparison to the advanced smoke and evacuation models that are more time consuming.

**CASE STUDY 1 - STRÅNGNÄSTUNNELN**

Strängnästunneln is a 3 km single track rail tunnel under construction in Sweden. The tunnel is a part of Svea land route and the purpose of building it is to increase the capacity in rush hour traffic.

**Tunnel description and geometry**

As mentioned above, the tunnel is about 3 km long and a part of the Svea land railway. The tunnel will be built below Strängnäs and is shown in the figure below as a dashed red line.

![Figure 1. The tunnel route.](image)

The tunnel is 8 meters wide and 7,6 meters high and has a section area of approximately 57 m². The section with a train profile is shown in figure 2 below.

![Figure 2. The tunnel section.](image)
In the tunnel, different train types can be expected and the design fire chosen was based on a risk analysis performed by Brandskyddslaget. The fire that will be examined in this report is a 15 MW fire with a t-squared growth rate of 0.003 kW/s² (slow).

**Smoke calculations**

Smoke calculations was performed with FDS version 5.3 and hand calculations based on the methods given by Ingason, et al [4]. A short summary of the input parameters are given below.

**FDS input**

The tunnel section geometry can be mimicked quite well in FDS, which is shown in figure 3 below.

![Figure 3. To the left: the tunnel section geometry in the FDS model. To the right: a close up on the geometry.](image)

The train has been assumed to stop 350 meters into the tunnel. The tunnel has a small gradient but this is considered handled by the tunnel ventilation velocity and not by inclining the tunnel in the model. The tunnel with the train in it is shown in figure 4.

![Figure 4. The tunnel with the train in it.](image)

A ventilation flow of 1 m/s has been attributed to the left tunnel entrance. The fire is assumed to start in the far left part of the train, meaning that all evacuation will be conducted upstream of the fire, through smoke.

The heat release rate (HRR) of the fire is assumed to be a slow 15 MW fire. In the FDS calculations, the “spread rate” function have been used, meaning that the fire grows gradually along the surface, creating a stair function. See figure 5 for the input and output of the HRR below.
Other input parameters of interest are summarized in Table 1 below.

**Table 1. Input parameters.**

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gridsize around the fire [m]</td>
<td>0.2x0.2x0.2</td>
</tr>
<tr>
<td>D*/δx [-]</td>
<td>14.4</td>
</tr>
<tr>
<td>Gridsize in other parts of the tunnel [m]</td>
<td>0.4x0.4x0.4</td>
</tr>
<tr>
<td>Heat of combustion [kJ/kg]</td>
<td>20</td>
</tr>
<tr>
<td>Fuel composition [-]</td>
<td>C: 4.56</td>
</tr>
<tr>
<td></td>
<td>H: 6.56</td>
</tr>
<tr>
<td></td>
<td>O: 2.34</td>
</tr>
<tr>
<td></td>
<td>N: 0.4</td>
</tr>
<tr>
<td></td>
<td>Based on 40 % PU and 60 % wood [5]</td>
</tr>
<tr>
<td>Soot yield [g/g]</td>
<td>0.09 [6]</td>
</tr>
<tr>
<td>CO yield [g/g]</td>
<td>0.10 [6,7]</td>
</tr>
<tr>
<td>CO₂ yield [g/g]</td>
<td>2.20 [6,7]</td>
</tr>
<tr>
<td>Tunnel temperature [°C]</td>
<td>10</td>
</tr>
</tbody>
</table>

**Hand calculation input**

For the empirical hand calculations, the tunnel section area is assumed to be the same (57 m²) with the same height (7.6 m). Since the section is assumed to be rectangular, this gives a tunnel width of 7.5 m. Again, the tunnel length is assumed to be 3 km and the ventilation flow is assumed to be 1 m/s. The temperature is assumed to be the same, i.e. 10 °C. The density of air is assumed to be 1.2 kg/m³ and the specific heat capacity is assumed to be 1 [4]. The yields of the fire and the heat of combustion are also assumed to be the same as mentioned above. The combustion efficiency is assumed to be 0.7 [4]. For calculations of visibility, Dmass is assumed to be 144 based on a aggregate between wood (60 %) [4] and polyurethane (40 %) [8] as the fuel is composed in the FDS simulations. Also, signs in the tunnel are assumed to reflecting, which means that K is assumed to be 3, which is the default value in FDS [9].

**Results**

In the calculations, emergency exits are assumed to be located 800 meters from the fire source. In regards to this, these 800 meters are where the results are compared. However, for temperatures only
250 meters are shown as the differences in results are very small at further distances.

The FDS averages are based on three measurements, one close to the ceiling, one in the middle of the tunnel and one close to the floor.

**Figure 6. A comparison of the average temperatures in the tunnel.**

As the figure shows, the temperatures calculated with FDS are around 10-30 °C while the hand calculated temperatures give a range of 10-100 °C. After approximately 15-20 quite substantial differences start to show for the 100-150 meters closest to the fire. For distances further away from the fire, both calculative models give similar answers throughout the time studied.

The calculated visibility is shown in figure 7 below. Here, the visibility is slightly greater in the hand calculated scenario. Approximately, the hand calculated results lags the FDS results with about 5 minutes. Also, in the FDS calculations the impact of the train can be seen in the results for the first 180 meters from the fire.

For the FDS calculations, these results are for 2 meters above the tunnel floor but for the hand calculations, an average is calculated.
In figures 8 and 9, different concentration profiles from CO and CO$_2$ can be seen for the different methods of calculations. In the FDS calculations, the local maximum of the concentrations are about 500 meters from the fire whilst for the hand calculations the closer to the fire, the higher the concentration. Also, the maximum of the hand calculated concentrations are about twice as big as the FDS calculations. Again this can be explained by the different ways of evaluation, for the FDS calculations, the concentrations are taken at 2 meters above the tunnel floor but for the hand calculations an average is given. So when the stratification is distinct because of the buoyancy effect close to the fire the difference is large but when the stratification is lost the results converge between the two methods.
Evacuation calculations

For the evacuation calculations, the comparison to hand calculations are simulations in the evacuation model STEPS v.5.2. In these calculations, the walking speed is reduced with the visibility according to the figure below. This is a composition between several studies on movement through smoke.

The graph shows walking speeds for three different person types, which are included in the STEPS calculations. For the hand calculations, only one person type is included, which is an average of the three included in STEPS and has the walking speed of person type B.

In both calculations, a train with 504 persons are set as the design scenario. To simplify the hand calculations, FED is only calculated for the first and last person, and these values are the ones compared to the STEPS calculations.

The train is assumed to be situated in accordance with figure 11. This means that the persons have to walk up to 700 meters to get to an exit. The exit discharge rate from the train is 0,2 persons/second and door because of the distance from the train to the tunnel floor. This means a total discharge rate of 4,8 persons/second from the train.
Figure 11. Position of the train.

Everyone is assumed to start their evacuation 5 minutes from fire start. In the FDS calculations, it was observed that the stratification of the smoke in combination with the increased airflow around the train lead to good conditions for evacuation here. This is not accounted for in the hand calculations and to compensate for this, everyone in the hand calculations were assumed to start their evacuation at the end of the train (150 meters from the fire). This means that they will have to walk 550 meters in the tunnel before reaching an exit.

For calculating FED, only the effects of CO and CO₂ have been considered.

Results

The results from the evacuation calculations are given below.

Table 2. A comparison of FED results.

<table>
<thead>
<tr>
<th>Person</th>
<th>FED - STEPS</th>
<th>FED - Healc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest FED</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>Highest FED</td>
<td>0.014</td>
<td>0.29</td>
</tr>
</tbody>
</table>

CASE STUDY 2 - VARBERGSTUNNELN

Varbergstunneln is a 3,1 km double track rail tunnel that is planned in Sweden. The tunnel is a part of “Västlänken” which is a route planned along the Swedish west coast.

Tunnel description and geometry

The tunnel is 16 meters wide and 8,5 meters tall and has a section area of approximately 100 m². The section with a train profile is shown in figure 2 below.

Figure 12. The tunnel section.

In this tunnel, both passenger and cargo trains could be expected. Hence, a quite severe design fire has been chosen according to the risk analysis performed.
Smoke calculations

The same models where used for smoke calculations in this case as in Strängnästunneln. A short summary of the input parameters are given below.

**FDS input**

The tunnel section geometry can be mimicked quite well in FDS, which is shown in figure 13 below.

*Figure 13. The tunnel section geometry in the FDS model.*

The train has been assumed to stop 600 meters into the tunnel. Similarly to Strängnästunneln, Varbergstunneln has a small gradient but this is handled by the tunnel velocity and not by inclining the tunnel in the model. The tunnel with the train in it is shown in figure 14. Observe that approximately one kilometre of the tunnel have been left out, since it is deemed not to affect the parts of the tunnel where evacuation is considered.

*Figure 14. The tunnel with the train in it.*

A ventilation flow of 1,5 m/s has been attributed to the left tunnel entrance. The fire is assumed to start in the far left part of the train, meaning that all evacuation will be conducted upstream of the fire, through smoke.

The heat release rate (HRR) of the fire is assumed to be a fast 50 MW fire. See figure 15 for the input and output of the HRR below.
Figure 15. HRR input/output from FDS.

Other input parameters of interest are summarized in table 3 below.

**Table 3. Input parameters.**

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gridsize around the fire [m]</td>
<td>0,2x0,2x0,2</td>
</tr>
<tr>
<td>D*/δx [-]</td>
<td>23,3</td>
</tr>
<tr>
<td>Gridsize in other parts of the tunnel [m]</td>
<td>0,4x0,4x0,4</td>
</tr>
<tr>
<td>Heat of combustion [kJ/kg]</td>
<td>20</td>
</tr>
<tr>
<td>Fuel composition [-]</td>
<td>C: 4,56</td>
</tr>
<tr>
<td></td>
<td>H: 6,56</td>
</tr>
<tr>
<td></td>
<td>O: 2,34</td>
</tr>
<tr>
<td></td>
<td>N: 0,4</td>
</tr>
<tr>
<td></td>
<td>Based on 40 % PU and 60 % wood [5]</td>
</tr>
<tr>
<td>Soot yield [g/g]</td>
<td>0,09 [6]</td>
</tr>
<tr>
<td>CO yield [g/g]</td>
<td>0,10 [6,7]</td>
</tr>
<tr>
<td>CO₂ yield [g/g]</td>
<td>2,20 [6,7]</td>
</tr>
<tr>
<td>Tunnel temperature [°C]</td>
<td>10</td>
</tr>
</tbody>
</table>

**Hand calculation input**

For the empirical hand calculations, the tunnel section area is assumed to be the same (100 m²) with the same height (8,5 m). Since the section is assumed to be rectangular, this gives a tunnel width of 11,8 m. The rest of the parameters are assumed to be the same as in Strängnästunneln.

**Results**

Same as previously, FDS averages are based on three measurements, one close to the ceiling, one in the middle of the tunnel and one close to the floor.
The temperatures calculated with FDS are around 25-130 °C while the hand calculated temperatures give a range of 15-200 °C. The main difference is very close to the fire, but after approximately 50 meters, the temperatures are very similar from the different models.

The calculated visibility is shown in figure 17 below. Again the FDS calculations are for 2 meters above the tunnel floor but for the hand calculations, an average is calculated.

A similar offset as in Strängnästunneln can be observed. However, since the visibility gets lower much faster in this scenario, the differences are not as obvious. After 15 minutes, the visibility is below 5 meters for both the FDS and the hand calculations.
The rapid fire growth can also be seen in the results of the CO and CO$_2$ concentrations. For the hand calculations, the concentrations reaches a maximum at the same time as the heat release rate and this concentration travels along the tunnel with the wind speed. This is shown in figure 18 and 19 below.

**Figure 18. A comparison of the CO concentration in the tunnel.**

**Figure 19. A comparison of the CO$_2$ concentration in the tunnel.**

**Evacuation calculations**

For these evacuation calculations, the simulations were made in the evacuation model STEPS v.5.3. The same effects on walking speeds were incorporated in the model as in Strängnästunneln. The hand calculations were performed in the same manor.
The scenario investigated was a fire in a freight train stopping next to the passenger train and blocking the closest emergency exit, see figure 20 below for an illustration. This gives a walking distance for the evacuees of about 400 meters. Similarly to the previous scenario, the distance was adjusted for the hand calculations as the conditions on the side of the train were recorded to be good in the FDS calculations. Hence, the distance in the hand calculations were set to 200 meters, as this is the distance from the end of the train to the closest emergency exit. The distance from the emergency exit to the fire was set to 500 meters.

Figure 20. Set up of the scenario investigated.

Results

The results from the evacuation calculations are given below.

Table 4. A comparison of FED results.

<table>
<thead>
<tr>
<th>Person</th>
<th>FED - STEPS</th>
<th>FED - Hcalc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest FED</td>
<td>0</td>
<td>14.6</td>
</tr>
<tr>
<td>Highest FED</td>
<td>1.31</td>
<td>30.7</td>
</tr>
</tbody>
</table>

As shown above, the hand calculations give a significant over estimation of the FED values.

DISCUSSION

The results above show significant difference between the calculative methods. Generally the hand calculations give far more conservative results than the calculations performed in FDS. There might be several reasons for this and a discussion on the results is given below.

The temperatures are generally significantly lower in the FDS calculations than in the hand calculations close to the fire. The difference is smaller in the scenario with a higher heat release rate. There might be several reasons for this but one source of error might be that the FDS average temperature is based on the average of three measurements, one close to the ceiling, one in the middle of the tunnel and one close to the floor. Close to the fire, where significant temperature stratification can be expected, the average temperature is probably affected by the low temperatures for the measurements below the hot layer in the FDS simulation. Here, better results could possibly be obtained if a weighted average would have been used as this could more accurately account for the profile of the hot gases.

Also, in the FDS calculations the fire is located within a train, which can be expected to have influence on the temperatures. Within the train cart the temperatures are higher in the FDS calculations, which indicate that not all heat transports out to the tunnel. This could be one explanation to lower temperatures in the FDS calculations.

The visibility is the only output data where FDS gives less conservative results than the hand calculations. However, close to the fire, the hand calculations give more conservative results. This is probably because of the stratification of the smoke, which is discussed more below.

One factor that has to be mentioned here is the assumption of $D_{mass}$, which has great influence on the visibility calculated by hand. The assumed value is a composition between values for wood and polyurethane as for the fuel in the FDS calculations. However, in the FDS calculations, a dominant factor for calculating visibility is soot yield, which is not necessarily related to the $D_{mass}$ value of a material. In the hand calculations this composition has a direct influence on the results, which could
explain some of the difference in result.

For the fire effluents, similar profiles are shown for the different species and calculative methods. However, between the models the profiles are very different. For the hand calculations the concentrations drop with the distance from the fire but with the FDS calculations the concentration peaks at about 500 meters from the fire in both cases.

The buoyancy of the smoke has the effect that in the FDS calculations higher concentrations are transported closer to the ceiling in the tunnel than the measurement and when this smoke is cooled down and drops, the concentration increases. This is related to the different regions of smoke stratification that can be determined through studying the Froude number. In the performed hand calculations, it is concluded that there is smoke stratification the first 300 meters from the fire after 30 minutes in Strängnästunneln and the first 550 meters in Varbergstunneln. However, at these distances from the fire the difference is still significant so this can only account for parts of the difference.

One reason for the higher values in the hand calculations close to the fire can probably be due to the same phenomena. I.e. in the hand calculations, an average in the tunnel section is calculated and probably this average is higher than the concentration at 2 meters above the floor. Because of the stratification effects, it could be assumed that more convergent results would be given between the models if higher ventilation velocities were studied as this would decrease this effect.

The same reasons as listed above is probably the reasons for the differences in FED values that are shown for each evacuation scenario above. In both cases, the hand calculations over estimates the FED values significantly. The over estimation from the hand calculations is greater in the case with higher heat release rate. This is probably because the higher heat release rate gives more effluents but also more differences in concentrations across the height section of the tunnel, which is accounted for in FDS/STEPS but not in the hand calculations.

CONCLUSION

Hand calculations and calculations made in FDS/STEPS give a significate difference in results when comparing the same scenarios. Based on these results, it is only suitable to make very rough estimates based on hand calculations if these are later to be confirmed by calculations with FDS and STEPS or similar. The estimates made with the hand calculations will be conservative, which is positive for rough estimations. However, the level of conservatism is quite severe, and the designer needs to be aware of this if using the models in this way.

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Feasibility Study: Dimensioning Passenger Loads in Underground Railway Stations

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2Swedish Transport Administration, Stockholm, Sweden

ABSTRACT

When designing exits from underground rail stations and evacuation routes from tunnels, the evacuation capacity is often the main dimensioning factor. In today’s practice (in Sweden), the typical criteria is that two crowded trains can be evacuated well before critical conditions arise. This can in turn result in unnecessarily high building costs or great uncertainties in projects. The purpose of the feasibility study is to explore the possibilities of finding an alternative approach to establishing the dimensioning passenger load, using guidelines based on traffic forecasts. An alternative approach is presented as a calculation example for a future commuter train station outside Stockholm, using forecast data in combination with existing statistical data for a similar station in operation today. In short, forecast models give the number of passengers that are expected to use a station on an average day. Statistics can be used to calculate how the maximum number of passengers relates to the average number. Hence, by combining forecast data with statistical data the expected maximum (dimensioning) passenger load can be established. The alternative approach is found to be more nuanced compared to the "traditional" method for establishing dimensioning passenger load currently used, and seems to be a plausible way forward. Finally, risk perspectives, uncertainties in forecasts and statistics connected to the alternative approach are discussed, followed by some suggestions for continued work in order to develop the line of thought further and formulate a working methodology.

KEYWORDS: dimensioning, underground railway station, evacuation, queue criteria

INTRODUCTION

Background

Railway facilities with tunnels and underground stations have to fulfil high requirements of safety for occupants, property and the environment. The railway should offer a safe way of travelling for the passengers who chose to travel there. High safety is achieved by introducing safety thinking at an early stage and continuing all the way, from planning and design to construction and operation.

Extensive safety work is carried out in the early stages of planning and construction of railway tunnels with and without underground stations. The safety works include determination of the facility’s safety concept, which should present an overall picture of the personal safety in the operating facility. The safety concept is based on three main points: the facility design, the safety equipment together with organization, and monitoring of the facility. The most important thing (in case of an accident) lies in strategies for evacuation and rescue, as these affect the layout of the plant to a large extent. Measures to enable self-evacuation are an important part of the facility's safety. The evacuation capacity controls the design of ramps in stations and evacuation routes from tunnels.
In addition to plant safety measures, the safety concept also presents strategies for managing different types of events. For example, there are events with overcrowded platform that could occur in case of extensive traffic interruptions or delays and in connection with various happenings (concerts, football matches etc.). In such cases, the safety concepts often refer to routines for managing overcrowded platforms. In the routines there may be instructions that, if necessary, include closing off entrances and the platform itself. The escape routes are usually not dimensioned for fire (which requires fast evacuation) in combination with a crowded platform, in accordance with the philosophy that two independent major events do not occur simultaneously.

When designing exits from underground rail stations and evacuation routes from tunnels, the evacuation capacity is often the main dimensioning factor. Evacuation capacity depends on the number of people to be evacuated and what queue times are acceptable. The dimensioning passenger load needs to be established and is then used as a basis to ensure adequate evacuation capacity. The dimensioning passenger load is used in evacuation calculations, where evacuation times are compared to calculations/simulations of different fire development scenarios. In today’s practice, the typical criteria is that two full trains can be evacuated well before critical conditions arise. Adopting a conservative approach, the train type with the largest passenger capacity that could occur in the station in question is used. The supposition is that the trains are completely full (crowded), with standing as well as seated passengers. The result is that stations with relatively low numbers of passengers can be designed for extreme situations that would normally only occur in more heavily used facilities. This can in turn result in unnecessarily high building costs or great uncertainties in projects. A more nuanced approach based on traffic forecasts and the expected risk situation could entail more effective designing and lower project costs.

**Purpose**

The purpose of the feasibility study is to explore the possibilities of finding an alternative approach to establishing the dimensioning passenger load, using guidelines based on traffic forecasts. The intention of the alternative approach is to find a different starting point for the design process, rather than the very conservative use of the maximum number of passengers in the largest possible train type. The long term goal is a methodology for achieving more homogenized, cost efficient and realistic design solutions in the future.

**Methodology and scope**

The authors/project team members are highly experienced and have in depth knowledge within the fields of fire and risk issues as well as traffic forecasting and analysis. The work has been conducted as a close collaboration in a number of workshops, discussing different inputs, approaches and methodologies.

Following an overview of current laws and regulations, the project did an inventory of existing principles for establishing dimensioning passenger loads. Different approaches are used when establishing dimensioning passenger loads for the verification of evacuation safety in tunnels and underground stations, the effects of which are illustrated. Examples of simple evacuation analyses using a given queue criteria were included to illustrate the interaction between evacuation route design and evacuation capacity. An alternative approach is then presented, using forecast data in combination with existing statistical data to calculate the expected maximum (dimensioning) passenger load.
CURRENT SWEDISH PRACTICE FOR DIMENSIONING PASSENGER LOADS IN UNDERGROUND RAILWAY STATIONS

Passenger safety when evacuating from underground railway stations is evaluated by evacuation analysis. The criteria for a safe evacuation often follows the queue criteria (maximum 8 min) according to the Swedish National Board of Housing, Building and Planning’s general recommendations on the analytical design of a building’s fire protection BBRAD [1].

The approach so far, regarding dimensioning passenger loads upon verification of the evacuation safety differ in different tunnel projects. A comparison of different tunnel projects is shown below (Table 1) regarding forecasts for number of passengers, number of passenger trains and the average number of passengers per train, together with the dimensioning passenger load used. The data is compiled from the different safety analyses produced within the respective projects. In the last column a quotient is calculated to illustrate the (exaggerated) relationship between the estimated average number of passengers on the trains and the chosen dimensioning passenger load for evacuation. The quotient is calculated as dimensioning passenger load on station (column 5) divided by two times average number of passengers per train (column 4), since the basis for the dimensioning passenger load is typically two trains (column 6).

Table 1 Comparing dimensioning passenger loads in different underground railway stations

<table>
<thead>
<tr>
<th>System</th>
<th>Expected number of passengers per day</th>
<th>Number of passenger trains per day</th>
<th>Average number of passengers per train</th>
<th>Dimensioning passenger load on station</th>
<th>Basis for dim. passenger load</th>
<th>Quotient(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughout Sweden</td>
<td></td>
<td>ca. 115</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Varbergstunneln station (year 2030)</td>
<td>14 000</td>
<td>132</td>
<td>106</td>
<td>1 360</td>
<td>Two trains (average load)</td>
<td>6,4</td>
</tr>
<tr>
<td>Västlänken</td>
<td>75 000</td>
<td>520</td>
<td>144</td>
<td>1 840+1 840=3 680</td>
<td>Two crowded(b) trains</td>
<td>12,8</td>
</tr>
<tr>
<td>Citybanan in Stockholm</td>
<td>250 000</td>
<td>600</td>
<td>416</td>
<td>1 840+1840=3 680</td>
<td>Two crowded trains</td>
<td>4,4</td>
</tr>
<tr>
<td>Citytunneln in Malmö (Year 2030)</td>
<td>92 000</td>
<td>450</td>
<td>204</td>
<td>788+1 576 or 788+788+788=2 364</td>
<td>Two or three trains(c)</td>
<td>5,8</td>
</tr>
<tr>
<td>Södertunneln in Helsingborg (Year 2037)</td>
<td>100 000</td>
<td>372</td>
<td>268</td>
<td>960+1 560=2 520</td>
<td>Train 1 fully seated+ train 2 crowded</td>
<td>4,7</td>
</tr>
<tr>
<td>Strängnäs-tunnel (Year 2030)</td>
<td>7 200</td>
<td>66</td>
<td>109</td>
<td>504</td>
<td>In tunnel one train fully seated</td>
<td>2,3</td>
</tr>
<tr>
<td>Mälarbanan (Year 2030)</td>
<td>52 000</td>
<td>378</td>
<td>137</td>
<td>1 840+1 844=3 684</td>
<td>Crowded X60+ crowded X40</td>
<td>13,4</td>
</tr>
<tr>
<td>Ostlänken (Year 2040)(d) Järna-Skavsta/ Skavsta-Linköping</td>
<td>32 900 / 28 800</td>
<td>224 / 176</td>
<td>147 / 163</td>
<td>2091</td>
<td>Two trains (average load)</td>
<td>6,7</td>
</tr>
</tbody>
</table>

(a) Calculated as (dimensioning passenger load on station) divided by two times (average number of passengers per train)
(b) Crowded train = train with full number of seated and full number of standing passengers.
(c) Two trains refer to one short + one long train, three trains refer to three short trains
(d) Ongoing project, new forecasts/information produced
DIMENSIONING PASSENGER LOADS IN RAILWAY TUNNELS

Passenger safety in railway tunnels is evaluated in the safety analysis according to the Swedish Transport Administration document BVH 585.30 [2]. The safety analyses includes several studies, among them studies of evacuation safety. As part of this work the distribution over time of different passenger train loads has to be chosen. The distribution should correspond to the traffic forecasts together with the number of passengers that is dimensioning for the tunnel system. A large number of scenarios with different passenger loads on the trains are evaluated in the safety analysis. The dimensioning passenger loads in the tunnels including traffic forecasts and the distribution over time of different passenger loads constitute important conditions for the overall tunnel safety analysis. The influence of taking the estimated passenger distribution over time into account in the tunnel analyses is illustrated by the quotient in the last column of Table 2, which is considerably lower than the quotient for the stations in Table 1.

Table 2 Comparing dimensioning passenger loads in different railway tunnels

<table>
<thead>
<tr>
<th></th>
<th>Passenger load in different situations</th>
<th>Assumed distribution %</th>
<th>Estimated average load in verification/ forecast</th>
<th>Quotient verification load/ forecast load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Citybanan (a)</td>
<td>1840 / 1200 / 400</td>
<td>1 / 27 / 72</td>
<td>630/ 416 per train</td>
<td>1,5</td>
</tr>
<tr>
<td>Västlänken (b)</td>
<td>1836 / 1212 / 508 / 150</td>
<td>1 / 2 / 30 / 67</td>
<td>156000/ 75000 per day</td>
<td>2,1</td>
</tr>
<tr>
<td>Varbergstunneln (c)</td>
<td>680 / 250 / 150</td>
<td>2 / 48 / 50</td>
<td>913/ 730 per train</td>
<td>1,25</td>
</tr>
<tr>
<td>Mälarbanan (d)</td>
<td>1840 / 920 / 240</td>
<td>2 / 10 / 88</td>
<td>380/ 240 per day</td>
<td>1,6</td>
</tr>
</tbody>
</table>

(a) traffic disturbance / high traffic intensity / low traffic intensity
(b) crowded / full / half full / normal
(c) full / half full / normal
(d) crowded / high traffic intensity / low traffic intensity

EXAMPLE EVACUATION CALCULATIONS

A couple of basic evacuation analyses have been performed for an underground station in order to investigate the influence from different passenger loads on the evacuation capacity requirements in terms of number of stairs and escalators. The studied scenario consisted of an evacuation from a middle platform with one train on each side. In one of the trains there is an ongoing fire in one carriage.

The criteria for a safe evacuation follows the queue criteria (the queuing time should be limited not exceed maximum 8 min) according to BBRAD [1]. A smoke exhaust system is assumed to be in place to maintain tenable conditions during the evacuation phase. Hence, the queue criteria (not the fire and smoke gas) will be dimensioning for the evacuation capacity from the platform.

The evacuation from the platform is assumed to take place via both stairs and escalators. The direction of the escalators will be essential. Downward escalators are expected to be stopped (not reversed) in case of a fire, in order to be available for the evacuation. Since the escalators sometimes are blocked during service and maintenance, the evacuation analysis include blocked escalators.
Five limiting factors can be identified during an evacuation from the platform:
- Upward escalators
- Stationary escalator (out of order or downward that have been stopped due to the fire)
- Blocked escalator
- Stairs
- Door openings

**Basic Case**

In the basic case illustrated in Figure 1, the following is assumed:
- Evacuation is ongoing for 3 min before an exit is blocked due to the fire.
- Simultaneously an escalator is being blocked at the other exit, for instance due to maintenance. The capacity in this escalator is set to 0 person/minute.
- At least half of the remaining escalators are moving upwards.
- Escalators moving downwards are stopped on detection of fire and are therefore available for evacuation.

![Figure 1](image)

**Figure 1**  *Evacuation from a middle platform with two exits and two trains*

**Evacuation capacity from the platform**

A variety of different configurations of exits from underground rail stations are possible and the capacity can also be divided between multiple exits. In this case, a platform with exits at each end is studied. Each exit is assumed to be designed according to one of the three options presented below (configuration 1-3) and the symbols used are explained in Table 3.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>Blocked escalator</td>
<td>0 p/min</td>
</tr>
<tr>
<td>Silver</td>
<td>Stopped escalator</td>
<td>30 p/min</td>
</tr>
<tr>
<td>Gray</td>
<td>Staircase in use</td>
<td>ca. 80-170 p/min depending on stair width</td>
</tr>
<tr>
<td>Green</td>
<td>Working escalator</td>
<td>100 p/min</td>
</tr>
<tr>
<td>Strikethrough</td>
<td>Fire blocking the exit after 3 min</td>
<td>0 p/min after 3 min</td>
</tr>
</tbody>
</table>

In this case, the stair rise is assumed to be less than 15 meters in all scenarios. The door configuration has not been especially studied. The capacity is assumed to exceed the capacity of the exits.
Configuration 1: Two escalators at each exit

<table>
<thead>
<tr>
<th></th>
<th>Exit no. 1</th>
<th>PLATFORM</th>
<th>Exit no. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity pers/ min</td>
<td></td>
<td>Capacity pers/ min</td>
</tr>
<tr>
<td>0-3 min</td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>3-8 min</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>800</td>
<td>0</td>
<td>390</td>
</tr>
</tbody>
</table>

Configuration 1 has, at exit 1, a working escalator with the capacity of 100 p/min and a blocked escalator, i.e. a capacity of 100 p/min at exit 1. Exit no. 2 has a working escalator and one not functioning which gives a capacity of 130 p/min. Exit no. 2 is blocked after 3 min. This gives a total capacity during 8 min for configuration 1 as follows;
- Exit no. 1: 100 p/min * 8 min = 800 persons
- Exit no. 2: 130 p/min * 3 min = 390 persons

Therefore, the total capacity during 8 minute is 1190 persons.

Configuration 2: three escalators at each exit

<table>
<thead>
<tr>
<th></th>
<th>Exit no. 1</th>
<th>PLATFORM</th>
<th>Exit no. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity pers/ min</td>
<td></td>
<td>Capacity pers/ min</td>
</tr>
<tr>
<td>0-3 min</td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>3-8 min</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>1040</td>
<td>0</td>
<td>480</td>
</tr>
</tbody>
</table>

Configuration 2 has, at exit 1, a working escalator with the capacity of 100 p/min, one escalator not functioning with the capacity of 30 p/min and one escalator that is blocked, i.e. a capacity of 130 p/min at exit 1. Exit no. 2 has one functioning and two non-functioning escalators which gives a capacity of 160 p/min. Exit no. 2 is being blocked after 3 min. This gives a total capacity during 8 min for configuration 2 as follows;
- Exit no. 1: 130 p/min * 8 min = 1040 persons
- Exit no. 2: 160 p/min * 3 min = 480 persons

Therefore, the total capacity during 8 min is 1520 persons.

Configuration 3: two escalators + straight staircase (width 2-4 m) at each exit

<table>
<thead>
<tr>
<th></th>
<th>Exit no. 1</th>
<th>PLATFORM</th>
<th>Exit no. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity pers/ min</td>
<td></td>
<td>Capacity pers/ min</td>
</tr>
<tr>
<td>0-3 min</td>
<td>80-170</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>3-8 min</td>
<td>80-170</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td>1434-2154</td>
<td>0</td>
<td>627-897</td>
</tr>
</tbody>
</table>

Configuration 3 has, at exit 1, a staircase where different widths of the stair is evaluated, a blocked escalator and one functioning escalator with the capacity of 100 p/min. Exit no. 2 has a staircase where different widths of the stair is evaluated, a functioning escalator with the capacity of 100 p/min and one non-functioning escalator with the capacity of 30 p/min. Exit no. 2 is blocked after 3 min.
Results

A summary of the results is presented in tables 4 and 5 to show the number of people evacuated before the queuing time exceeds 8 min for configuration 1-3.

Table 4  Summary of results, configuration 1-2

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Available capacity (persons/min)</th>
<th>People evacuated before queuing time &gt; 8 min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exit 1</td>
<td>Exit 2</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>130 for 3 min</td>
</tr>
<tr>
<td>2</td>
<td>130</td>
<td>160 for 3 min</td>
</tr>
</tbody>
</table>

Table 5  Summary of results, configuration 3

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Stair width</th>
<th>Available capacity (persons/min)</th>
<th>People evacuated before queuing time &gt; 8 min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Exit 1</td>
<td>Exit 2</td>
</tr>
<tr>
<td>3</td>
<td>2,0 m</td>
<td>179,2</td>
<td>209 for 3 min</td>
</tr>
<tr>
<td>3</td>
<td>2,5 m</td>
<td>201,7</td>
<td>232 for 3 min</td>
</tr>
<tr>
<td>3</td>
<td>3 m</td>
<td>224,2</td>
<td>254 for 3 min</td>
</tr>
<tr>
<td>3</td>
<td>3,5 m</td>
<td>246,7</td>
<td>277 for 3 min</td>
</tr>
<tr>
<td>3</td>
<td>4,0 m</td>
<td>269,2</td>
<td>299 for 3 min</td>
</tr>
</tbody>
</table>

The result shows how the number of escalators and width of the staircase increases depending on the dimensioning number of persons. According to standard practice dimensioning methods, the number of people evacuated before queuing time exceeds 8 min should be more or equal to the dimensioning number of persons.

The dimensioning passenger load has a great impact on the number of staircases and their widths, as well as the number of escalators. See, for example 1500 compared to 3000 people, in Table 6.

Table 6  Need for escalators/ stairs for different dimensioning number of persons

<table>
<thead>
<tr>
<th>Dimensioning number of persons</th>
<th>Need for escalators/stairs at every exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 persons</td>
<td>Two escalators</td>
</tr>
<tr>
<td>1500 persons</td>
<td>Three escalators</td>
</tr>
<tr>
<td>2000 persons</td>
<td>Three escalators and one staircase with a width of 2 m</td>
</tr>
<tr>
<td>2500 persons</td>
<td>Three escalators and one staircase with a width of 3 m</td>
</tr>
<tr>
<td>3000 persons</td>
<td>Three escalators and a staircase with a width of 4 m</td>
</tr>
</tbody>
</table>

The width of the exits effects the platform width which could have a major influence on the cost of the project, for example by impacting the station structure or track alignment.

There are of course possibilities to use other combination of stairs/escalators and more exits than two, but this example illustrates that the dimensioning number of people has a major impact on how to design the rail station.
ALTERNATIVE APPROACH

Basic input

Traffic forecasts
The Swedish Transport Administration uses a national transport model system called Sampers. The system is used to forecast future travelling and to evaluate how it will be affected as a result of changes in infrastructure, ticket prices or private car operating costs. The calculations include trips by car, bus, train and airplane, and the system consists of a national model as well as separate regional models for different parts of Sweden. The national model entail trips longer than 100 km, while the regional model allows for shorter trips.

Somewhat simplified, the system can be divided into three parts:
- Input data
- Calculation relationships
- Results

Input data is updated on a yearly basis, when population data and transport networks are amended according to their latest forecasts and plans. The calculation relationships give the number of trips, what mode is used and what route is taken, between different origins and destinations.

The model output can, for example, be number of travelers on a certain road or public transport line, numbers embarking/disembarking at a station etc., and is produced for the current situation as well as one or more forecast years. At present, the current situation is 2014 and the forecast year is 2040.

Statistics
In order to add to the information gained from the traffic forecasts we need to obtain the number of people in the trains and on the platforms, during different times of day.

For Stockholm subway and commuter trains there is technology that weighs axle loads. Through average passenger weight assumptions, wagon load data is obtained, i.e. how many passengers are in a subway or train wagon at a given time. The operator (MTR) collects and processes the data for the subway. Commuter trains send data in real time to an application called "Commuter Forecast", that shows how crowded (green, yellow, red) individual wagons are, so that travelers can choose where to board the train. It is unclear, however, if this data has been stored up to date, which makes it difficult to use for analysis.

The Stockholm commuter trains also have equipment for automatic traffic counts in each door pair. Data is collected and analyzed by SL (Greater Stockholm Local Transit Company). Their system RUST makes it possible to extract the number of people getting on/off and the number of passengers on the train at departure, at different stations. Several different report layouts are available and data can be obtained for separate departures. This in turn makes it possible to analyze how the number of passengers vary between different departures and different days. Following a certain departure on a certain day is as close to raw data as we can possibly get. Data is collected by door pair, so data from every wagon position must be added to obtain the total number of passengers on board the train.

Calculation principle

Traffic forecasts yield the expected number of passengers at a station on an average day. When dimensioning for an evacuation situation, however, the maximum number of passengers is of interest. Statistics can be used to calculate how the maximum number of passengers relates to the average. Thus, by combining information from traffic forecasts with statistical data the expected maximum load can be calculated, as illustrated in Figure 2.
Example Vega Station

The calculation example below refers to Vega Station, a commuter train station connecting to the commuter train network in Haninge in the south part of Stockholm County. The station is currently under construction and will be opened to traffic in 2019. Since Vega Station isn’t operational yet, there is no data on the actual travel patterns there. Instead, statistics from Stuvsta Station are used. The characteristics of Stuvsta Station are similar to Vega Station, as they are both located in largely residential areas, ca 10-15 km south of Stockholm Central Station.

Traffic forecast
The model system Sampers was used to forecast the number of travelers at Vega Station in 2040. Tables 7 and 8 present the model results for an average weekday and the morning peak respectively.

By *embarking* and *disembarking* we mean passengers getting on and off the train at Vega Station, and *people on board* is the number of passengers that pass Vega. In total, 256 people on average occupy (passing, getting on or off) Vega station at each departure. The corresponding number for the morning peak is 222 passengers at each departure. The number for the morning peak being lower than the daily average can be explained by the fact that morning traffic is more directional (many going into the City, fewer going in the opposite direction) as well as the train frequency being higher.

<table>
<thead>
<tr>
<th>Table 7</th>
<th>Number of passengers at Vega Station on an average weekday 2040, forecast according to the Sampers model system.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forecast values:</strong></td>
<td><strong>Embarking</strong></td>
</tr>
<tr>
<td>- North bound</td>
<td>2 000</td>
</tr>
<tr>
<td>- South bound</td>
<td>700</td>
</tr>
<tr>
<td><strong>Total departures per day</strong></td>
<td>126</td>
</tr>
<tr>
<td><strong>Calculated average per train:</strong></td>
<td></td>
</tr>
<tr>
<td>- North bound</td>
<td>16</td>
</tr>
<tr>
<td>- South bound</td>
<td>5</td>
</tr>
<tr>
<td><strong>SUM</strong></td>
<td>16 + 6 + 107 + 5 + 15 + 107 = 256</td>
</tr>
</tbody>
</table>
### Table 8  
**Number of passengers at Vega Station during the morning peak (7:00-9:00 am) 2040, forecast according to the Sampers model system.**

<table>
<thead>
<tr>
<th></th>
<th>Embarking</th>
<th>Disembarking</th>
<th>People on board</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forecast values:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- North bound</td>
<td>320</td>
<td>80</td>
<td>1,950</td>
</tr>
<tr>
<td>- South bound</td>
<td>90</td>
<td>160</td>
<td>950</td>
</tr>
<tr>
<td><strong>Departures during morning peak</strong></td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Calculated average per train:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- North bound</td>
<td>20</td>
<td>5</td>
<td>122</td>
</tr>
<tr>
<td>- South bound</td>
<td>6</td>
<td>10</td>
<td>59</td>
</tr>
<tr>
<td><strong>SUM</strong></td>
<td>20 + 5 + 122 + 6 + 10 + 59 = 222</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Statistics

Data was extracted from RUST and pertains to departures from Stuvsta Station between 15 January and 8 April 2016, including around 170 daily departures, from 05:30 am to midnight. However, during the data analysis we found that the material wasn’t as complete as expected, as several departures were missing from the database. Therefore it was decided that we create a *synthetic day*.

The synthetic day was created by combining all of the available statistical data and picking the maximum number of passengers for each minute of the day. This means that for minutes with data from more than one date, the highest of these values was used. Since the data is incomplete it is likely that data is missing regarding times of extra high loads, for example if two trains with unusually high number of passengers arrive at the station simultaneously. To compensate to some extent for this probable lack of extreme cases, a moving average over 60 min (excluding all minutes with 0 recordings) was calculated for every minute (i.e. minute 8:01 is based on maximum number of passengers 7:32-8:31). The maximum number of people during the same 60 minute period was also put down as the maximum for the minute in question.

The synthetic day was created to test the calculation principle and isn’t claimed to be an accurate representation of passenger flows for Stuvsta Station. If there had been a complete dataset for a longer period of time, the calculation could have been performed for each individual day instead. The moving average wouldn’t have been necessary either. Instead, an assumption could have been made that all embarking passengers arrive over a 10 minute period before departure and all disembarking passengers have left the station within 5 min after arrival.

**Maximum load**

Based on the calculations, a diagram was constructed, showing how passenger flows vary during the day at Stuvsta Station, on average and at maximum load (figure 3). The blue field refers to the average and the orange field refers to the maximum number of passengers.

According to the statistical data, 500 people on average are present at Stuvsta Station at any given time during the traffic day (defined as 06-22 to match the traffic forecast). During the morning peak (defined as 07-09), the average load is higher at 730 people. Maximum load is 1 140 passengers (both directions) and occurs at 8 am. Thus, between 7 am and 9 am there are 56% (calculated as 1140/730=1,56) more passengers during maximum load compared to the average. The corresponding value for the traffic day (06-22) is 128% (calculated as 1140/500=2,28).
Based on the synthetic day, calculations were made to examine the distribution of passengers at Stuvsta Station over the traffic day. It was found that during 95% of the time, there are 993 people or fewer present at the station. The relationship between 95% and average load during the traffic day (06-22) is thus 1,98 (calculated as 993/500 = 1.98).

Combination of model and statistical data
According to model data the number of passengers per departure at Vega Station is 222 during the morning peak and 256 during the day. By combining this with the calculated relationship between average and maximum number of passengers above, the result is a maximum of 345 passengers when using the morning peak, and 583 when using the whole day figure. Maximum number of passengers to be evacuated if using the 95%-level is 506 (Table 9).

It can seem illogical that there are more people when using daily figures rather than the morning peak, but this can be caused by a number of different factors. In part it can be because morning traffic is clearly directional and few people travel contrary to the rush hour flow. It can also be due to afternoon traffic (which isn’t modelled separately) experiencing the highest load. A third reason can be if the daily travel/traffic profile differs significantly between the modelled station and the station from which the statistical data was extracted.

Table 9  Calculated maximum number of people when using statistics of ”maximum load” (upper half) and ”95%-level” (lower half).

<table>
<thead>
<tr>
<th></th>
<th>Morning peak</th>
<th>Day</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum load</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Av. no. of people per departure</td>
<td>222</td>
<td>256</td>
<td>From model calculations</td>
</tr>
<tr>
<td>Quotient btw max. &amp; av. load</td>
<td>1.56</td>
<td>2.28</td>
<td>From statistics, “maximum load”</td>
</tr>
<tr>
<td>Calculated maximum load</td>
<td>222 x 1.56 = 345</td>
<td>256 x 2.28 = 583</td>
<td>Use the higher of the two values!</td>
</tr>
<tr>
<td>96%-level</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Av. no. of people per departure</td>
<td>n/a</td>
<td>256</td>
<td>From model calculations</td>
</tr>
<tr>
<td>Quotient btw max. &amp; av. load</td>
<td>n/a</td>
<td>1.98</td>
<td>From statistics, “95%-level”</td>
</tr>
<tr>
<td>Calculated maximum load</td>
<td>n/a</td>
<td>256 x 1.98 = 506</td>
<td></td>
</tr>
</tbody>
</table>
DISCUSSION

Risk perspective

The question is which percentile is reasonable to use for the dimensioning number of persons and if the choice could reflect the general view on risk and what might assume to be a reasonable choice. The following is a comparison between choices made due to the percentile in other risk areas.

- Dimensioning fires (maximum effect MW and growth rate) in buildings according to BBRAD 3 cover about 95-98 % of all fires [3]
- Dimensioned fire load (MW/m²) for buildings is often set to 80 % of the fractile [4]
- Dimensioned fires, a worst case scenario at stations should cover about 98 % of all fires [5]
- Socioeconomic calculations according to ASEK [6] are using a 50 % level in the basic calculations and uses a 85 % level when performing sensitivity analyses according to the successive calculation method.

From the comparison above, it may be a reasonable choice not to assume maximum load (full capacity in the seating areas and full capacity in the standing areas) in the trains, but instead use a percentile from the number of travelers. As a suggestion one might use a general percentile of 95 %. The percentile increases or decreases depending on how sensitive the facility is to traffic disturbance. It is assumed that traffic disturbances result in cancelled and overloaded trains. It means that if the percentile 95 % is used, the extreme cases are excluded. The extreme cases should be included in sensitivity analyses depending on how great the probability is for them to occur. When performing a sensitivity analysis only the effect of the fire is dimensioning, not the queue criteria of 8 min. As a support to estimate disturbance sensitivity one could calculate the tracks capacity utilization at a maximum time of 2 hours according to [7].

Uncertainties

Transport models
When analyzing model results it is important to keep in mind that there are uncertainties in input data as well as in calculation relationships. Population and land use development can differ compared to the assumptions made during the forecast work. Furthermore, suppositions are made regarding traffic supply and ticket prices, e.g. that a monthly ticket costs 900 SEK and that train frequency is every 10 min during peak times and every 20 min the rest of the day. If the traffic supply and ticket prices differ from this when the station is taken into operation, the forecast results will not mirror the actual traffic situation. It is also quintessential to remember that the calculation relationships embedded in the forecast models is a simplification of reality.

Statistical data
The historical data on number of people that embark, disembark and are present on the platforms at different stations that we have used here pertain to the Stockholm commuter train system. Therefore it can be questioned to what extent this information is transferrable to 1) other types of train systems (regional, high speed etc.) and 2) other types of stations in other parts of the country. However, the purpose here has been to test the principle for an alternative approach, not to establish absolute factors for possible future use. Further work should include deeper examination of availability of data detailed enough to obtain factors for typical underground railway stations.
Comparison current method and alternative approach

The calculations for Vega Station combined model results and statistical data. Based on this information the dimensioning number of passengers in 2040 is 583 people if maximum load is used, and 506 people if the criteria is to accommodate the load that exists 95 % of the time. This can be compared to the 3 640 passengers obtained, if using the currently prevailing method of two crowded trains (see Table 1). The difference is hence significant. The magnitude in this particular case can be explained by the fact that Vega Station has clearly directional traffic during the morning peak, and that the station is situated at a distance from the central parts of the transport network. The probability that two crowded trains would actually meet at Vega Station is judged to be basically non-existent.

CONCLUSION AND CONTINUED WORK

Statistical data
The calculations presented in the section “Alternative approach” above should be viewed as an example of a possible calculation method. The work carried out shows that the method seems to work, but that it needs further development, mainly in terms of availability of historical statistical data. There is a need for more extensive information from different types of stations and trains to see how much they differ between average and maximum load. For example, it can be expected that the travel demand for a long-distance train station differs from a commuter train station. Furthermore, it should be examined how long a period (number of departures) should be included, in order to catch the more rare cases of extreme passengers loads as well.

Traffic forecasts
An extensive planning process underlies the work in infrastructure projects. The journey from planning start, design, construction to start-up is long. The choice of dimensioning prerequisites takes place at an early stage of this process. Here, one must remember that all forecasts contain assumptions and therefore uncertainties about the actual number of passengers that are going to use the station. The population development, land use, time table and train types that will finally be the case may differ from the assumptions made during the forecast stage of the work. The possibilities for a continuous update of traffic forecasts and other analyses (during planning and design work) need to be reviewed.

Correlation between “worst case scenario” and alternative approach
Further investigation needs to be done on how the Swedish Transport Administration will relate to the correlation between “worst case scenario” (two crowded trains) and the outcome of the calculations in this feasibility study. One way to go is to use the percentile 95 % for travelers when deciding the evacuating capacity for underground railway stations. As a suggestion, the worst case scenario could be included in the sensitivity analysis without setting the queue criteria (8 min) as dimensioning. This can be compared to the Swedish Transport Agency proposal from 2016, which advises to use two crowded trains plus travelers on the platform, which is an even greater load than is currently being used when designing Västlänken and Citybanan. These are two completely opposite directions for execution, where the one from the Swedish Transport Agency is conservatively deterministic, while the other that uses a percentile of 95 % is probabilistic. The choice of dimensioning method should be evaluated further through Life Cycle Cost (LCC) analysis.

Proposal for continued work
This paper presents the results of a feasibility study that investigates the possibilities of developing an alternative method for selection of dimensioning passenger load. The results and conclusion from our analysis indicates that it is of interest to move forward with the idea of an alternative approach but further investigation and analyses need to be conducted in order to produce a guiding document or fully prepared methodology. Based on our comments and conclusions, the following list of ideas is presented on the direction and focus of further work.
Further investigation regarding available statistics, how data is organized (directional breakdown, maximum load during morning and afternoon, different daytime profiles etc.) and how it can be used in combination with model data.

Evaluate if a scenario with every other train cancelled may be used as an extreme case for sensitivity analysis. It is also possible that this extreme case may become the case used for choosing the dimensioning passenger load, depending on the outcome of further investigation.

The queue criteria should be challenged in an extreme case where evacuation shouldn’t result in any people being seriously injured, excluding the residual risk.

LCC-analysis, evaluation of cost savings due to alternative ways of determining the dimensioning passenger load compared to the expected risk situation.

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Revisiting NFPA 130 Criteria for Emergency Ventilation Systems in Rapid Transit Stations

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ABSTRACT

An opportunity exists to expand and clarify the criteria and concepts around emergency ventilation systems for rapid transit stations, which has undergone an evolution in the 12 versions of NFPA 130 that have been published since the standard was introduced in 1983. Modernization of these requirements will provide a much needed refresh on the approach, allowing for greater consistency in the application of the Standard. Project experience has brought to light a growing number of examples where variation or uncertainty in the interpretation and application has had direct impact on project or system complexity, cost, and analysis requirements. This paper revisits the structure and content of the related NFPA 130 definitions, requirements and supporting annex material with the intent of identifying potential improvements that would provide a more clear and unified framework.

KEYWORD: Emergency ventilation systems, smoke control, NFPA 130, enclosed stations, risk

INTRODUCTION

NFPA 130 (Standard for Fixed Guideway Transit and Passenger Rail Systems) [1] is in widespread use for rapid transit system projects. Since the first edition in the 1980s, requirements related to emergency ventilation and supporting guidance in the annex material have expanded. Requirements and annex material have been subject to variations in interpretation between projects, resulting in inconsistency in the developed approaches, acceptance criteria, and key objectives from project to project. This paper presents background and context relative to important emergency ventilation system considerations, and provides suggestions for revisiting the content of the standard to provide an updated approach to ventilation system evaluation that is consistent with current knowledge and technology.

While NFPA 130 includes criteria related to emergency ventilation for both stations and trainways, in general, the more complicated geometry of stations corresponds with increased opportunity for varying interpretation and application of the NFPA 130 criteria. Consequently, the focus of this paper is on emergency ventilation for stations. In this paper the following recommended revisions are discussed:

1. Review the consistency of requirements related to the provision and design of emergency ventilation throughout the Standard. Create cross-references to enhance cohesion.
2. Improve definitions for Open/Enclosed and Point of Safety to clarify intended interpretation and application.
3. In Chapter 5, clarify the intended interpretation of prescribed evacuation times vis-à-vis evaluation of tenability.
4. In Chapter 7, clarify the intent with regard to the required ‘zone’ of tenability.
5. Re-organize, consolidate and update annex material related to emergency ventilation to include technical references, consistent context, and to reflect the current industry knowledge.
6. Introduce the concept of risk, similar to other transportation standards.

BACKGROUND

NFPA 130 was first issued in 1983, realizing work by the Fixed Guideway Transit System Committee that had been formed in 1975. One of the primary concerns addressed by the committee in shaping the original document was the potential entrapment of large numbers of people using mass transportation systems. In the first edition, the essential fire protection requirements addressing that concern appear to borrow from measures that existed earlier in various transit design guidelines [2], including the use of ventilation strategies for smoke control.

Throughout the 12 revised versions that have been published since the original, criteria specifically related to emergency ventilation has expanded from a few paragraphs and one annex to a dedicated chapter and four related annexes. Other requirements integral to emergency ventilation system design are present throughout each of the other 11 chapters. The informational material currently spread across multiple annexes is likely an artefact of the standards development process and the industry needs at the time of revision. Original language that was based on general performance goals with few prescriptive measures and targets now encompasses a much wider range of measurable parameters and specific recommendations in terms of factors to consider during analysis. This evolution has resulted in material that lacks fluidity in application and consistency in developing the intended unified framework. Advancements in the fire industry and evolutions of other pertinent NFPA standards create an opportunity to update technical references, add important technical context, modernize the legacy approaches and direction.

The first edition of NFPA 130 stated that “fire safety on a fixed guideway transit system is achieved through a composite of facility design, operating equipment, hardware, procedures and software subsystems which are integrated to provide requirements for the protection of life and property from the effects of fire.” With the continual expansion of material related to emergency ventilation, the cohesion of information needed to achieve the desired integrated approach has become obscured.

A few additional points are worthy of note within the context of this discussion. First is a note that appears at the beginning of each annex in the NFPA standards stating: “This annex is not part of the requirements of this NFPA document but is intended for informational purposes only.” Experience indicates that this caution is frequently missed—i.e., information in the annexes has been applied prescriptively, without regard to project context, as if it represents mandatory requirements that supplement requirements in the main body of the standard. Secondly, NFPA 130 often refers back to other Standards and to the “locally applicable building code.” For stations in particular, NFPA 130 should be viewed as a supplement to local codes, adhering to the core intent and objectives of those codes, providing criteria that recognizes conditions specific to transit systems while adhering to the core intent and objectives of those codes, which are generally to limit the spread of fire to the floor of fire origin, to protect people and to protect property.

MOTIVATION

Motivation for this paper has developed through recent project experience that has highlighted a growing number of examples where the interpretation and application of NFPA 130 requirements and supporting Annex materials has had significant impact on the complexity, cost, analysis requirements, and/or implementation of a project. Issues that have been observed include the following:

- Differences in interpretation of the concepts of tenability boundaries and point of safety, and associated implications relative to emergency ventilation performance analysis and criteria;
- Varying interpretations of evacuation time requirements as they relate to potential fire locations and emergency ventilation system performance;
• Uncertainty in interpreting “open station”;
• Appropriate use of models and appropriate usage in 1-D versus 3-D models; and
• Annex information related to a required distance for survivability from thermal effects being misinterpreted as applicable to visibility for purposes of wayfinding.

In addition to the above, significant variation has been observed in the approach to establishing parameters for analysis of emergency ventilation systems. Such analysis is inherently performance-based, but the assumptions and fire scenarios, which carry with them significant potential implication for system design, are often developed and implemented in absence of risk context.

An example that illustrates the importance of design fire context is the evaluation of ‘trash’ or other transient combustible fires at concourse or platform public circulation areas. Disproportionately onerous public area ‘trash’ design fires have been specified, resulting in impacts to station design and complexity as outlined below:

• In order to achieve project-defined tenability criteria for large trash fires, both platform-specific and concourse-specific smoke exhaust systems have been specified in some stations. The systems are designed to be automatically activated based upon operation of smoke detectors. Both platform and concourse exhaust modes would conflict with the train fire emergency ventilation response mode; consequently, if either system were activated by smoke detectors in the event of a train fire, occupant life safety could be negatively impacted.
• Development of a ventilation response strategy for concourse trash fires has involved the use of emergency ventilation fans serving the trackway at platform level. The fan response for concourse fires differed from the train fire response, adding complexity to the ventilation system operating modes.

In these examples, the assumption of unrealistically large fires in public circulation areas, as well as the further assumption that platform emergency ventilation conceived for train fires would be an appropriate response to such fires, resulted in increased system complexity. In the event of a train fire, this increased complexity could correspond with an increased risk of delayed initiation of ventilation response, or worse, inappropriate fan operation. Accordingly, guidance relating to design fire scenario selection and consideration of the likelihood/consequence relative to the life safety risk could further benefit the use and interpretation of the standard.

INTENT

Considering the issues discussed above, the underlying intent of this paper is to revisit the NFPA 130 requirements and annex structure/materials in an effort to help develop the standard towards a more clear and unified framework through the following areas of focus:

1. Evaluate NFPA 130 requirements and definitions to address key areas of ambiguity and where wide variation in interpretation has been observed;
2. Establish and reinforce cohesion between NFPA 130 requirements and the supporting annex material;
3. Consolidate and modernize Annex material; and
4. Update Annex material to include important context, considerations, technical references, and consideration of risk context to support performance based design principles that are currently not addressed.

APPROACH

Figure 1 illustrates key requirements and links that will need to be addressed throughout NFPA 130 in an effort to improve material related to interpretation and application of emergency ventilation system concepts.
As stated earlier, annex material in NFPA 130 does not form part of the requirements of the document, but is instead included for informational purposes to provide guidance. Information related to emergency ventilation system evaluation and design has been added over time such that it is now spread across four annexes. Some material is lacking in consistency, missing appropriate technical references, and/or missing important context for technical material or numerical values that are presented. Accordingly, the related annexes are in need of reorganization and modernization. Figure 2 presents an overview of restructuring considerations and possible direction.

Figure 1  Concept schematic outlining NFPA 130 requirements to be revisited

Figure 2  Overview of restructuring considerations for the supporting annex material
KEY CONCEPTS

Open Versus Enclosed Stations

Within the framework of NFPA 130, emergency ventilation is not required in “open system stations”. Open stations are defined as stations having a configuration that is “open to the atmosphere”, such that “smoke and heat are allowed to disperse directly into the atmosphere”. This definition applies whether the station is elevated, at grade, in a trench or depressed guideway, or of any other general configuration provided that the underlying dispersion principle is satisfied. The definition has been subject to interpretation, which is further complicated by the wording “open system station’ in Chapter 7 where the inclusion of the word “system” has been interpreted to imply consideration of the transit system as a whole. Figure 3 illustrates an example of an open, elevated rapid transit station—i.e., there are large openings above the track and at either end of the platform level.

Enclosed stations are defined as a configuration “that does not meet the definition of an open station”—i.e., a configuration where the effects of fire may spread beyond the area of origin to other portions of the station. Such stations are required to be provided with emergency ventilation. Where supported by an engineering analysis, a non-mechanical ventilation system (e.g., natural ventilation) is permitted. The inclusion of the term “system” for non-mechanical ventilation provisions has caused some uncertainty as to whether a physical ventilation system would still be required, albeit with an absence of fans. Our interpretation of the intent is that natural ventilation strategies in general would be permissible provided an engineering analysis demonstrates that the tenability criteria of the project is satisfied.

More clarity in the NFPA 130 definitions of “open station” and “enclosed station” would be beneficial to address issues of interpretation, specifically:

- Use of the term “system” should be re-evaluated;
- For both terms, it should be clarified that dispersion of smoke and heat to the atmosphere relates to minimizing the spread of the effects of fire beyond the area of fire origin and, most importantly, to means of egress serving that area; and
For “enclosed station”, the definition should provide definitive information of what “enclosed” is rather than what it is not (i.e. “that does not meet the definition of an open station”).

Point of Safety

The definition of a point of safety has generally remained consistent throughout the evolution of the NFPA 130 standard; however, some of the intended context of the concept of a point of safety has been obscured in the wording adopted for the 2010 edition of the standard (Table 1).

Table 1    Evolution of the definition of point of safety within NFPA 130 (emphasis added with underlining)

<table>
<thead>
<tr>
<th>NFPA 130 Edition</th>
<th>Point of Safety Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>An enclosed fire exit that leads to a public way or safe location outside the structure, or at-grade point beyond any enclosing structure, or other area that affords adequate protection for passengers</td>
</tr>
<tr>
<td>2007</td>
<td>In a transportation system, an enclosed fire exit that leads to a public way or safe location outside the station, trainway, or vehicle, or to an at-grade point beyond the vehicle, any enclosing station, trainway, or vehicle, or another area that affords adequate protection to passengers</td>
</tr>
<tr>
<td>2010-present</td>
<td>A point of safety is one of the following: (1) an enclosed fire exit that leads to a public way or safe location outside the station, trainway, or vehicle; (2) an at-grade point beyond the vehicle, enclosing station, or trainway; (3) any other approved location</td>
</tr>
</tbody>
</table>

The definitions prior to 2010 included clear wording related to the intent of a point of safety: an area that affords adequate protection of passengers. With the present wording this intent has been lost. An updated definition is needed to clarify to practitioners and authorities having jurisdiction what is intended to be the basis for the general term “any other approved location”, provide cohesion with the rest of the standard and the supporting annex material, and reinforce the current wording in Section 5.3.3.3 of the standard:

5.3.3.3 For stations where the concourse is protected from exposure to the effects of a fire at the platform by distance, geometry, fire separation, an emergency ventilation system designed in accordance with Chapter 7, or as determined by an appropriate engineering analysis, that concourse shall be permitted to be defined as a point of safety.

Given the above information, the definition of a point of safety should be updated to make it explicitly clear that an intermediate location within a station (such as a concourse) that is protected by an emergency ventilation system for a period of time greater than the required time of tenability can be considered a point of safety.

Evacuation Times

Chapter 5 of NFPA 130 outlines requirements relating to evacuation times in two contexts: a platform evacuation time of 4 minutes or less, and evacuation from the most remote point on the platform to a point of safety in 6 minutes of less. The 4 minute platform clearance time is intended for determining the size and location of platform egress routes based on simple arithmetical calculations of occupant load versus flow rates and travel speeds. The 6 minute timeframe is a function of the platform evacuation time plus the travel time to reach an area that is protected from the effects of the fire.

The evacuation timeframes in these requirements are established as a baseline to correspond with a required level of performance relating to egress from the fire area (the platform) to a protected area.
(point of safety). As stated in the annex material attached to these requirements, it is not intended that the times be required to account for delays due to impacts of combustion by-products, pre-movement time of occupants, delays due to movement of those who are unable to achieve self-evacuation, or other factors.

For emergency ventilation analysis, the implication is that, for station designs that comply with the 4 and 6 minute requirements, tenability is to be evaluated along means of egress from the point at which occupants leave the platform. Accordingly, performance of the emergency ventilation system should be focused upon (1) maintaining the means of egress leading from the platform tenable, (2) protecting the concourse such that it is a point of safety for evacuating occupants, and (3) evaluation of life-safety criteria at emergency waiting areas, areas of refuge, or relative to other provisions for occupants who are unable to self-rescue where applicable. Including this interpretation of the relationship between the 4 minute and 6 minute evacuation time criteria and emergency ventilation system performance would assist in clarifying the application of related NFPA 130 requirements. Further discussion regarding tenability criteria and occupants who are unable to self-rescue is provided later in this paper.

Emergency Ventilation Objectives

Stations are primarily pedestrian connections to and from trains at platforms. NFPA 130 supports that functionality by permitting interconnections between various station levels and allowing stairs and escalators to remain open. Additionally, NFPA 130 permits those open stairs and escalators to be counted as contributing to the required egress capacity. For enclosed stations, the emergency ventilation system provides an alternative to fire separation of those egress routes. NFPA 130 requires stations to be of noncombustible construction and limits the combustibility of finishes and furnishings. As such, trains are reasonably considered to be the most significant potential fire source in a station. (Refer also to the discussion under ‘Fire Scenarios’ later in this paper.) Accordingly, the fundamental objective for an emergency ventilation system in an enclosed station is to provide protection for passengers evacuating from a train fire.

In order to comply with the requirements of NFPA 130, an emergency ventilation system in an enclosed station will protect evacuation routes as follows:

1. Exhaust smoke from a train fire while drawing in fresh make up air through the station along the means of egress. (Air will also be drawn in from the adjacent tunnels, the proportion of which needs to be accounted for with appropriate boundary conditions in the engineering analysis.)
2. Maintain tenability of the means of egress serving the platform (i.e., the stairs and escalators).
3. Provide protection for areas where evacuating passengers may accumulate (i.e., point(s) of safety).

A simplified schematic of an enclosed station configuration illustrating the above objectives is provided in Figure 4.
Figure 4  Simplified schematic illustrating general objectives of an emergency ventilation system in a typical station configuration

The linking of emergency ventilation system objectives as described above to other NFPA 130 parameters, such as the concept of a point of safety and associated implications for emergency ventilation system performance on evacuation time, is ambiguous. Providing better cohesion between the requirements of Chapters 5, 6 and 7 and the supplementary guidance in the annexes would serve to limit the variation in interpretation and application that is observed from project to project. Subsequent sections of this paper discuss potential improvements in this regard.

TENABILITY CONSIDERATIONS

A remaining factor in engineering analysis that is subject to interpretation and variation in application is tenability criteria and areas in which tenability is evaluated.

The definition of a tenable environment has evolved over the history of the NFPA 130 standard. Originally defined as ‘an environment that supports human life for a specific period of time’, the definition was revised in 2003 to ‘an environment that permits the self-rescue of occupants for a specific period of time’. The documentation for this change indicates that the revision was intended to recognize that maintaining the conditions necessary for occupants to self-evacuate is more stringent than maintaining those relating to life safety, such as thermal effects and toxicity.

For most projects, tenability criteria are typically defined for visibility, temperature, radiant heat, and toxicity. With the addition of expanded discussion of application of tenability in the Annex material and the introduction of additional considerations such as the time required for emergency responders to sweep the station for occupants that are unable to self-rescue, the intent of the application of the different aspects of tenability have been blurred. For the majority of fire characteristics that would be considered for a rapid transit station analysis, visibility (such as 10 m to walls/doors, or 30 m to light emitting signs as described in Annex B of the standard) represents the most onerous of the tenability criteria. In general, the temperature and toxicity criteria are not expected to be near their respective tenability limits where the visibility criterion is satisfied. Accordingly, visibility is the criterion that will result in an area being considered ‘untenable’ prior to the other criteria reaching their limits.

The visibility criterion is established with the more recent NFPA 130 definition of tenability in mind; such that the wayfinding of occupants is sufficient to facilitate self-rescue. In contrast, the temperature, radiant heat, and toxicity criteria are established based upon the impact on the survival of occupants (Table 2).

<table>
<thead>
<tr>
<th>Tenability Criterion</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visibility</td>
<td>Wayfinding</td>
</tr>
<tr>
<td>Temperature and Radiant Heat</td>
<td>Survivability</td>
</tr>
<tr>
<td>Toxicity</td>
<td>Survivability</td>
</tr>
</tbody>
</table>
Passengers Able to Self-Rescue

For the evacuation of ambulatory passengers who are able to use all available egress routes for the purposes of egress, visibility evaluated in accordance with the information in Annex B of NFPA 130 is generally the most onerous tenability criterion as they locate and navigate the means of egress. The visibility criteria is most directly applicable where passengers are locating and moving towards exits. For transit station platforms that are designed in accordance with the means of egress requirements in NFPA 130 related to travel distance and maximum length for ‘dead ends’, travel times will be relatively short and the majority of the platform clearance time will be driven by queueing. Where occupants are queued at the base of stairs or escalators, the required wayfinding capacity to continue onto the means of egress is limited and criteria specific to visibility of 10 m to walls and doors and 30 m to a light emitting exit sign is less relevant than survivability criteria of thermal effects and toxicity. The visibility criteria are therefore applicable to:

1. Navigation and way finding on the means of egress (i.e., stairs and escalators) serving the platform, and
2. Egress paths to a point of safety (i.e., the concourse).

Passengers Unable to Self-Rescue

In the context of evacuation of occupants from a rapid transit system, those who are potentially unable to self-rescue in the event of a fire would be passengers with a physical condition or disabilities that would impair their ability to navigate non-accessible egress routes. In the absence of a barrier free path of travel, these occupants will require assistance from emergency personnel in order to evacuate. Measures that could be incorporated in the design of a system to address life safety for passengers unable to self-rescue could include:

1. Implementation of emergency waiting areas where the survivability criteria can be maintained,
2. Implementation of areas of refuge that provide a physical barrier between occupants and the effects of fire, or
3. Continued operation of elevators during an emergency to provide a barrier-free path of egress for non-ambulatory passengers up to the period where the elevator may be compromised by smoke.

NFPA 130 currently has limited guidance relating to occupants who are unable to self-rescue. Section B.2.3 of Annex B includes “the time for emergency personnel to search for, locate, and evacuate all those who cannot self-rescue” as a factor that should be considered in establishing the time of tenability; however, there is significant variation in interpretation of how tenability is considered within this context. These considerations warrant further clarification within Annex B, and increased technical substantiation of how time of tenability should be evaluated. Context for the response and deployment time for emergency personnel should come from documents and standards NFPA 1710 (Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments) and input from the appropriate fire departments or first responder personnel.

Geometric Considerations

There are a number of geometry considerations that relate to how tenability is evaluated within an engineering analysis. This discussion focuses on two of those: height and boundary.

In conventional buildings, tenability criteria are typically evaluated at a height that is intended to be representative of occupant head height. In previous editions of NFPA 130, the Annex B guidance material referenced an evaluation height of 2.5 m (8.2 feet), considering an occupant height of approximately 2.0 m (6.6 feet) with a 25% safety factor to account for modelling accuracy. This evaluation of increased occupant height, to account for modelling uncertainty and accuracy, correlates with consideration of a defined smoke layer height. However, in transit stations with emergency
ventilation system operating, typically with large quantities of air moving longitudinally with respect to concourses and platforms, the concept of a defined smoke layer is flawed. Instead, tenability should be evaluated at a representative occupant height and model uncertainty or accuracy should be evaluated or accounted for with other means, such as appropriate sensitivity analysis. These considerations highlight the importance of engineering analysis being conducted by engineers with sufficient knowledge and experience in the applied methodologies. On this basis, it is suggested that the NFPA 130 guidance is updated to be consistent with other documents and standards, such as the International Building Code, which stipulates a 1.8 m height for evaluation of tenability.

Annex B of NFPA 130 currently contains discussion regarding geometric measures relative to tenability, including a general statement regarding application of tenability criteria beyond the perimeter of the fire. Specifically, Section B.2.2 states that the application of tenability criteria at the perimeter of the fire is impractical, and therefore the zone of tenability should apply at some distance away from the perimeter of the fire. An example is given, stating that the boundary could be as much as 30 m (100 feet). The 30-metre boundary measure, introduced in the 2003 edition, was not based on scientific rationale but rather on precedence in design of some unidentified transit systems (Figure 5).

Of key importance, this wording was specific to temperature and thermal exposure; the survivability tenability criteria. In practice, this 30 m value has been applied to evaluation of visibility on the platform, establishing a hard limit of 30 m from the incident vehicle where visibility must be maintained for wayfinding. Additionally, this distance value has been interpreted as an absolute requirement, rather than a general guideline to be considered within the context of several other factors mentioned in the surrounding Annex wording.

The observed use of this value as a tenability limit resulted in updated wording in the 2014 edition of NFPA 130, with additional substantiation added to clarify the intended application to thermal exposure and radiation. However, recent experience has shown that this revision has been insufficient to mitigate interpretation of this value as a hard limit applied to all tenability criteria, including visibility for wayfinding. This interpretation can result in highly onerous tenability criteria that is not believed to be intended by the original introduction of this annex wording, and has the potential to directly impact the design and complexity of the emergency ventilation system. Accordingly, it is suggested that the Annex B wording be revised to remove general distance references that are easily taken out of context.

New Material Appendix B: The tenability criteria should not be applied in the immediate vicinity of a fire. The precision offered by computer modeling methods, such as CFD, allows estimation of the temperatures in the proximity of the fire. This gives rise to the issue that the maximum tenability temperature criteria (usually 140°F (60°C)) will be violated within a certain distance from the fire. A number of projects have allowed the temperature criterion to be violated by as much as 100 feet (~30 m) from the perimeter of the fire. The reasoning is that those who can not self-rescue will be moved at least that distance by others. Since this tenability distance may vary as a function of the fire heat release rate (and time), qualitative wording addressing this issue should be added to the definition of tenable environment.

Figure 5 Excerpt of May 2003 ROP, outlining the substantiation for the inclusion of the 30 m (100 feet) Annex B wording for the 2003 edition of NFPA 130
CONSIDERATION OF RISK IN THE DESIGN PROCESS

Risk is the combination of probability of occurrence and potential consequence (or severity). In an engineering analysis of emergency ventilation system performance, the design fire scenario that is defined represents a specific level of risk that is being used for the purposes of design. In a given project the analysis assumptions, design fires, model parameters, and acceptance criteria all contribute to the inherent risk. Zero risk is not an achievable goal, and the concept of absolute safety is not obtainable.

Evaluating specific design fire scenarios relative to performance and tenability objectives is inherently performance based design. The SPFE Guide for Performance Based Fire Protection [3] provides guidance relative to establishing credible scenarios and taking consideration of the potential impact on the design given appropriate risk context:

“\textit{A design fire scenario that is highly improbable and too conservative can lead to an uneconomical building design, which can cause the building not to be built or be functional. On the other hand, a design fire scenario developed using a non-conservative approach, e.g., a long incipient phase or a slow rate of fire growth, could lead to a building design in which there is an unacceptably high risk to occupants.}”

The International Fire Engineering Guidelines [4], produced through a collaborative effort involving the National Research Council of Canada (NRC), the International Code Council (ICC) in the United States, the New Zealand Department of Building and Housing (DBH), and the Australian Building Codes Board (ABCB), also provides guidance regarding to the determination of design fire scenarios:

“\textit{Usually, a number of severe scenarios which have a reasonable probability of occurrence and significant potential for loss (life, property, etc.) are selected for analysis. Care and judgement should be used to avoid unnecessarily analysing events with a very low probability of occurrence, but where the scenario may have very high adverse consequences, due consideration should be given if not for the primary analysis at least in the sensitivity studies.}” [1.2.11.2]

“\textit{For the purposes of sensitivity studies, less rigorous factors of safety may be appropriate in order to avoid overly conservative outcomes.}” [1.2.10.2]

Key analysis parameters, such as the design fire, will depend on what is considered as acceptable risk.
for the purposes of design, which may vary depending on the jurisdiction or project. Establishing analysis assumptions and performance criteria that are based upon those specific objectives is fundamental to establishing acceptable risk and is a collaborative process.

The underlying principle of risk analysis is an evaluation of probability and potential consequence to establish an estimate of risk relative to acceptance criteria, using a range of possible qualitative or quantitative approaches. ISO 31000 defines the level of risk as the “magnitude of a risk, or combination of risks, expressed in terms of the combination of consequences and their likelihood.”

Risk Analysis Applications and Methodology

Discussion of risk, risk analysis, and the implications on the design process is absent from the current Annex material of the NFPA 130. Methodologies for risk analysis are well established, such as those outlined in NFPA 551 (Guide for the Evaluation of Fire Risk Assessments) [5], ISO 31000, (Risk Management – Principles and Guidelines) [6], and MIL-STD-882D (Department of Defence Standard Practice for System Safety) [7], and are readily applied in other applications and industries.

Risk analysis is explicitly required for road tunnels in the Trans-European Road Network by the European Directive 2004/54/EC [8]. A range of risk analysis methods are applied by different countries [9]. In this context, a general risk analysis process is summarized in the PIARC schematic shown in Figure 7.

![Figure 7](image)

**Figure 7**  Risk analysis overview from PIARC document [8]

The American Public Transportation Association (APTA) has a recommended practice for fire safety analysis using risk methodologies for passenger railroads as a result of requirements introduced by the Federal Railway Association. PR-PS-RP-005-00, *Recommended Practice for Fire Safety Analysis of Existing Passenger Rail Equipment* [10], provides a risk analysis methodology for all categories of passenger railroad equipment and service based upon information introduced in 49 CFR Section 238.103(d) [11]. An important consideration is outlined in the recommended practice document:

“APTA believes that passenger railroads must recognize that a fundamental feature of this approach is that some residual risk must be accepted.”
The APTA Recommended Practice document outlines a risk evaluation methodology based upon MIL-STD-882-D, in which hazard severity and probability are categorized with numerical values, and corresponding risk is assessed with a risk index. This approach is consistent with material in NFPA 551 (MIL-STD-882-D and the risk matrix method is referenced in Annex A of NFPA 551), and the SFPE Guide for Performance Based Fire Protection. The overall concepts of the APTA document are consistent with the information outlined in ISO 31000. Application of this type of risk index methodology is illustrated conceptually in Table 3 and Table 4. The concept of risk already exists in the rapid transit and passenger rail industry. The SFPE Handbook [12] provides a discussion of fire risk in mass transportation applications.

**Table 3**  Example of Risk Scoring Matrix.

<table>
<thead>
<tr>
<th>Probability</th>
<th>5 - Frequent</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 - Probable</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>3 - Occasional</td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>2 - Remote</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>1 - Improbable</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

**Table 4**  Example of Risk Score Descriptions.

<table>
<thead>
<tr>
<th>Risk Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-25</td>
<td>Unacceptable: Poses immediate threat to personal safety.</td>
</tr>
<tr>
<td>8-12</td>
<td>Acceptable short-term: May pose a threat to personal safety.</td>
</tr>
<tr>
<td>4-6</td>
<td>Acceptable with management review: Deemed acceptable or unavoidable risk after review by key stakeholders.</td>
</tr>
<tr>
<td>1-3</td>
<td>Acceptable: Deemed to be an acceptable risk.</td>
</tr>
</tbody>
</table>

**FIRE SCENARIOS**

Design fires are selected to represent conservative, but credible fire scenarios with respect to the anticipated fire hazard and building occupancy. The original basis of the emergency ventilation system requirements in NFPA 130 relates to a train fire occurring within the station. Over the evolution of the standard since its inception in 1983, piecemeal additions to the annex material have introduced reference to many other types of potential fire scenarios. However, technical context and substantiation for these additional scenarios has not been incorporated and related discussion has spread amongst multiple annexes that address similar considerations.

**Train Fires**

Modern rapid transit stations that are compliant with NFPA 130 are of noncombustible and fire hardened construction. Within this environment a train fire represents the most significant fire hazard.

The development of a fire inside a train vehicle is dependent on a number of factors, including the fire performance of interior finish materials, the size and location of the initiating fire, the size of the enclosure where the fire is located, the interconnection of train cars, and the ventilation into the enclosure. A limited number of full-scale train fire tests and estimates from actual fire incidents have yielded data regarding heat release rate and growth behaviour, and some references to the findings of these tests have been included in Annex H of NFPA 130. However, the technical context of the full scale tests are absent from the current Annex material, and deriving conclusions from this data in the absence of context has the potential to result in design fire sizes that may not correlate with credible fire scenarios for a given system. The peak fire sizes and burning characteristics reported from full scale fire testing of a specific rail vehicle inherently contains assumptions relating to the specific material ignition properties, the igniting scenario and location, ventilation conditions within the...
vehicle, and the overall train configuration.

The suggestion is that the updated material include important context associated with each citing of fire test results such as legacy train materials present on the vehicles, longitudinal tunnel ventilation conditions that may not be representative of conditions for a train stopped at a station, and the size of ignition sources. This would aid users of the document to have a better understanding of the referenced material in their determination or evaluation of design fires.

Public Area/Trash Fires

Experience has shown that the specification of public area fire scenarios involving trash or other transient combustibles has become more apparent in the engineering analysis for emergency ventilation systems in rapid transit stations. The NFPA 130 requirements and Annex material do not directly address the use of emergency ventilation for fires involving transient combustible material, outside of general reference to potential trash scenarios in Annex A and H.

The risk related to these types of fires is addressed through provisions within NFPA 130, such as non-combustible construction, limited flame spread behaviour of interior finishes, restriction of combustibles in public areas (such as seating and trash receptacles), and compartmentation of other occupancies that may interface with the public areas of the station. Accordingly, where such measures are implemented, public area concourse and platform fires would be limited to an individual trash bin, or other accumulated transient materials and potential fire sizes would be expected to be on the order of 0 to 300 kW [13,14,15,16,17]. However, experience has shown that increasingly large public area trash fire scenarios, ranging from 1.0 to over 2.0 MW, are being specified for projects, and these design fire assumptions are having direct impacts on the complexity of emergency ventilation systems and operational response modes. As discussed earlier in this paper, this increased complexity could result in an increased likelihood for delayed initiation of ventilation response in the event of a train fire, or worse, inappropriate fan operation.

In consideration of the above information, the Annex material of NFPA 130 would warrant updates to include appropriate context and technical references relative to the trash and transient material fire scenarios that are currently identified in a general sense in Annex A and H.

Selection Methodology

Given the importance of context and the identification of conservative but credible design fire scenarios, a more scientific but generalized approach would benefit the design fire selection process. An example of a suggested methodology is outlined below:

1. Evaluate and identify potential fire scenarios.
2. Evaluate probability and potential consequence for identified fire scenarios.
3. Evaluate/rank risk and obtain stakeholder input to establish a reasonable and credible risk profile for the purposes of design.
4. Perform an engineering analysis of the emergency ventilation system relative to project objectives, design fire scenarios, and acceptance criteria corresponding to the established design risk profile.

The application of this type of methodology to a modern transit system operating only modern vehicles (i.e. no existing legacy vehicle fleet) that are compliant with NFPA 130 is summarized conceptually in Table 5, where the risk profile for the purposes of design for the specific project is established using risk evaluation and assessment approaches such as those discussed earlier in this paper.
Table 5  Selection methodology example relative to establishing design fires.

<table>
<thead>
<tr>
<th>Approximate Severity/Consequence</th>
<th>Likelihood</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insignificant</td>
<td>Frequent</td>
<td>Station public area/transient combustible fire. Risk addressed by provisions restricting combustible content and measures reducing propensity for fire spread. Minor fires dealt with through operational procedure/protocol</td>
</tr>
<tr>
<td>Severe</td>
<td>Remote</td>
<td>Train fire: large ignition source resulting in fire development to adjacent combustible materials within the train, fire spread involving a portion of the vehicle</td>
</tr>
<tr>
<td>Catastrophic</td>
<td>Improbable</td>
<td>Train fire: extreme ignition source sufficient to drive fire development throughout the vehicle, with sufficient conditions and ventilation to result in full vehicle involvement</td>
</tr>
</tbody>
</table>

This type of methodology would require project specific considerations where aspects of perceived risk, or what is considered to be acceptable risk, may be subject to key stakeholder considerations; including issues such as arson or terrorism.

SUMMARY

Material in NFPA 130 related to emergency ventilation within stations has evolved and grown throughout the 12 revised editions of the standard. Recent project experience has highlighted aspects of the current standard—including definitions, requirements and associated informational annex material—that are subject to variations in interpretation, which have been observed to have direct impacts on station design and system complexity.

In this review, the requirements and supporting annex information were revisited with the objective of identifying potential improvements to clarity, consistency and a unified framework throughout the standard. From this process, the following recommendations were outlined:

1. Review the consistency of requirements related to the provision and design of emergency ventilation throughout the Standard. Create cross-references to enhance cohesion.
2. Improve definitions for Open/Enclosed and Point of Safety to clarify intended interpretation and application.
3. In Chapter 5, clarify the intended interpretation of prescribed evacuation times vis-à-vis evaluation of tenability.
4. In Chapter 7, clarify the intent with regard to the required ‘zone’ of tenability.
5. Re-organize, consolidate and update annex material related to emergency ventilation to include technical references, consistent context, and to reflect current industry knowledge.
6. Introduce the concept of risk, especially with regard to design fires, similar to other transportation standards.
REFERENCES

Craeybeckxtunnel: from fire test to new ventilation strategy

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¹Fire Engineered Solution Ghent, Ghent, Belgium
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ABSTRACT
The current paper presents the existing and the upgraded ventilation system in the Craeybeckxtunnel, a 1600 m long road tunnel in Antwerp, Belgium. The tunnel is equipped with a semi-transversal ventilation system, which was designed for daily ventilation purpose. A series of fire test was performed in 2014 in order to evaluate the capabilities of the installed ventilation system to confine the smoke in case of fire. CFD simulations were performed before performing the experiments in order to evaluate the reliability of the numerical results. After the tests, the authorities decided to renovate the ventilation system and to install a longitudinal ventilation system. The paper discusses the different steps in the design of a longitudinal ventilation system. The design of the upgraded ventilation system in the Craeybeckxtunnel is made with a one-dimensional approach (IDA tunnel) and later validated with a CFD model (FDS). While the 1D-model performs fast calculation using some approximations for the simulation of three dimensional flows, FDS performs slower calculations with higher accuracy. The results of the two models have been compared together showing some remarkable differences regarding the heat exchange modelling and the treatment of three dimensional flows near the fans. In the 1D-model the temperature remained higher along the tunnel compared to FDS, this induces higher pressure losses due to friction and lower pressure rise at the fan downstream the fire. The performance of the jet fans in the 1D-model are overestimated if the mutual interaction of the jet fans is neglected a better estimation can be obtained by reducing the efficiency of 25%. The decay velocity tends to increase for multiple jets in parallel and increasing the co-flow velocity. It has been shown in the Craeybeckxtunnel that a verification of the tunnel ventilation design by a tridimensional calculation is necessary.

KEYWORD: Fire testing, ventilation design, FDS

INTRODUCTION
The Craeybeckstunnel is a 1600 m long road tunnel located in Antwerp in the north of Belgium [1-4]. The tunnel, which was built in 1970, consists of two unidirectional tubes, each is 11.5 m wide (four traffic lanes) and 6.3 m high. Originally a semitransversal ventilation strategy has been installed, mainly for daily ventilation. In 2013 the authorities decided to conduct fire tests to study the performance of the ventilation system. It was decided to perform a CFD study before the actual test to determine the predicting capability. Further, based on the results of the fire tests, it was decided to upgrade the ventilation strategy. The new ventilation strategy is later designed with a 1D model and verified with detailed 3D simulations to assess its performance.

ON SITE FIRE TEST OF ORIGINAL VENTILATION DESIGN
While the majority of ventilation systems in road tunnels are longitudinal or transversal, [5,6], the ventilation system in the Craeybeckxtunnel is atypical. Here, the smoke is extracted at the lowest point and the fresh air is supplied at the highest point, which is not optimal for the stratification. The ventilation system was not designed for fire situations. It consists of a total of 128 fans (each with a flow rate of 30 m³/s), uniformly distributed over both tubes. The cross-section of the tunnel and the principle of ventilation can be seen in the figure below.
In the beginning of 2013 the authorities decided to conduct fire tests representing a car fire to study the performance of the ventilation system. Performing a full scale test with a large fire (>10 MW) would be expensive in terms of monetary value and also could damage the structural integrity of the tunnel. To avoid these concerns, a controlled fire load would be used for fire testing. Two fire loads were proposed. The first one is a pool fire with a mixture of 40l of gasoline and 20l of diesel in a 1.5m² pan, based on guidelines for fire tests in Austrian tunnels (Figure 1). The second fire is a mock car with wood pallets inside, currently used by fire brigade for training purposes. Based on the burning surface, the heat release rate was estimated to be around 3 to 3.4 MW.

A PRIORI CFD SIMULATION ON SMOKE SPREAD

It was decided to perform a CFD study before the actual tests to determine the predicting capability of the CFD. The scenario considered by the authorities were chosen to minimize the effects from different variables. Certain simplifications were made (e.g. imposed fixed HRR as a pool fire on height of window openings instead of wood pallets) and only 2 ventilation scenarios (combination of extraction points and air supply in tunnel) with steady ventilation were modeled in CFD at this stage. For practical reasons, the ventilation was started first and when steady-state conditions were reached, the fire was ignited by the fire brigade.

The tunnel is divided into three sections roughly 500m each, and in these 2 scenarios the ventilation

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1 Usually due to the number of variables involved, a CFD study is performed afterwards to compare the data with the measurements during the experiments.
of the north section (fire) was set to 100% manually (in scenario 2 the supply close to the fire was shut down). The simulations do not take into account the effects of wind and the fire was lit when the ventilation has already turned into regime. This reduces the uncertainty due to changing flow profile.

As explained earlier, the supply point is located at the top height of the tube and the extraction points are at the bottom of the tube. The tunnel is 1600m long with 64 supply and extraction vents uniformly distributed which results 50m distance between each supply point and similarly for the extraction vents.

Each supply/extraction vent on average has a flow rate of $27m^3/s$ and using the correct effective area results in a velocity of $9m/s$ at each point. During the site visit it was also noted that the supply vents have an angled flow due to the location of supply vent in between 2 extraction vents. These measured values were also implemented in the CFD model, Figure 2.

![Elevation Top view](image)

**Figure 2 Angle of supply vents.**

As mentioned earlier the CFD calculations were only performed before the results of the actual fire tests on 15th November, 2014 were known. As a consequence, this is a good measure of the predictive capabilities of CFD. The CFD results indicate that for a 3.4MW fire, the north section (fire zone) was filled with smoke within 5 minutes from the start of the fire, Figure 3.
Similar smoke spread was observed during the actual fire experiment which confirms the results from the CFD study, Figure 4. Taking into account all uncertainties (unknowns) and important phenomena, the CFD results in terms of temperature measurements (thermocouple trees close to the fire and infrared cameras) and smoke spread (compared to video image and visual observations) can be considered to be accurate.
Due to the atypical ventilation system, the temperature profile (Figure 5) at the location of fire shows that closer to the floor level the temperature is higher compared to the temperature closer to the ceiling. This is due to the extraction performed closer to the floor level. This also results in smoke spread at lower heights which hinders the evacuation. The results at the height of 2m shows that the even after 2 minutes for a small fire of 3.4MW, the visibility is less than 10m in close vicinity of the fire. The visibility is reduced further in the section 150m in both upstream and downstream after 5 minutes.

For a fire load of approximately 3MW, the CFD results and the observations during the actual tests show good agreement which strengthen the trust in the CFD simulation and correct use of the sub-models. Increasing the fire load will reduce the efficiency of the ventilation system even greatly.

From the CFD study we can conclude following 2 main points:

1. Even with the unknowns and uncertainties, the CFD results show good similarities with the fire test and predicts the important phenomena correctly (smoke spread, temperature etc.). The comparison was done using the temperatures near the fire and the visual observation of smoke spread [1].
2. Based on the 2 scenarios where the ventilation was 100% active in the fire zone, the smoke spread and visibility does not support tenable conditions after 5 minutes in 150m section on both sides of the fire (3.4MW).
DESIGN OF A NEW VENTILATION SYSTEM

Due to the low effectiveness of the semitransversal ventilation installed it was decided in 2015 to design a new and effective ventilation strategy. In order to keep the refurbishment costs under control a longitudinal ventilation strategy was chosen by the end client [5-6].

One important boundary condition of the new ventilation design, was to try to limit the need for pressurising the emergency exits. Several alternatives were studied and the flow field in the tunnel was simulated with a one-dimensional model, IDA for the new design [7-8]. The installation of new boosters in the tunnel has to meet several constrains related to the evacuation process and the available space beneath the ceiling.

The jet fans installed in the tunnel should have a limited size and the tunnel should have a pressure lower than the atmospheric value. The low pressure in the tunnel is necessary to avoid the smoke to spread in the emergency exits on the side of the tunnel. The current constrains limited the possible locations of the boosters in the tunnel, and the design study showed that the jet fans should be located near the exit in order to induce an underpressure along the tunnel. The tunnel has been equipped with four jet fan batteries, which can be activated depending on the fire scenario. One battery is located at the inlet portal while the other three batteries are located near the outlet. This solution allows to keep the tunnel in undepressure and to drag fresh air from the emergency exits which work as short cuts for

<table>
<thead>
<tr>
<th>Time</th>
<th>Visibility at 2m height (North section only)</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0m, 500m</td>
<td>150m</td>
<td>350m</td>
</tr>
<tr>
<td>60s</td>
<td>30.0</td>
<td></td>
</tr>
<tr>
<td>120s</td>
<td>28.0</td>
<td></td>
</tr>
<tr>
<td>300s</td>
<td>26.0</td>
<td></td>
</tr>
<tr>
<td>480s</td>
<td>24.0</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 6 Visibility at 2 m height in the North section.*
the ventilation system and reducing its efficiency. The different design steps are discussed below.

**One-dimensional model**

Tunnels are often considered as one-dimensional structures due to the size of their length compared to the other two dimensions [6]. The properties of the fluid are assumed to be uniform along the cross section of the tunnel and to vary only along the longitudinal direction. The spatial domain is discretized with one dimensional elements which represent branches of the tunnel with an associated area and length. These elements are connected among them by nodes where two or more branches converge. The equations describing the motion of the fluid along the tunnel are the same controlling a tridimensional flow but they are written as function of one variable [7-8]. The continuity equation describes the conservation of the mass in one branch or in one node. The momentum equation describes the balance of inertial and external forces along a generic branch. The energy equation describes the balance of heat fluxes and internal energy of the fluid. The one-dimensional form of the Navier Stokes equations doesn’t allow to include any tridimensional effect. These are taken into account in a simplified way as it is done in the Bernoulli equation using pressure loss coefficients [8].

In the emergency stairways the pressure loss coefficient is calculated considering 3 U-turns along the shaft which represent the stairs. Near a jet fan the flow field is fully tridimensional because of the large eddy growing beneath the jet fan. The pressure rise doesn’t occur at the jet fan section, but is related to the decay distance [9-10], this cannot be depicted by the one-dimensional model and the pressure rise is applied as concentrated force. The pressure rise induced by a jet fan is calculated based on the momentum conservation, equation (1).

\[
\Delta P_{\text{fan}} = \rho \frac{A_f}{A_t} k_j u_f (u_f - u_t)
\]

Where \(u_f\) is the discharged velocity of the fan \(A_f\) is the area of the fan \(A_t\) is the area of the tunnel and \(u_t\) is the velocity of the tunnel. The efficiency \(k_j\) is function of the position of the jet fan, this has been estimated in experimental works [9,10,11,13] and is reported as function of the position and of the distance between the fan and the wall. The installation efficiency is initially estimated basing on the correlations for a single jet fan. The efficiency is later reduced to consider the mutual effect of the jet fans and the short distance between the batteries.

In the fire region due to the mixing of fresh air and smoke there are additional pressure losses which cannot be depicted, since they are fully three-dimensional. In the 1D model the pressure loss induced by the fire is proportional to the HRR and equal to 0.1 Pa per MW of fire [14-15].

The 1D approach has some limitations due to the lack of accuracy in the parts of domain where the flow is three-dimensional, however it is the most applicable tool for design process thanks to its low computational cost, allowing to investigate many design options and sensitivity studies.

**Tridimensional modelling**

After the design phase done with the 1D model, the proposed solution is investigated with a more sophisticated tool. Computational fluid dynamics (CFD) relies also on the Navier Stokes equations, but these are solved in a tridimensional domain. For the Craeybeckstunnel the CFD code Fire Dynamic Simulator (FDS) is chosen because of its specific development for fire safety problems [16]. FDS solves the equations of Navier Stokes with a low Mach number approach and the flow is assumed to be incompressible [17]. The interested reader can find a comprehensive description of the models implemented in the FDS technical guide [17].

FDS is more accurate than the 1D model in the simulation of the flow field, but it requires also a much higher computational time. With the current available computational power, it is not possible to design a new tunnel with CFD because this toll is still too time consuming. However, it is a valuable help to evaluate the effectiveness of the proposed solution.

The new design has to meet the following targets:

- Confine the smoke downstream the fire
- Keep the egress ways clear of smoke
• Size the jet fans in order to leave enough space for the vehicles
• Use the minimum amount of jet fans

The present objectives are in conflict among each other and the new proposed solution should be effective for every position of the fire. The design fire for the ventilation system was determined by the client to have a HRR of 100 MW [18]. The fire load is placed in the center of the tube and later is moved along the tunnel in order to evaluate the effect of its position. The proposed solution is to install batteries of jet fans near the exit portal in order to have a pressure lower than the atmospheric value and a battery at the inlet. The features of the ventilation devices are presented in Table 1.

Table 1  Jet fans’ features.

<table>
<thead>
<tr>
<th>Battery location [m]</th>
<th>Fan discharge velocity [m/s]</th>
<th>Number of Jet fans</th>
<th>Diameter of the fan [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>27.58</td>
<td>3</td>
<td>1250</td>
</tr>
<tr>
<td>1450</td>
<td>15.38</td>
<td>4</td>
<td>500</td>
</tr>
<tr>
<td>1450</td>
<td>22.63</td>
<td>4</td>
<td>630</td>
</tr>
<tr>
<td>1450</td>
<td>20.15</td>
<td>1</td>
<td>900</td>
</tr>
<tr>
<td>1500</td>
<td>25.97</td>
<td>8</td>
<td>710</td>
</tr>
<tr>
<td>1500</td>
<td>20.15</td>
<td>1</td>
<td>900</td>
</tr>
<tr>
<td>1550</td>
<td>23.55</td>
<td>8</td>
<td>1000</td>
</tr>
<tr>
<td>1550</td>
<td>20.15</td>
<td>1</td>
<td>900</td>
</tr>
</tbody>
</table>

The battery at the inlet will only be activated for a fire scenario at a certain distance of the tunnel inlet, in order to guarantee the critical velocity. The battery at the inlet cannot be activated for a scenario close to the inlet portal, due to the resulting overpressure over the first couple of 100 m. When the jet fans are installed near the exits there are some critical aspects to take into account: the distance between the batteries and the distance from the exhaust portal. The pressure rise induced by the fan is not occurring in the jet fan section as a sudden pressure jump, but the pressure increases gradually as the high-speed jet decays and the momentum is transferred to the main flow field [9]. Therefore, if two jet fan batteries are too close to each other or they are too close to the exit portal the high-speed jet is not fully decayed and part of the induced momentum (or pressure rise) is lost. This loss of momentum transfer (or pressure) cannot be depicted with a 1D model because, as seen before, the effect of the jet fans is taken into account as a sudden pressure jump, equation (1). The designer has to leave sufficient space between multiple batteries of jet fans in order to limit this effect. In the Craeybeckstunnel, due to geometrical constraints (the ceiling height is not constant) it was decided to install three batteries near the downstream portal at 1450 m, 1500 m and 1550 m. The last one being at only 50 m from the portal. The one battery near the upstream portal was installed at 50 m from the portal. The jet fans are activated depending on the operating conditions of the tunnel, in particular depending on the location of the fire. The main tunnel is connected to the outside through emergency doors and through the stairway shafts. The doors are located on the outer side of the tunnel at different longitudinal positions: +75 m, +175 m, +275 m, +375 m, +475 m, +575 m, +675 m, +775 m, +875 m, +975 m, +1075 m, +1175 m, +1275 m, +1375 m, +1475 m from the inlet portal. In the scenarios described below the doors located downstream the fire have been considered closed when studying the ventilation. While the stairway shafts upstream the fire are considered open to allow the egress of people trapped upstream the fire. In the models the portals are considered open with no wind, the pressure is fixed at 101325 Pa. The ambient temperature is set at 15 °C in every case.

In the one-dimensional model the spatial discretization of the model was done within the program, but for FDS the mesh is drawn by the user. The most critical regions of the simulations are those near the fire and near the jet fans where the flow is strongly three dimensional. The mesh size in the region near the fire and near the jet fans is 0.25 m while far from them the mesh size is 0.50 m or 1.00 m. The mesh is designed to have multiple blocks in order to reduce the computational time and to speed up the simulation.
Analysis of selected scenarios
Several cases have been modelled in this study but for sake of brevity only some of them are reported:

- Scenario 0: the fire is not included in the model and the downstream batteries are activated. All the doors connecting to the evacuation shafts are open.
- Scenario 1: the fire is located at the beginning of the tunnel at 250 m and only the downstream batteries are activated. Only the first two doors are open.
- Scenario 2: the fire is located in the middle of the tunnel at 800 m and all batteries are activated. The first eight doors are open.
- Scenario 3: the fire is located near the exit of the tunnel at 1400 m and all the batteries are activated. The first fourteen doors are open.

The results for the different scenarios are presented hereafter comparing the outcome of the two models. The velocity and temperature averaged on the cross section are presented along the tunnel, Table 2. In the following sections the temperature refers to the temperature averaged on the cross section for FDS.

Table 2  Comparison of different fire scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Velocity at inlet portal [m/s]</th>
<th>Maximum average temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IDA</td>
<td>FDS</td>
</tr>
<tr>
<td>Scenario 0</td>
<td>3.59</td>
<td>3.51</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>3.48</td>
<td>3.24</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>3.65</td>
<td>3.71</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>3.24</td>
<td>3.28</td>
</tr>
</tbody>
</table>

Scenario 0
A preliminary simulation is carried out without fire in order to evaluate the discrepancies between the models. Both calculations are isothermal and only the batteries at the downstream portal are activated. The velocity along the tunnel and the pressure are presented as function of the longitudinal coordinate X in Figure 7.

The velocity along the tunnel shows a similar trend for the two models but the installation efficiency has a strong influence. The installation efficiency calculated basing on the fan’s position is strongly overestimating the longitudinal velocity along the tunnel. The efficiency is reduced of 25% for every fan in order to consider the inefficiencies related with the batteries’ configuration. For sake of completeness the efficiency is reduced by 50 %, but this configuration is too conservative. In the next section the results are evaluated considering an efficiency reduction of 25%. The pressure rise induced by the jet fan is much larger in the one-dimensional model compared to the tridimensional one. The difference apart of the effect of the installation coefficient is consequence of the jet fan modelling, in FDS the pressure increases gradually while in the 1 D model there is sudden pressure rise.
Scenario 1
For the first scenario the velocity and temperature are presented in steady state conditions, Figure 8, the velocity is slightly overpredicted by the 1D models compared to FDS. In both cases the velocity increases after crossing the fire because of the expansion of the gases and the mixing of fresh air with smoke, however the velocity is much higher in the 1D models than in FDS. The higher velocity downstream the fire obtained with the 1D model are consequence of the higher velocity at the inlet of the tunnel and of the temperature rise. Knowing the temperature of the air after the fire the velocity in the section can be approximated, neglecting the effect of the mass produced by the fire as:

\[ u_{ds} = \frac{T_{ds}}{T_{us}} \]

Where the temperatures and the velocities are considered just before and after the fire. The temperature obtained in 1D model and in FDS are in well agreement regarding the maximum value near the fire, but in the 1D model the temperature remains higher along the tunnel compared to FDS. This is consequence of the different heat transfer models between the two programs. In FDS there is a velocity drop in front of the fire which is not evident in the 1D model, this is consequence of the partial backlayering occurring in the 3D simulation Figure 13. When the smoke is flowing against the main flow it has a negative velocity therefore in the section near the fire the average velocity drops.

\[ \text{Figure 8} \quad \text{Velocity and Temperature in Scenario 1.} \]

Scenario 2
In the second scenario the fire is moved to the center of the tunnel at 800 m from the inlet portal and the jet fans upstream are activated. The velocity predicted by the 1D model is about 0.06 m/s lower than the value obtained in FDS at the tunnel’s inlet. The velocity in the region downstream the fire is higher in the 1D model, consequence of the different gas expansion and different heat losses, Figure 9. The maximum temperatures obtained with the two models are in well agreement near the fire region. But the temperature obtained with the 1D model is higher downstream the fire showing a lower heat exchange with the walls. The lower velocity obtained with the 1D model is consequence of the higher temperature and velocity at the jet fans section at the tunnel’s outlet.
Scenario 3
In the third scenario the fire is located at the end of the tunnel at 1400 m from the inlet portal, all the batteries are activated and the smoke is still warm when it impinges the fans. The velocity profiles are in well agreement between the models in the portion of tunnel upstream the fire, Figure 10. The temperature in the downstream part is much higher in the 1D model than the temperature obtained with FDS. The reason behind the great difference in the temperature lies in the different heat exchange of the two models. In FDS the region near the fans has high local velocities and turbulence therefore is expected a rapid cooling of the smoke.

Analysis of the differences between the two models

After comparing the results obtained with the two approaches it is interesting to understand the reason of the different temperature profiles downstream the fire. In the 1D model the heat transfer model assumes that the fluid has uniform temperature along the section. The heat exchanged between the wall and the gas is estimated with a simple convective heat transfer law [14]:

\[ q = \alpha (T_g - T_w) \]  \hspace{1cm} (3)

Where the coefficient \( \alpha \) takes into account both convective and radiative parts and \( T_g \) and \( T_w \) are the temperatures of the gas and of the wall. In the FDS model the gas temperature and the heat flux change are function of the position. The heat exchange between the wall and the gas is the sum of radiative and convective heat transfer [17], equation (4).

\[ q = \alpha (T_g - T_w) + \varepsilon (q_{r,inc} - \sigma T_w^4) \]  \hspace{1cm} (4)

Where \( \alpha \) is the convective heat transfer coefficient, \( q_{r,inc} \) is the incident radiative flux, \( \varepsilon \) is the emissivity and \( \sigma \) the constant of Stefan and Boltzmann. The second equation is obviously more accurate, but the results produced by the 1D model are more conservative since the fans downstream the fire are working with higher volume flow rates and they are inducing a lower pressure rise.
previous comparison the temperature and the velocity showed a good agreement between the models, but also the pressure should be included in the comparison. The gas pressure along the tunnel is presented for scenarios 1 and 2 in Figure 11.

![Figure 11: Pressure distribution in scenarios 1 and 2.](image)

The pressure obtained with FDS shows a peak near the fire while in the 1D model the pressure has a more linear trend. The results obtained with FDS have been further investigated showing that the current pressure solver presents some numerical problems for long sealed structure with fire. The problem is well known by the developers which are working on the implementation of a new and more stable pressure solver. Despite this lack in accuracy in the pressure prediction further sensitivity analysis shows that the other results are reliable.

With FDS the velocity is lower compared to the 1D model and this is consequence of the different working conditions of the jet fans. These are not simply inducing a local pressure rise, but they generate a tridimensional flow and the effectiveness of the jet fan is not an input parameter, but a result of the calculation. Due to the vicinity of the batteries it is not possible to distinguish the effect of every single jet fan in terms of pressure rise so the velocity field is presented near the downstream portal, Figure 12. Near the jet fans the high-speed jet is still compact and the flow is not uniform, so the momentum is not fully exchanged between the jet and the main flow. This loss of efficiency is not depicted by the 1D model because the pressure rise is assumed to occur suddenly after the fan. While in FDS the pressure rises gradually as momentum is being transferred over a certain distance. In FDS the velocity is presented along the middle plane of the tunnel showing a compact jet and a recirculation zone beneath the jet fan. The jet is not fully decayed before flowing into the next battery of jet fans therefore the efficiency of the jet fan is lower than expected. In 1D models the efficiency of the jet fans and the decay distance were evaluated for single jet fan, while when the jet fans work in batteries and in co-flow these quantities might change. [19-20] The comparison of different efficiencies showed that with a reduction of 25% of the efficiency for this specific case a better agreement was found.
In the 1D model the backlayering cannot be simulated since the smoke has a tridimensional pattern. In order to evaluate the capability of the ventilation system to confine the smoke downstream the fire the velocity along the tunnel is compared with the critical velocity. The critical velocity is defined as the velocity capable to confined the smoke downstream the fire in a tunnel. This has been investigated by several authors who proposed different correlations. In this paper the critical velocity has been calculated with the correlations proposed by Kennedy [21], Li [22] and Wu-Bakar [23], Table 3. The critical velocity is evaluated considering an obstruction area of 12 m² which reduces the critical velocity of a factor 0.91.

In all the scenarios the velocity in front of the fire is higher than the values found by Kennedy and Li. The values found by Wu-Bakar are slightly higher than those found with the 1D model and this is consequence of the large aspect ratio of the tunnel. In FDS the longitudinal velocity is lower compared to 1D model, so it is possible to have some backlayering in the tunnel, this can be depicted by the simulation since the flow field is three dimensional. From Figure 13 it is evident that the smoke is confined upstream the fire place, but remains stratified and the backlayering length never exceeds 50 m.
The comparison of the two methods for different fire scenarios shows that FDS predicted more conservative velocities compared to the 1D model, for the tunnel under study. The differences are related to the fire modelling, heat exchange between walls and gases and the jet fan modelling. However, the 1D model still give a valuable estimation of the longitudinal velocity and the temperatures, in particular the difference between the values never exceed 0.3 m/s. 1D model has been used for the design of the ventilation in the tunnel, since the computational time required to run one case is about 1 minute, so many different scenarios have been investigated. One single FDS calculation lasted about 10 days since the flow in the tunnel has to reach steady state conditions, therefore FDS can be used as verification tool only for some critical case but it can’t be used as design tool.

CONCLUSIONS
Performing full-scale fire tests are important to convince the authorities how the existing ventilation system behaves for different type of fires. Due to the cost, it can be beneficial to complement the small sized fires with predicted consequences through CFD models, which can easily include large fires.

As the CFD-analysis was performed before the full-scale fire tests, confidence can be gained in the accuracy of CFD-models when the correct boundary conditions are imposed. Based on the results, the authorities decided to upgrade the ventilation system in the Craeybeckxtunnel.

Different steps in the design of the ventilation system were described and the differences between the one dimensional analysis and CFD were discussed. Where the 1D-analysis provided a design solution which fulfilled the required criteria, however the current solution had to be further investigated to evaluate its performance. The one dimensional model has some limits in the description of the flow field where this is three dimensional, like near the batteries and near the fire [9,15]. These limits can be overcome with a more sophisticated model, like computational fluid dynamics, CFD, which can simulate correctly the three dimensional effects [10]. For the analysis of the flow field in the tunnel the code Fire Dynamic Simulator (FDS 6.3.1) is chosen due to its long term development in fire modelling [16-17]. The jet fan batteries in FDS are simulated as local sources of mass and momentum, therefore their impact on the flow field is evaluated by FDS and it is not imposed by the user [14]. This is important because the efficiency of the boosters is often evaluated based on correlations which might not be representative of the operating conditions of the fans. This aspect is
critical for this specific tunnel where the fans where installed in batteries and they were placed close to each other in order to be located near the exit. The FDS simulations revealed that the effectiveness of the jet fans was overestimated by the one dimensional analysis, but the designed solution is still capable to keep the smoke confined near the fire.

The new simulation provided many data about the flow field inside the tunnel but they also required more time to be completed. Therefore three dimensional simulations cannot be used in a design phase but should be performed in a final stage as verification of the previous modelling.

In general, the recommendation can be made that the verification of a ventilation design by a tridimensional calculation is necessary in 2 following cases: for higher heat release rates to correctly take into account the throttling effect and whenever there is an uncertainty on the effective efficiency of the jet fans (e.g. batteries of jet fans are used).

REFERENCES

Proof of proper functionality of emergency ventilation system in emergency stations of GBT using fire tests and CFD simulations

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ABSTRACT

This paper presents the methodology employed to prove the proper functionality of the emergency ventilation system installed in the multifunctional stations (MFS) of the Gotthard base tunnel (GBT). This paper outlines the emergency ventilation system, the functionality tests, the aerodynamic measurements as well as the calibration and application of a 3-D computational fluid dynamics (CFD) numerical model necessary to predict the behaviour of the emergency ventilation system in case of a 10 MW fire. Following a thorough testing and analysis campaign for the emergency ventilation system of the world’s longest railway tunnel enabled the engineers to provide the proof of functionality, acceptable to the Swiss Federal Office of Transport (FOT), the authority having jurisdiction (AHJ), thereby enabling the timely inauguration and operation of tunnel in December 2016.

KEYWORD: Fire tests, smoke propagation, rescue conditions, ventilation strategies, Computational Fluid Dynamics (CFD) simulations

INTRODUCTION

After almost 17 years of continuous planning and construction, the world’s longest railway tunnel, the Gotthard Base Tunnel (line length of 57.01 km), is fully operational since December 2016. The tunnel was built under the supervision of the AlpTransit Gotthard Ltd [1]. The tunnel consists of two single track tubes connected by four cross-overs and 178 cross passages along with two multifunctional stations (MFS) namely MFS Sedrun and MFS Faido. Apart from technical rooms for the railway system equipment, two lane change tracks and two emergency stations are also located within each of these two MFS. These emergency stations are provided with 6 escape doors each leading to a defined point of safety.

In addition to the regular tunnel portals namely “Erstfeld” in the north and “Bodio” in the south, there are two access tunnels in Amsteg and Faido located about 8 km and 16 km from the north and south portals respectively. An anti-recirculation shaft is located at about 280 m from the northern portal to avoid the undesirable recirculation of exhaust gases out of the tunnel. A dedicated access tunnel is located in Sedrun that leads to one of the two main ventilation stations. Two vertical access shafts (Shaft I and Shaft II) each approx. 800 m long depart from the ventilation station in Sedrun. Shaft I is primarily used for the supply air whereas Shaft II is primarily used for exhausting the air via an exhaust shaft in Val Nalps. A general layout of the GBT is shown in Figure 1.
With respect to the security of passengers and the train staff, the fire emergency scenarios set the highest demands on the design of the ventilation system. The Swiss Federal Office of Transport (FOT), being the authority having jurisdiction (AHJ), demanded a proof of proper functionality of the emergency ventilation system. The main focus of this paper is to present the detailed methodology followed to provide the proof of proper functionality of the emergency ventilation system. Following such a methodology leads to an increased confidence in the designed system and help recognize system weakness under certain operational conditions not reproducible by means of on-site tests alone.

GOALS AND OBJECTIVES
The goal of the emergency ventilation in the case of fire is to control the smoke propagation and keep the escape routes free of smoke for as long and as far as possible. The required functionality of the emergency ventilation system has been defined as being achieved when the following criteria are achieved:

- Functionality test of the installed detection system (smoke detectors, thermal imaging cameras and linear heat detector cables) showing the correct localization of fire and smoke by means of hot smoke tests.
- Functionality test of ventilation control system i.e. appropriate automatic switching from one ventilation mode to another based upon the inputs from the detection system.
- Show that for a 10 MW fire on board a train coming to a stand-still in an emergency station, the air velocity of fresh air entering the emergency station via the escape doors remains greater than 2 m/s for adverse aerodynamic conditions i.e. unfavourable portal pressure and presence of other moving trains in the tunnel network.
- At least 90% of the emergency station walkway area should assure a visibility level above 10 m for a minimum time period of 5 minutes (defined evacuation time) in case of a fire in the emergency station.
- Escape routes should be kept at temperatures below 40°C at least for the complete period of evacuation in case of a fire in the emergency station.
- The non-emergency tunnel should be kept at a minimum over-pressure of 50 Pa.
WORKING METHODOLOGY

To provide proof of the objectives and achievement of the criteria above, a series of aerodynamic, fire and smoke tests were carried out in various sections of the tunnel network. These tests formed an integral part of the commissioning tests of the detection and ventilation system. In order to avoid any damage to the infrastructure, the working temperature (and hence the fire power) had to remain below 50°C during the hot smoke tests. The smoke tests helped to predict the smoke propagation and the visualization of the air flow.

However these tests alone were not acceptable by the AHJ as a proof of proper functionality of the ventilation system. It had to be proven that a full scale 10 MW Fire could be handled by the systems correctly. Also, Portal pressure differences cannot be “produced” on demand. In order to resolve these discrepancies between feasibility and objectives, a 3-dimensional “Computational Fluid Dynamics (CFD)” model was applied.

As it is well known that CFD results are strongly dependent on the boundary conditions, the model had to be properly validated and calibrated. Calibration was successful, after the CFD model parameters and boundary conditions were seen to replicate the aerodynamic test results within a given tolerance. With the calibrated CFD model, a full scale fire was simulated under different reasonable worst case conditions such as high portal pressure difference and effect of train movements in the system, to see if the designed emergency ventilation system can achieve the goals set by the AHJ to declare the system as properly functional.

TRAIN LOGISTICS, EMERGENCY VENTILATION AND FIRE DETECTION SYSTEM

A fire on board a train can occur at any point in a tunnel. As a general practice, a train on fire should be driven out of the tunnel as the first priority. If the train is unable to do so, it should stop in an emergency station. If all else fails, the train comes to a stop anywhere in the tunnel. For the present work only the scenario of a train burning in an emergency station is considered.

In terms of emergency stopping, the GBT is divided into three sections. If the fire is reported when the train is in the first of the three sections i.e. prior to the arrival of the first emergency station, the train is directed to stop in the next emergency station. The passengers are then evacuated from the emergency station into the MFS via the 6 escape doors located in the emergency station. It is important to note that this directive of stopping in the emergency station of an MFS and hence the activation of ventilation system is only applicable if the time required to stop the train safely in the emergency station is available. The emergency ventilation should be in full operation prior to the stopping of burning train in the emergency station. Full operation of the emergency ventilation system means that both the supply and exhaust fans are running at 100% of the set point. The activation takes about 3 - 5 min.

In case the train cannot be stopped in the next emergency station (first in the row), the train is directed to pass by the unprepared (1st MFS in the row) emergency station and stop in the next, fully prepared emergency station (2nd MFS in the row). In case the conditions are such that the train is not able to stop in the 2nd emergency station or the train has already passed by the 2nd tunnel section, it is directed to leave the tunnel. In the worst case of the burning train being unable to travel out of the tunnel, the tunnel fire emergency scenario is activated which is beyond the scope of the presented paper.

In order to minimize the adverse effects of smoke propagation, any train which at the time of alarm is outside the GBT is directed to come to a stop outside of the tunnel. All the trains which are behind the burning train in the emergency tunnel are directed to stop immediately whereas those ahead of the burning train in the emergency tunnel should leave the tunnel with their normal operational speed. In order to stabilize the aerodynamic conditions and generate an effective over-pressure from escape tunnel to emergency station and tube to tube as quickly as possible, all the trains in the adjacent non-emergency tunnel are directed to reduce their operational speed down to 40 km/h. All the trains in the
non-emergency tunnel which have passed the stopped train should leave the tunnel.
The dedicated emergency ventilation system of the emergency stations consists of fresh air supply
with air flowing through the 6 escape doors into the emergency station, each having a cross sectional
area of 4.4 m². The polluted air is removed via 7 exhaust shafts at the ceiling level of the emergency
station above the train track. Each of the shaft openings having an area of 25 m² is fitted with a
motorized damper enabling the exhausting of smoke and hazardous gases locally in a concentrated
mode i.e. near to the fire or distributed over the 7 shafts. The air is supplied and exhausted by means
of axial fans located in ventilation stations in Sedrun and in the portal building in Faido. The supply
air fans in ventilation station in Sedrun are dimensioned to supply a maximum volume flow of 236
m³/s whereas those in ventilation station in Faido can supply a maximum volume flow of 213 m³/s.
The exhaust fans are capable to extract a maximum volume flow of 277 m³/s and 268 m³/s in
ventilation stations Sedrun and Faido respectively. All these fans, deployed for emergency ventilation
are 100% redundant and equipped with impeller vane adjustment, frequency converter and dedicated
cooling unit. The exhaust fans are fire rated to withstand a temperature of 400°C for duration of 90
minutes. In addition to the described axial fans there are six reversible jet fans, with a thrust of 860 N
each, installed at each portal to assist the ventilation system and generate a pressure difference
between the two tubes.

As soon as a burning train is reported to be running in the tunnel, the emergency ventilation system in
the relevant emergency station is activated via the tunnel control centre. In the default activation
mode, 120 m³/s of fresh air is supplied via the 6 escape galleries towards the emergency station and
250 m³/s of polluted air is exhausted via the 7 exhaust ducts into the main exhaust duct. The
difference between the supplied volume flow and exhausted volume flow is compensated by the flow
entering the emergency station via the adjacent tunnel sections. The adjacent non-incident tube is
provided with additional 200 m³/s of fresh air and kept at a higher pressure by activating the jet fans
located at the tunnel portal. A schematic layout of the ventilation principle for a burning train in the
emergency station “Sedrun West” is shown in Figure 2. For the fire scenario shown in Figure 2, the
doors of the emergency station “Faido East” are opened to bring in the additional air.

![Figure 2](image)

**Figure 2** General layout of emergency ventilation for a standing burning train in emergency
station “Sedrun West” of GBT.

The cross sectional area of the emergency station is 45.6 m² and that of the adjacent tunnel section is
41.4 m². Each emergency station of the GBT is equipped with 5 video surveillance cameras located
on escape side platform, 14 thermal imaging camera (7 on each side of the track), two independent
loops of linear heat detection cables (one on each side of the track) and 7 smoke detectors. A general
layout of the detection system is shown in Figure 3. The upper part of the heat detection cable loop
covers the region near the ceiling level, liable for a fire on top or on-board the train whereas the lower
part of the loop is meant to detect fires at the bottom of the trains. The smoke detectors are located at
the junction of the smoke exhaust ducts. There is no detection system in the tunnels sections between
the portals and emergency stations.
Once a fire is localized by means of the cameras and detection systems in the emergency station, the default ventilation mode of exhausting over the 7 exhaust dampers is changed to “local exhaust mode” in which only three exhaust dampers remain open and the rest are closed.

**TEST CONCEPT AND SETUP**

In realm of providing a proof of proper functionality of emergency ventilation system, the aerodynamic and ventilation measurements together with smoke and fire test were meant to establish a profound basis to calibrate and validate a CFD model that can be used to investigate different full scale fire scenarios.

The measurement concept is based on measuring and documenting the followings:
- Calibrated single point air velocity in each of the escape door
- Validated single point air velocity measured in the tunnel sections adjacent to the emergency station. The velocity validation was done using ultrasound cross sectional measurement.
- Pressure difference between the eastern and the western tunnels (upstream of fire) measured at a cross connection
- Pressure difference between the eastern and the western tunnel (downstream of fire) measured at a cross connection
- Supply and exhaust air volume flow generated by the fans in operation
- Wall and air temperature in the emergency station as well as near to the ceiling level in vicinity of fire
- Documentation of the meteorological conditions at tunnel portals for the complete duration of the tests
- Documentation of train speeds in the tunnel

Different tests with varying fire position and constellation of train movement in the tunnel network were performed. For the presented paper, only one of the test results is mentioned that was later used for calibrating the CFD model.

**Emergency ventilation setup and test**

The emergency ventilation tests were conducted for each of the emergency station under different operational conditions. For the provision of the proof of proper functionality, the emergency station “Sedrun West” was chosen. The reason for choosing “Sedrun West” as proof object was based on the fact that it is geometrically located at farthest distance from the supply and exhaust fans and it showed the lowest velocities in the escape doors when compared to the test results of other emergency stations.

A schematic layout of the test arrangement is shown in Figure 4.
In addition to the velocities in the escape doors (U1 – U6), flow velocities in the tunnel sections (U_{tunnel, south} and U_{tunnel, north}) adjacent to the emergency station (Sedrun West) were measured. The measurements were taken in the escape door openings and at the centre of the railway track with the sensors located on a tripod at about 2 m from the track. The location of the velocity measurement apparatus used for the tests are shown in Figure 5.

The velocities in the escape doors play a vital role in judging the proper functionality of the ventilation system. Using the log-Tchebycheff network method [2] [3], the single point volume flow measurements were compared and accordingly calibrated to the detailed network measurement in one of the doors using the formula:

$$\dot{Q} = a \cdot \overline{v}_0 + b$$  \hspace{1cm} (1)

Where:

- $\dot{Q}$ = Volume flow through the escape doors [m$^3$/s]
- $\overline{v}_0$ = Averaged flow velocity measured in the door with 1 point measurement [m/s]
- $a, b$ = Calibration constants (depending upon the location of the 1 point measurement and the door type)

Due to the layout of the extraction system (position of exhaust fan, geometrical layout of ducts etc.), the angle of the damper blades in each of the shaft have to be appropriately set so as to have an equal distribution of exhaust air over the 7 open dampers. In order to have this distribution, a set of 1- and
3-D numerical simulations were previously conducted to find out a correlation between the pressure loss coefficients and opening angle of the damper blades. This information was then used in ventilation control system to adjust the opening angle of the damper blades separately for each of the 7 dampers for different emergency ventilation scenarios (uniform or local smoke extraction). A detailed description of the complete numerical investigation conducted to find out the appropriate damper bland opening angle for different cases is beyond the scope of present paper and is not presented here.

For the proof of the emergency ventilation, a diesel locomotive with 2 open carriages of type Am843 with total length of 74 m was used. An ICE-S with a total length of 94 m was used to represent the presence of traffic in the tunnel. For the station “Sedrun West”, 3 test cases were performed i.e. a) the ICE-S was kept stationary at west tunnel chainage, km 220.3, b) ICE-S started at west tunnel chainage, km 220.3 and left the north portal with a maximum velocity of 250 km/h and c) ICE-S ran into the tunnel towards the emergency station with a maximum velocity of 250 km/h and stopped at west tunnel chainage, km 220.3 (see Figure 4 for the description of tunnel chainage). For the proof of functionality, only the results of the case a) were considered for calibration.

During the tests, the portal conditions were continuously documented. The temperature during the calibration test case (case a as defined previously) remained 4°C ± 0.5°C with a slight overpressure of about 1 hPa ± 0.5 hPa on the north portal as compared to the south portal.

**Smoke and fire tests**

The smoke tests were conducted in accordance with the VDI 6019 standard [4] to determine the propagation of smoke (hot and cold) in the emergency station, check the detection sensors’ functionality (heat and smoke detectors), visualization of smoke and air flow and activation of the ventilation system for different fire positions. Smoke was generated using 4 smoke generators of the type “VC 2.2 Compact” [5], each capable of generating up to 340 m³/min of non-toxic smoke.

For the hot smoke tests the “Fire trainer E1502”[6], equipped with a water bath propane gas burner that can provide a fire power of up to 310 kW, was employed. All the equipment was mounted on a carriage that rolled on the track as shown in Figure 6.

![Figure 6 Test apparatus and setup used: (a) complete assembly mounted on a rolling carriage in emergency station of GBT during the test, (b) Smoke generator and (c) Fire trainer.](image)

As mentioned above, a temperature limit of 50°C had to be observed at all points in the station (except at the fire location itself) during the tests.
TEST RESULTS

Prior to the complete fire emergency detection and ventilation system tests, the contractor performed individual component functionality tests including their communication with the control centre. These components involved the smoke detectors, thermal imaging camera and the heat detector cable. Smoke detectors were tested by means of local smoke detector spray, the thermal imaging camera by means of placing a heated up metal plate within the frame of view of different cameras and the heat detector cable by attaching a local heat source (electro-thermal source) to the linear heat detection cable.

As mentioned previously, the emergency ventilation of the emergency station “Sedrun West” was tested for 3 different scenarios on 8th December 2016. Only one out of the three tests was used as calibration basis for 3-D CFD validation study. The test sequences along with the observations are given in Table 1.

Table 1 Sequence for the emergency ventilation tests carried out on 08.12.2016 in the emergency station “Sedrun West” of GBT.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event/Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:40</td>
<td>Start of emergency ventilation in uniform exhaust mode (all 7 dampers open, all emergency doors to escape gallery open)</td>
</tr>
<tr>
<td>12:44</td>
<td>Emergency ventilation reached its maximum operational point</td>
</tr>
<tr>
<td>12:47</td>
<td>Start of fire and smoke generators (Fire located 20 m south of exhaust damper 3)</td>
</tr>
<tr>
<td>12:47</td>
<td>Flow direction towards south portal</td>
</tr>
<tr>
<td>12:47</td>
<td>Heat detection cable response in zone 3 i.e. region between exhaust damper 3 and 4</td>
</tr>
<tr>
<td>12:48</td>
<td>Smoke back-layering observed with smoke reaching exhaust damper 3</td>
</tr>
<tr>
<td>12:50</td>
<td>Swirl noted in front of escape door 3</td>
</tr>
<tr>
<td>12:56</td>
<td>All the escape doors of emergency station closed automatically except door 3 due to disruption of an earth cable leading to high velocities in the door. Three doors of the adjacent emergency station (Sedrun East) remained open</td>
</tr>
<tr>
<td>12:57</td>
<td>All the doors of emergency station “Sedrun West” were re-opened and those of “Sedrun East” were manually closed</td>
</tr>
<tr>
<td>13:05</td>
<td>Stopping emergency ventilation and fire and smoke generation</td>
</tr>
</tbody>
</table>

The measured velocities in the 6 doors (U1 – U6) as well as the velocities in the middle of the tunnel sections adjacent to the emergency station “Utunnel_South” and “Utunnel_North” are shown in Figure 7 whereas Figure 8 shows the corresponding pressure difference between the two tunnel tubes measured at the cross connection QS 65 and QS 70. The distance between QS65 and northern end of the 450 m long emergency station is about 1.52 km whereas that between the southern end of emergency station and QS70 is about 170 m. The location of the cross connection along with their respective tunnel chainage is shown in the general test layout in Figure 4.

With the emergency ventilation system in operation, the velocities in all the doors of emergency station “Sedrun West” are showing positive values (see Figure 7) in the range between 3.5 and 5 m/s (positive sign for velocities through the emergency doors denotes that the fresh air is drawn towards the emergency station). An exception to this velocity trend is observed at time 12:56 where the door 3 could not be completely closed leading to air velocities as high as above 10 m/s in the door. A positive value of “Utunnel_South” shows a longitudinal inflow into the emergency station from the southern tunnel junction whereas a negative value of “Utunnel_North” represents an inflow from the northern tunnel junction into the emergency station. The plot in Figure 7 shows that there is fresh air is drawn into the emergency station via the adjacent tunnel sections. As per basic ventilation concept, the doors of emergency station Faido east were kept open for additional air supply. The pressure difference plot in Figure 8 marks the events of full operation of exhaust
system in the form of decrease in pressure difference from 600 pa to around 200 pa (negative sign denotes that there is an over-pressure in the non-incident tube).

Figure 7 Variation in flow velocity measured during the test a (see previous sections for the description of tests). The velocity scale is cut-off at 10 m/s.

Figure 8 Variation in pressure difference across the two tunnel tubes measured at cross connection 65 (QS 65) and cross connection 70 (QS 70) during the test a (see previous sections for the description of tests).

CFD MODELLING

The 3-dimensional geometrical model used for numerical simulations consists of the complete “Sedrun West” emergency station (450 m in length), the walkways, 6 escape doors, a part of the
escape gallery and exhaust shafts along with single track tube at each end of the station extending 120 m beyond the emergency station ends. The installed damper in each exhaust shaft is modelled as pressure loss coefficient to further simply the simulation model. In addition to the geometrical setup of the emergency station, a train is included in the model to replicate the flow hindrance and the related turbulence effects. The position and type of train geometry depends on the investigated fire scenario. The scenario used for the fire and smoke tests explained in the previous section is modelled in CFD as seen in Figure 9.

The geometrical model was created using AutoCAD Inventor [7] whereas the computational grid was generated using Star CCM+ [8]. The complete computational domain was meshed with approx. 5.5 million cells. The computational grid is locally refined in regions with steep flow gradients e.g. near the fire location and obstacles. In addition to the local refinement, the wall boundaries have been resolved by “prism layers” to ensure accurate flow conditions near the walls. The validation of grid insensitivity was carried out using stationary simulations.

The boundary conditions were applied as volume flow at the domain ends i.e. outlet with total exhaust volume flow of 250 m$^3$/s, supply volume flow of 120 m$^3$/s, inlet flow velocity (variable as function of time taken from test results) at tunnel junction north with pressure loss coefficient (varied to achieve calibration), opening with a pressure of about 230 Pa and a pressure loss coefficient (varied to achieve calibration) at tunnel junction south, pressure loss coefficients at exhaust dampers (obtained from an earlier CFD parametric study not part of this paper), pressure loss coefficients at escape doors (varied to achieve calibration) and a heat source of 310 kW corresponding to the fire generator. The train model used for calibration case was simplified but kept geometrically similar to the carriage/locomotive assembly used in test.

In order to estimate the turbulence effects, the “two-equation all $y^+$ k-$\varepsilon$” turbulence model [8] was used. The thermal buoyancy was modelled using the ideal gas law. The radiative heat transfer was modelled using the participating media radiation model [9]. Participating media radiation passes through media that can absorb, emit, or scatter thermal radiation. STAR-CCM+ accounts for participating media effects by using the Discrete Ordinate Method (DOM) [9].

To numerically solve the entire computational domain, a 2nd order discretization scheme [8] was used. To progress in time, an adaptive time scheme was employed which keeps a balance between the numerical quality of the solution and the calculation time required. The conservation criteria (and
hence the convergence limit) for URANS (Unsteady Reynold Average Navier Stokes) equation was set to below 0.1%.

All the calculations were carried out on a 64 core Intel Xenon cluster. A single simulation of 5 minutes required about 15 to 20 hours computing time. As it is well known that CFD results strongly depend on the boundary conditions, the need for a properly validated and calibrated model was inevitable to proof the proper functionality of the ventilation system by means of CFD simulations.

**CFD Model calibration**

In order to ensure that the numerical model is capable to predict the behaviour of the emergency ventilation system in case of a 10 MW fire, the calibration of the CFD model is necessary. For the calibration of the simulation model the realised fire and smoke tests within the emergency station were replicated and compared to the measured values presented above. A 3-D representation of the CAD model (left) and real image of emergency station during the test is shown in Figure 10.

![Figure 10 CAD visualisation of the used simulation model for the calibration (left) and a picture of the fire and smoke tests (right) within the emergency station](image)

In order to replicate the executed fire and smoke tests by means of a numerical simulation, the test conditions were carefully recorded and mapped accordingly to the simulation model. As the velocities in the escape doors and exhaust shafts play a vital role in judging the proper functionality of the ventilation system, these velocities obtained via simulations were compared against the measured values of velocities during the test as the “judgement criteria” for a successful calibration. The pressure loss coefficients at the ends of the escape doors and adjacent tunnel ends were repeatedly adjusted until the measured and simulated velocities in the escape door were within acceptable range. The calibrated simulation model with the adjusted loss coefficients at ends of the calculation domains shows a good agreement (maximum deviation < 6%) with the measured values as shown in Table 2.

**Table 2**  
Comparison of the average airflow velocity out of the escape doors and in the exhaust shafts considering the fire and smoke tests conditions.

<table>
<thead>
<tr>
<th>Escape doors</th>
<th>ED 1 m/s</th>
<th>ED 2 m/s</th>
<th>ED 3 m/s</th>
<th>ED 4 m/s</th>
<th>ED 5 m/s</th>
<th>ED 6 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoke and fire test, average airflow velocity out of the escape doors into the emergency station without train movement</td>
<td>5.1 m/s</td>
<td>4.5 m/s</td>
<td>4.6 m/s</td>
<td>4.3 m/s</td>
<td>4.1 m/s</td>
<td>4.7 m/s</td>
</tr>
<tr>
<td>Simulation, average airflow velocity out of the escape doors into the emergency station without train movement</td>
<td>5.0 m/s</td>
<td>4.3 m/s</td>
<td>4.8 m/s</td>
<td>4.3 m/s</td>
<td>4.1 m/s</td>
<td>4.8 m/s</td>
</tr>
<tr>
<td>Rounded up deviation between measurement and calibrated simulation model</td>
<td>2.0 %</td>
<td>4.6 %</td>
<td>-4.1 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>-2.1 %</td>
</tr>
</tbody>
</table>
This model is then further used for simulation cases with different boundary conditions, allowing reliably evaluating the influence of different governing factors such as portal pressure difference, train type, fire power, and fire position or exhausting scenario on the escape conditions which could not be investigated simply by means of aerodynamic, ventilation, fire and smoke tests.

**Scenario analysis using calibrated CFD model**

The calibrated and validated CFD model is employed for the simulation of defined realistic worst case scenario required by the AHJ as proof the proper functionality of the ventilation system. The results presented in this study correspond to a full scale fire (10 MW) on board of a train coming to a standstill in the emergency station Sedrun West under worst case conditions considering high portal pressure difference to verify if the designed emergency ventilation system can achieve the goals set by the AHJ to declare the system as properly functional. The goal of the emergency ventilation is to control the smoke propagation and keep the escape routes free of smoke.

The required functionality of the emergency ventilation system has been defined as being achieved when the following major criteria’s are achieved:

- At least 90% of the emergency station walkway area should assure a visibility level above 10 m for a minimum time period of 5 minutes (defined as the required evacuation time)
- No smoke entrance in the escape doors (average outflow velocity >2 m/s)
- Escape routes temperatures remain below 40°C

All the boundary conditions other than the fire power, train type, and portal pressure were kept similar to those defined previously. The varied boundary conditions used in full scale simulations are as follows:

- 10 MW fire located in front on board of an ICE train. The total train length was modelled to be 375 m. The train is considered to stand still in the emergency station. The incident coach is modelled with broken windows and roof to reproduce a worst case condition for the smoke spread
- Two investigated ventilation scenarios
  - Uniform distributed extraction of 250 m³/s via the 7 exhaust shafts
  - Local smoke extraction of 250 m³/s near the fire via 3 exhaust shafts
- Reasonable worst case portal pressure of 1000 Pa (95%-value of the measured portal pressures over an year)

**Results**

**Scenario 1: Uniformly distributed smoke extraction**

The simulation results for the default emergency ventilation mode in the emergency station i.e. uniform extraction via all the 7 exhaust dampers is shown in Figure 11 as 3-D iso-surface of visibility, 2-D visibility and temperature, presented on a horizontal plane located 2.2 m above the walkway (representing the height of the passenger’s heads) as well as on a vertical central plane running along the walkway.
The results show that the longitudinal flow due to the portal pressure difference causes a propagation of the smoke into the emergency station. Due to the uniform extraction, the smoke concentration is reduced at each exhaust shaft along the emergency station. It is seen that the fresh air supply through the escape doors cause turbulence thereby influencing the smoke stratification within the station and reducing the visibility locally. The majority of the smoke is noted to be exhausted via the exhaust shafts EX5 and EX6 located closest to the fire.

The analysis of the visibility plots show that after 5 minutes, ca. 18% of the emergency station has a restriction in visibility (visibility <10 m at a height of 2.2 m). No smoke enters the escape gallery. The minimum flow velocity in the escape door is seen to be 4.3 m/s (ED5). Temperature plot analysis show that other than in the extreme vicinity of fire, the temperatures remain below 40 °C.

**Scenario 2: Local smoke extraction**

For the case of a successful detection of fire location, the default emergency ventilation mode is shifted to the local exhaust mode in which 3 exhaust dampers located close to the fire are opened to draw out the smoke (in the investigated case EX5, EX6 and EX7 are open). The results of the CFD simulation for a local smoke extraction under worst realistic conditions are shown in Figure 12.
The results show that the longitudinal flow due to the portal pressure difference causes a propagation of the smoke into the emergency station. Due to the local extraction by means of 3 open exhaust shafts close to the fire, majority of smoke remains confined to the region between the 1st and last open exhaust shaft.

The analysis of the visibility plots show that after 5 minutes, about 8% of the emergency station has a restriction in visibility (visibility <10 m at a height of 2.2 m). No smoke enters the escape gallery. The minimum flow velocity in the escape door is seen to be 4.5 m/s (ED5). Temperature plot analysis show that other than in the extreme vicinity of fire, the temperatures remain below 40 °C.

CONCLUSIONS

Based on the results of the simulations using a calibrated and validated CFD model, the following conclusions can be made:

- For the default emergency ventilation mode i.e. uniform extraction of smoke via 7 exhaust shafts, under extreme portal pressure conditions (1000 Pa);
  - A visibility level above 10 m for 90% of the walkway area could not be guaranteed (effective result 82% area above 10 m)
  - The temperature at a height of 2.2 m above the walkway as well as in the escape galleries remained below 40°C for the complete simulation time of 5 minutes (corresponding the required evacuation time)
There is no air flowing from the emergency station into the escape galleries.

The minimum air velocity in the escape doors remained well above 2 m/s (effective result 4.3 m/s).

- For the ventilation mode with local extraction via 3 exhaust shafts in the vicinity of the fire;
  - A visibility level above 10 m for 90% of the walkway area could be guaranteed (effective result 92% area above 10 m).
  - The temperature at a height of 2.2 m above the walkway as well as in the escape galleries remained below 40°C for the complete simulation time of 5 minutes (corresponding the required evacuation time).
  - There is no air flowing from the emergency station into the escape galleries.
  - The minimum air velocity in the escape doors remained well above 2 m/s (effective result 4.5 m/s).

- The minimum pressure difference between the two tunnel tubes are shown by means of measurements.

- Prior to the emergency ventilation test, functionality test of the installed detection system (smoke detectors, thermal imaging cameras and linear heat detector cables) were carried out, showing that the correct localization of fire and smoke can be guaranteed (study is beyond the scope of this paper).

- Prior to the emergency ventilation test, functionality test of ventilation control system i.e. appropriate automatic switching from one ventilation mode (uniform extraction) to another (local extraction) were carried out, showing that based upon the inputs from the detection system, the ventilation mode can be appropriately switched.

It can be seen that under extreme portal pressure conditions, only for the ventilation mode with local extraction all the defined criterion could be reached. It can however be concluded that due to the presence of dedicated fire and smoke detection system (reliability and functionality proved by means of field tests), an early fire and smoke detection is possible. The non-availability of more than 90% walkway area with visibility above 10 m is accepted as calculated risk that exists for the time period until the local fire detection occurs and the ventilation system shifts automatically to the local extraction mode. Analysis of the flow fields show that for lower portal pressure differences the ventilation goals can be achieved even without switching to local extraction mode. The temperature development for a 10 MW fire does not pose a threat to the evacuees except in the immediate vicinity of the fire. Due to the presence of 6 escape doors leading to a dedicated escape gallery with fresh air supply, a safe evacuation conditions can be guaranteed.

This paper gives an overview of the methodology of the commissioning tests and simulation work used in the GBT. It is shown that following a systematic approach using measurements, field tests and calibrated numerical simulation models, difficult, though realistic but non-reproducible test conditions can be reliably investigated. The calculated risks, consequences and possible mitigation measures can be effectively identified as a result of such a combined methodology. Using the combination of on-site tests and validated CFD simulations not only avoids the costs associated with a full scale fire test but also allows to investigate different operational scenarios.

ACKNOWLEDGEMENT

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REFERENCES

A Computational Study of Critical Velocity in Rail Tunnels

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ABSTRACT

Longitudinal tunnel ventilation is often used to direct smoke from a fire in one direction, whilst occupants can escape in the opposite upwind direction in relatively clear air. The minimum flow velocity to achieve this purpose is known as “critical velocity”. Though specific to road tunnels and not expressly intended for rail tunnels, NFPA 502 has been referenced in several instances for providing a basis for estimating critical velocity. The publication of the 2017 Edition of NFPA 502 included modifications to the critical velocity calculation that, when applied to rail tunnels for fires of 10 MW in magnitude or less, yields airflow requirements on the order of 30 to 50% higher than the 2014 Edition of the same standard.

Two Computational Fluid Dynamics (CFD) programs, ANSYS CFX (v17) and Fire Dynamics Simulator (v6) are validated against the experimental results that contributed to the changes in the critical velocity calculation. The simulation set up, limitations and findings are discussed to provide guidelines for their use in rail tunnel applications. Using CFD also highlights the influence that train and tunnel geometries have on smoke movements, effects which the analytical critical velocity calculation cannot consider.

FDS is used to identify appropriate minimum airflow criteria in a test case. Results of the simulations show that the application of the NFPA 502 2014 calculation can lead to controlled backlayering (i.e. limiting backlayering to a certain length upstream of the fire) which could be acceptable for emergency operations, while the application of the critical velocity calculation described in NFPA 502 2017 prescribe higher performance to the tunnel ventilation system.

KEYWORD: critical velocity, tunnel ventilation, computational fluid dynamics

INTRODUCTION

During a fire in a rail tunnel, the tunnel is often ventilated longitudinally to direct smoke in one direction, whilst occupants escape in the opposite direction in relatively clear air. An often used correlation for calculating the minimal flow velocity to achieve this purpose (called critical velocity) is described in Appendix D of the NFPA 502 – Standard for Road Tunnels, Bridges, and Other Limited Access Highways. Although NFPA 502 is a road tunnel specific standard, it has often been referenced as a basis for estimating critical velocity in rail tunnels.

The recent publication of the 2017 Edition of NFPA 502 [1] included modifications to the critical velocity calculation. When applied to rail tunnels for fires less than 10 MW in magnitude in a manner consistent with industry practice, the revisions would yield airflow requirements on the order of 30 to 50% higher than if calculated using the expression from the 2014 Edition of the same standard [2]. The amendments to the expression are adapted from a correlation of a different form developed from recent scale experiments [3, 4].
The revised expression represents a subtle shift in the definition of critical velocity and required smoke control performance. Depending on the specific tunnel considered, the earlier expression can allow for a limited degree of backlayering [5]; the revision makes the performance absolute in terms of zero backlayering (i.e., the reverse flow of smoke from a fire in the tunnel). While a more accurate definition, this does not necessarily reflect the minimum required level of performance for emergency operations, given that tenability near the fire may be compromised by other factors than backlayering, for example radiation from the fire itself.

**REVIEW OF NFPA 502 – 2017 EDITION AND ITS APPLICATION TO RAIL TUNNELS**

Historically, the most widely recognised critical velocity calculation is that proposed by Kennedy [6], also used in the tunnel ventilation program Subway Environmental simulation (SES) [7] and in NFPA502 up to the 2014 version. These expressions and their associated constants result from model scale tests presented in [5], wherein a velocity corresponding to limiting backlayering to 1.2 times the tunnel height is defined as critical velocity. In the generally used form, they are as follow:

\[
V_c = K_1 K_g \left( \frac{gQH}{\rho_0 c_p A T_f} \right)^{1/3} \tag{1a}
\]

\[
T_f = \frac{Q}{\rho_0 c_p A V_c} + T_o \tag{1b}
\]

Where \( V_c \) is the critical velocity, \( K_i \), the Froude number factor, \( K_g \) the grade factor, \( g \) the acceleration of gravity, \( H \) the tunnel height at the fire, \( Q \) the heat that the fire is adding directly to air at the fire site, \( \rho_0 \) the average density of the upstream air, \( c_p \) the specific heat of air, \( A \) the area perpendicular to the flow, \( T_f \) the average temperature of the fire site gases, and \( T_o \) the temperature of the upstream air. The grade factor takes into consideration the effect of gradient working against the ventilation. The Froude number is a dimensionless parameter that measures the ratio of the inertial (velocity) forces to the gravitational (weight) forces of a fluid. The tests in [5] showed that the critical value of the Froude number ranges from 4.5 to 6.7, and therefore the conservative value of \( Fr=4.5 \) was used for calculating the critical velocity. Through the 2014 Edition of NFPA 502, \( K_i \) was therefore based on this constant value of the critical Froude number, leading to the constant \( K_i=0.606 \).

In a recent paper, Li, et al. [3] raised concerns regarding the accuracy of the system of equations and argued that the velocities previously calculated do not represent a true critical velocity. Rather they represent confinement velocity, where the backlayering is limited to a certain length and not critical velocity, where there is no smoke upstream of the fire site. The research indicated that the current set of equations underestimates critical velocity, based on the zero backlayering definition of that term. A new correlation based on dimensionless heat release rates and velocities to estimate a dimensionless backlayering length (with a different formulation from the Kennedy expression) was then proposed in [3, 8]. In [9], a blockage ratio correction was also proposed for rail tunnels. A series of numerical model-scale tests with blockage ratios varying from 0 to 0.71 showed good correlation of the blockage ratio correction to the numerical results (±15%); however, no investigations were done for saloon fires.

Even though the newly proposed expressions and corrections correlated well with scaled experiment for pool fires in tunnels, the new NFPA 502 [1] did not adopt the new formulation. Instead it retained the original critical velocity expression in the form of Equation 1a, and introduced a newly defined \( K_i \) coefficient that varies with the heat release rate, to correlate with the new research. This creates ambiguities in the application of the expression in rail tunnels in terms of the tunnel geometry characteristics and the characterisation of the heat release rate of the fire. A study of the effect of varying convective ratio, tunnel height, aspect ratio and blockage ratio in the various critical velocity formulations is presented in [10]. A brief discussion on the main ambiguities is discussed in the following sections.
Cross-sectional Area
The formulation proposed by Li does not explicitly account for the cross-sectional area of the tunnel section. This implies the assumption that the behaviour is two dimensional and the cross-sectional area is not important, only the tunnel height. Such a formulation is generally appropriate for road tunnels where blockage ratios of vehicle frontal area to tunnel cross-sectional area is relatively small.

Industry practice in estimating critical velocity within rail tunnels has generally considered calculation of velocity required in the train annulus area, with the temperature similarly determined using conditions also within the annulus. This approach is logical as Equation 1b represents the change in the air temperature due to the heat release rate of the fire and the denominator represents the mass flow of air within the tunnel annulus. However, NFPA 502 2017 does not define which area should be used and the critical velocity varies greatly using different areas. Table 1 summarises the change in critical velocity for a 10 MW fire (total heat release rate) at a 0% gradient for different area interpretations.

Table 1: Critical velocity calculation for a 10MW fire with various area assumptions and Total HRR

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Annulus Area</td>
<td>Full Tunnel Area</td>
<td>Annulus Area</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Total HRR</td>
<td>2.18 m/s</td>
<td>2.95 m/s</td>
<td>3.30 m/s</td>
<td>3.01 m/s</td>
</tr>
</tbody>
</table>

Convective Fraction
A further confounding effect of implementing the revised equations is the choice of heat release rate. The formulation proposed by Li utilises total heat release rate for correlating purposes. However, NFPA 502 2017 does not clearly define which heat release rate to use, whether the full, convective or another value. For a 10 MW fire at a 0% slope, the estimated critical velocities are shown in Table 2.

Table 2: Critical velocity for a 10MW fire with various area assumptions and convective HRR

<table>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Annulus Area</td>
<td>Full Tunnel Area</td>
<td>Full Tunnel Area</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Convective HRR</td>
<td>2.01 m/s</td>
<td>2.67 m/s</td>
<td>2.95 m/s</td>
<td>3.01 m/s</td>
</tr>
</tbody>
</table>

Grade Correction Factors
In addition to the previously discussed NFPA 502 amendment, Ingason and Li [11], proposed a modification to the grade correction factor promulgated by NFPA 502. The current expression is based on the work of Bakke and Leach [12] and the applicability to ventilated tunnels has been drawn into question. As a result, Li proposed adopting an expression developed by Atkinson and Wu [13] based on propane fire tests specifically evaluating the effect of slope on critical velocity. The expression has correlated well to additional experiments over a range of -15° to 15°. When comparing the two expressions, the NFPA 502 expression overestimates the impact of negative slopes while not allowing for the benefit afforded by positive slopes.

METHODOLOGY
Given the large bracket of critical velocity values that can be obtained from different interpretation of the new NFPA 502 2017 expression, especially for rail tunnels, in this article CFD is used as an alternative means to verify system performance and identify minimum airflow criteria. An essential first step is to confirm an appropriate modelling methodology to predict smoke spread and backlayering.

To avoid any software specific bias, two different software packages were used to compare CFD results with the experiments in [3, 4]. ANSYS CFX (v17) and Fire Dynamics Simulator (v6), were
selected based on their relative strengths in addressing complex geometry and flows, or in estimating fire effects due to combustion, including the distribution of heat under longitudinal airflows.

**Fire Dynamic Simulator (v6)**

Fire Dynamics Simulator (FDS), is a computational fluid dynamics model of fire-driven fluid flow. FDS solves numerically a form of the Navier-Stokes Equations appropriate for low speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. FDS is widely used by industry professionals and has been extensively validated by its developer NIST and other testing entities. FDS is a purpose-built software, developed and optimised for fire protection, with the capability of simulating combustion models. However, it is inflexible with respect to input geometries when compared to other CFD codes. Simulations presented here follow the guidelines in [14].

**ANSYS CFX (v17)**

ANSYS CFX is a general purpose CFD software, used for modelling fluid flow and other related physical phenomena. CFX offers better capabilities than FDS in representing complex, non-orthogonal geometries. The disadvantage is that the application of CFX does not consider combustion. As a result, the extent of the flame or combustion zone is applied as a user specified boundary condition. For this study, the fire is represented as a heat source in a three-dimensional volume. The prescribed ventilation airflow informs the shape of the volume so that the source is de-coupled from the airflow. Simulations are performed using the settings described in [15, 16].

**EXPERIMENTAL COMPARISON**

The experimental procedure utilised by Li involved varying the flow rate in a scale tunnel to yield different backlayering lengths. The resultant backlayering lengths were plotted against tunnel velocity and then extrapolated to determine the velocity at which the backlayering length is zero.

CFD models were created for each scale tunnel and simulated with a similar approach wherein velocities were varied between models and the smoke backlayering length approximated from the temperature profile in the model tunnel. That is, a sharp change in temperature within the model was used to predict the leading edge of the smoke reverse flow.

For the fire scenarios studied, three velocity sensitivity tests were conducted, with velocities ranging within a 10% margin from the experimental critical velocity. In each case the backlayering length was determined from the temperature profiles formed, and then plotted and linearly extrapolated to determine a velocity of zero-backlayering length; taken to be equal to the upwind edge of the burner. The temperature gradient was considered to start when the temperature raised by 10% of the ambient temperature.

**Geometry**

The experiments consisted of two tunnel geometries as shown in Figure 1, each 12m in length. The fire source, a propane-fed porous bed burner of diameter 100mm for Tunnel A and 150mm for Tunnel B was placed at the centre of the tunnels flush with the tunnel floor. A third experiment included a thin-walled steel section within Tunnel B to simulate a stationary vehicle within a tunnel (referred here as Tunnel C). The vehicle has a wall thickness of 1mm, is 8m long, 0.15m wide and 0.2m high. To measure the temperature profile within the tunnel, thermocouples were placed along the centreline of the tunnels. For Tunnel A, they were placed 10mm below the ceiling, and ranged from 1.50m upstream to 1.00m downstream of the fire at 0.05m intervals. For Tunnel B, thermocouples were placed 20mm below the ceiling, and ranged from 2.7m upstream to 2m downstream of the fire at 0.1m intervals.
Figure 1: Cross sections of model tunnels: (a) Tunnel A; (b) Tunnel B. Dimensions in millimetres

FDS
For Tunnel A, the exact experimental cross-section was used in the simulations. For Tunnel B, because of FDS limitations in representing curved geometries, the ‘horse-shoe’ cross-section in the experiments was simplified to a rectangular cross-section. The height and width of the cross section were adjusted from 393 mm to 400 mm and from 380 mm to 375 mm, respectively, to maintain the experimental cross section area of approximately 0.15 m².

All temperature devices were located one cell below the centreline of the ceiling with an interval of 0.05 m in Tunnel A and with an interval of 0.1 m in Tunnel B.

CFX
Simulations were modelled as per the experimental geometries and gas temperatures measured at the same location as the experiments along the length of the tunnel ceiling.

The flame in each simulation was introduced as a volumetric source of the total heat shaped as an oblique square-base pyramid. The dimensions of the fire’s square-base were determined by maintaining the known area of the burner. The height of the flame was determined by conducting FDS simulations for a given burner area and heat release rate and validated against the flame height determined by [17]. The angle of the flame tilt, influenced by the cross-wind velocity, was prescribed in the model. The angle is a function of the flow velocity and mass burning rate [18].

To maintain the volume of the fire in Tunnel C, the fire was split and translated to the side walls of the vehicle as shown in Figure 2 below.

Figure 2: Flame representation in CFX
(a) Longitudinal view: oblique square-base pyramid, with an angle of tilt
(b) Front view: the flame is split in the centre and translated to the walls of the vehicle
(c) Isometric view: Tunnel C with flame
Experimental Inputs
The model inputs for velocity, ambient temperature and heat release rates are provided in [3]. The velocity sensitivity tests were undertaken by selecting three velocities within 10% of the critical velocities determined by the experiments. For FDS three velocities of $0.9v_c, 0.95v_c$ and $v_c$ were adopted, whereas for CFX three velocities of $0.9v_{c,exp}$, $v_{c,exp}$ and $1.1v_{c,exp}$ were used. The properties of propane considered for the simulations are given in Table 3 as per [19].

Table 3: Properties of propane

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel heat</td>
<td>43.7</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Soot Yield</td>
<td>0.024</td>
<td>-</td>
</tr>
</tbody>
</table>

Computational Mesh
CFD methods solve the fundamental equations of fluid motion and thermodynamics dividing the region of interest into numerous small cells. Within each cell, the governing equations are solved. FDS and CFX use different methods to divide the computational domain. A mesh independency test was carried out to check the prescribed resolution was appropriate.

FDS
The non-dimensional expression $D^*/\delta x$ was used to evaluate the cell size in FDS. The $\delta x$ is the nominal cell size and the $D^*$ is calculated through the equation in [14]. The quantity $D^*/\delta x$ can be thought of as the number of computational cells spanning the characteristic diameter of the fire. The more cells spanning the fire, the better the resolution of the calculation. $D^*/\delta x$ values ranging from 4 to 16 were studied in a validation study sponsored by the U.S. Nuclear Regulatory commission. These values were used to assess the adequacy of the model resolution, as shown in Table 4. Alternatively, the number of cells spanning the model ‘burners’ were 8 and 12 for the ‘A’ and ‘B’ tunnels, respectively.

Table 4: Selected grid size for FDS simulations

<table>
<thead>
<tr>
<th>Fire Size in simulations (kW)</th>
<th>Cell size</th>
<th>Values of $D^*/\delta x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7 kW to 18.4 kW</td>
<td>$12.5 \text{ mm} \times 12.5 \text{ mm} \times 12.5 \text{ mm}$</td>
<td>4 to 16</td>
</tr>
</tbody>
</table>

CFX
In CFX the geometries have been meshed by mean of a hybrid structured and unstructured grid. The cell count of the models are approximately 4 million cells and the general cell edge length is approximately 10mm, however local refinements down to 2.5mm are included to resolve the anticipated high local spatial gradients of flow properties near the fire.

A prism mesh has been used along the tunnel and train walls to capture the boundary layer using a maximum $y^{+}=10$. Based on literature reviews and model verification against experiments, an appropriate turbulence model which effectively solves boundary layers was used [20]. The accurate solution of the boundary layer was found to be essential in the correct prediction of the backlayering distance, especially if zero-backlayering performance needs to be verified.

Boundary conditions
A velocity was applied at the inlet of the tunnel, while a relative pressure of 0 Pa was applied to the outlet of the tunnel. At both boundaries, the temperature was set to the ambient temperature provided by the experimental data inputs. Tunnel walls were simulated with the properties of steel for tunnel A and steel and concrete for tunnel B, as per the experiments. In CFX the vehicle was modelled as a hollow air-filled object with wall properties of steel. FDS considered the vehicle as a solid object.

Although combustion is not modelled in the CFX model for this study, radiation was considered from the flame volume and the radiative effects of combustion products (typically carbon dioxide, water
vapour and soot) were considered through the addition of extra terms into the fluid absorption coefficient. The total absorption coefficient is represented as the sum of each combustion product [21]. The soot and propane products contribution to the absorption coefficient are taken from equations in [22] and [23].

Three-dimensional heat transfer through the tunnel walls is considered in the CFX models. FDS only accounts for one dimensional heat transfer through the walls.

Results

In the following, the dimensionless critical velocities \( V_c^* \) obtained from the experiments with Tunnel A, B and C are compared to the value obtained from the simulations. Points below the line indicate under-prediction of the critical velocity, points above the line indicate over-prediction.

FDS

The comparison of the dimensionless critical velocities \( V_c^* \) obtained from the experiments and from the FDS simulations is shown in Figure 3. Results for Tunnel A where the cross-section is accurately represented shows a bias of \(+5\%\) or a tendency to over-predict the required critical velocity. In Tunnel B, where the geometry was simplified the average bias was \(-11\%\) or a tendency to under-predict the required critical velocity. Tunnel C critical velocity is greatly underpredicted with the used resolution. The resolution required below the bottom of the train to accurately predict the flow would make the simulation times impractical.

Note that both thermocouple and gas-temperature devices were used in the simulations to measure temperature. Both devices were included to explore the potential over prediction of temperature that radiation might cause on the thermocouples. However, it was found that the differences in the derived critical velocities are minor and the averaged deviation was only 2%.

Figure 3: FDS non-dimensional numerically determined critical velocity versus experimentally determined critical velocity

CFX

Figure 4 shows the comparison of the dimensionless critical velocities \( V_c^* \) obtained from the experiments and the CFX simulations. On average, the numerically determined dimensionless critical velocities have a deviation of 10% from the experimental equivalent. All results lie in the negative
region of the plot, indicating that the velocities calculated are under-predictions of the experimentally derived results. Tunnel A results are greatly under-predicted as the low heat release rate made them highly dependent on the prescribed flame shape.

Figure 4: CFX non-dimensional numerically determined critical velocity versus experimentally determined critical velocity

**Extrapolation of Critical Velocity**
To investigate the critical velocity approximation by means of linear extrapolation, the extrapolated critical velocity of 0.45m/s in Tunnel B with a heat release rate of 3.5kW was tested with an additional run to verify whether no backlayering occurs at this velocity. As indicated in the black line in Figure 5, the high temperature gradient remains within the fire zone, defined as the distance between the first thermocouple (placed every 0.01m in the experiment) and the location of the fire.

Figure 5: Critical velocity profile below the tunnel ceiling
Effect of Tunnel Shape

The FDS simulation results for Tunnel B showed a tendency to under-predict critical velocity, while the predictions based on the Tunnel A were generally conservative. Since the FDS simulations for Tunnel B did not fully represent the tunnel cross-section shape, a further study was undertaken to evaluate the influence of different cross-sectional shapes on the predictions of critical velocities. A single Tunnel B case (HRR = 8.5 kW, \( V_{cr} = 0.70 \text{ m/s} \)) was simulated in FDS with three cross-sections.

The first considered the rectangular approximation used in the remainder of the analysis which conserved cross-sectional area but slightly increased height and narrowed the (max.) width.

The second shape considered a similar rectangular cross-section but increased the width to preserve cross-sectional area while incorporating blockages at the upper sides of the tunnel, with the intent to approximate the effect of tunnel curvature to create of a relatively narrow channel for smoke and heat flow at the top of the tunnel.

The third shape considered a stair-stepped approximation of the experimental Tunnel B. It is acknowledged that the stair-stepped approximation is relatively coarse and has the potential to introduce spurious flow effects.

The test shapes and results comparison is provided in Table 5. The results indicate improvement in predictions as the approximation of the shape, in particular the channel created along the tunnel soffit, is improved. The channelling effect tends to capture heat, particularly on the upwind side enhancing the buoyancy effects in relation to the momentum of velocity effects. When the curved cross-section is approximated as a squared section, FDS under-predicts critical velocity.

The same test with cross-sections in Scenario 1 and Scenario 3 was performed with CFX for a 16.9kW heat release rate and a longitudinal velocity of 0.82m/s. Results show the same trend as presented in Figure 6.

The tests indicate the importance of shape and aspect ratio in critical velocity predictions that may not be easily captured in rail tunnels with a simple algebraic expression or poor CFD representation of the geometry.

Table 5: Different Tunnel B approximated cross-sections

<table>
<thead>
<tr>
<th>Item</th>
<th>Experiment tunnel</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-section (m²)</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.141 m²</td>
</tr>
<tr>
<td>Shape</td>
<td>![Rectangular Shape]</td>
<td>![Rectangular Shape]</td>
<td>![Rectangular Shape]</td>
<td>![Stair-stepped Shape]</td>
</tr>
<tr>
<td>Ceiling temperature along the tunnel @ 0.7 m/s</td>
<td>![Temperature Graph]</td>
<td>![Temperature Graph]</td>
<td>![Temperature Graph]</td>
<td>![Temperature Graph]</td>
</tr>
<tr>
<td>Critical velocity</td>
<td>0.7 m/s</td>
<td>0.63 m/s</td>
<td>0.64 m/s</td>
<td>0.73 m/s</td>
</tr>
<tr>
<td>Error or Bias</td>
<td>-</td>
<td>-10%</td>
<td>-8.5%</td>
<td>+4%</td>
</tr>
</tbody>
</table>
Conclusions of Verification

Both CFD packages can estimate critical velocity, utilizing an approach like that utilized in the experimental work, within an accuracy of roughly 10%. Some considerations can be made upon the results of this work:

- The train and tunnel geometry are complex and can be more accurately reproduced in CFX. FDS is not well suited to round tunnels or to represent details, such as walkway and train shape with enough detail;
- More powerful meshing options are available in CFX that allow areas of high gradients to be better or selectively resolved at a significantly lower computational cost, compared with FDS;
- CFX offers opportunities to examine conditions steady-state, representing conditions at ‘long’ times or durations as would be appropriate for tunnel smoke control applications;
- Unlike FDS, standard CFX cannot simulate the combustion of fuel and approximations and tuning needs to be performed every time a new fuel needs to be used. It is noted that in rail tunnel fires, the “fuel” is often unknown and conservative assumptions are usually taken.
- FDS can predict the shape of the flame under the effect of ventilation, CFX needs it to be fixed “a priori” instead.

RAIL TUNNEL FIRE SIMULATION

The verification process carried out showed that CFD can predict the critical velocity for a pool fire and for an undercarriage fire in a tunnel with an accuracy of about 10%. The CFD models could not be tested against a saloon fire scenario due to a lack of publicly available results.

During the process, it was found that the flame envelope is important for a correct prediction of the flow and temperature for fires occurring within the tunnel. This effect was predominantly related to flame tilt under imposed airflows and the effects on plume temperature distribution, and in turn the temperature measurement locations subject to the highest temperatures, which were used in determining the predicted backlayering length. Because of the methodology for representing the combustion zone of a fire (i.e., flames) in CFX utilises a fixed volumetric source of heat and species, the distribution of heat released within the domain is not predicted. Rather, an approximation of flame tilt appropriate to the cross-airflow velocities was used to fix the combustion zone a priori. In FDS when the flame was developing in the annulus between the train and the tunnel, the accuracy of results was poor due to the low resolution in this zone.
However, when an in-saloon fire is considered, the flame is not directly impacted by the prevailing tunnel airflows. For in-saloon fires where the fire is not under-ventilated and flaming combustion is assumed to occur within the vehicle envelope, the convective transfer of heat from the saloon to the tunnels is achieved primarily through open doors due to buoyancy generated pressure differentials arising from the elevated compartment temperature. If window breakage does not occur, it is expected that there would be ample ventilation through the open side doors to support a typical 10 MW worth of combustion within the saloon interior with negligible, if any, flame extensions. Therefore, in the following FDS simulations, it has been assumed that flames are contained in the carriage on fire, thus removing the dependence of tunnel air temperature distribution on a pre-defined flame shape. A series of simulations for a large-scale squared tunnel with a fully involved (10 MW) fire were performed to determine rail tunnel critical velocity.

Geometry, Model and Inputs
The chosen tunnel geometry is a cut and cover section which includes an emergency egress platform. The doors closest to the emergency egress walkway remain open in the model to simulate the state of the train during emergency egress. A tunnel section containing five train carriages (135 m) was modelled with the fire located on the floor of the middle carriage. The dimensions of the tunnel and the incident carriage are illustrated in Figure 7. The train and tunnel have been meshed by a structured grid of cell size of 100 mm. The total number of cells is approximately 3.7 million. The model, mesh and solver were set up following the guidelines used for the model verification. Thermocouple devices were installed at the centerline of the ceiling at an interval of 1 m along the longitudinal axis.

Table 6: Simulation inputs – values from a typical high capacity modern metro train

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRR</td>
<td>10</td>
<td>MW</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>27.0</td>
<td>°C</td>
</tr>
<tr>
<td>Tunnel Gradient</td>
<td>-2.9</td>
<td>Deg</td>
</tr>
<tr>
<td>Fuel heat</td>
<td>14.68</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Soot Yield</td>
<td>0.051</td>
<td></td>
</tr>
</tbody>
</table>

The required velocity was applied at the inlet of the model, while a relative pressure of 0 Pa was applied to the outlet. At both boundaries, the temperature was set to the ambient temperature. The tunnel walls were simulated with the properties of concrete and the back surface was set at the deep sink soil temperature.

Based on the critical velocity expression provided in the 2017 version of NFPA 502, critical velocity is estimated to be 3.1 m/s. To obtain sufficient back-layering length and to further determine the containment velocity, three ‘sub-critical’ velocities of 2.8 m/s, 2.6 m/s and 2.4 m/s were adopted and applied at the upstream tunnel boundary condition.

![Figure 7: Train-tunnel geometry in FDS](image-url)
Results

According to the temperature results recorded from the simulations, the back-layering length can be determined when the gas temperature distribution below the tunnel ceiling shows a sharp drop as illustrated in Figure 8. The back-layering lengths against velocities of 2.8, 2.6 and 2.4 m/s are plotted in Figure 9. Extrapolating the curve to zero backlayering yields a critical velocity of 2.82 m/s.

While determination of ‘critical velocity’ was the primary objective of the analysis, the results also afford the opportunity to assess conditions that arise under ‘sub-critical’ conditions. Figure 10 shows temperature contours rendered 2 meters above the tunnel walkway adjacent to the train. While the degree of back-layering ranges from roughly 0 to 15 m from the front end of the incident carriage for imposed velocities of 2.8 and 2.4 m/s, respectively, temperatures are relatively low upstream of the incident carriage.

Examining the results in greater detail, temperatures 2 meters above the walkway have been extracted and plotted in Figure 11 to identify the conditions through which occupants may be subjected evacuating in the upstream direction away from the fire incident. Temperatures remain below 60 °C upstream of the incident carriage regardless of the examined velocities. While there is some evidence of temperature rise upstream of the incident carriage at the 2.4 m/s velocity, conditions remain within commonly accepted limits for thermal exposure. The significant increases or spikes in temperature occur at the location of the open carriage doors from where flame extensions may emanate. Conditions downstream of the incident carriage are highly erratic due to turbulence but are largely equivalent across the three velocities. In this particular case, it can be concluded that tenability under longitudinal ventilation is not necessarily coupled to ‘critical’ velocity. Achieving containment at ‘sub-critical’ velocities provide an acceptable degree of safety to occupants evacuating from a fire incident or for firefighters approaching the incident from the upstream direction.

Figure 8: Temperature contours along the walkway center line: (a) at 2.8 m/s (b) at 2.6 m/s (c) at 2.4 m/s
Figure 9: Back-layering lengths at 2.4 m/s, 2.6 m/s and 2.8 m/s

Figure 10: Temperature contours 2 m above walkway: (a) at 2.8 m/s, (b) at 2.6 m/s, (c) at 2.4 m/s

Figure 11: Temperatures at 2 m above the central line of the walkway.
CONCLUSIONS

The 2017 Edition of NFPA 502 introduced a revision to the definition of and calculation methodology for determining critical velocity. The revised calculation methodology would suggest that for rail tunnels airflow rates would need to be increased in the order of 30 to 50% when compared to the expression in the 2014 Edition of NFPA 502. However, the implementation of the revised expression to rail tunnels has been found to have different possible interpretations.

To better characterize the required airflows for rail tunnels, a study was undertaken to first validate CFD ability to predict critical velocity. Once done, with the predictive capability found to be within roughly 10% of experimentally determined values, in-saloon train fires within a typical rail tunnel were modelled to evaluate tenability for a range of different ventilation airflow.

The study demonstrated that airflow rates lower than those specified in the 2017 Edition of NFPA 502 can satisfy the intent of longitudinal ventilation smoke control within the studied rail tunnels. That is, smoke backlayering was contained such that it did not extend beyond the upwind end of the train.

In conclusion, CFD demonstrated that the Li, et al. method for calculating critical velocity in rail tunnels for undercarriage fires is acceptable. For in-saloon fires, the same equations could be used for a first estimate during concept design. However, if used for the further stages of a rail tunnel design, it might lead to over-conservatism with great impact on space-proofing, materials and ultimately cost of construction.

Fires in carriages (or saloon fires) have characteristics that are very different from pool fires or undercarriage fires and are highly influenced by the train and tunnel geometries. The paper provides a methodology for estimating and optimising tunnel ventilation requirements, which take into consideration the impact of key design characteristics including tunnel geometry. The study also highlights that CFD should be used in a controlled manner ideally verifying and testing the models against small or full-scale tests. Future experimental and computational work could concentrate on in-carriage fires, especially to study the flame projection out from saloon doors in the annulus.

REFERENCES

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Guidance and Methods for Categorizing Road Tunnels According to Dangerous Goods Regulations (ADR)

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ABSTRACT
ADR 2013 contains provisions concerning restrictions on the passage of vehicles carrying dangerous goods in road tunnels. The rules allow routing control for the transport of dangerous goods through tunnels, i.e. either granted passage through the tunnel or refer to an alternative route. Routing control is based on each tunnel is assigned to tunnel category A-E, which to varying degrees regulate the types of goods to be allowed to go through the tunnel in order to avoid accidents with major consequences for human or tunnel construction. In this paper a comprehensive approach for categorizing road tunnels according to ADR 2013 is presented as a three step method. The first is a logical decision model which, when followed should lead to well-founded basis for decisions regarding the appropriate categorization. The second is a simplified risk analysis method that can be used in the risk-based categorization of existing and new tunnels. Finally, expert assessment as a method for risk-based categorization is introduced as a third step.

KEYWORDS: Dangerous goods, risk analysis, categorization, ADR, road tunnels

INTRODUCTION
This paper presents a method to categorize Swedish road tunnels according to the regulation ADR-S 2017, which regulates the transport and carriage of dangerous goods by road. The purpose is to enable and support the categorizing of Swedish road tunnels according to the regulation ADR-S based on risk analysis. This paper takes standpoint in the regulatory conditions that are applied in Sweden and is divided into two parts:

1. Development and presentation of an overall approach to categorize road tunnels in the Swedish regulatory environment. This approach consists of a flow chart decision model, with references to appropriate tools and more detailed risk analysis methods. Furthermore, what types of risk aspects that has to be analyzed when a risk analysis is used as a basis for decision, are presented.

2. Development and reporting of a simplified risk analysis method that can be used in the context of risk-based categorization.

About transport and carriage of dangerous goods on road
In the preparatory international work established for the regulation of dangerous goods transport, it is clear that the transport of dangerous goods is associated with risks (1). Despite the risks associated with the transport of dangerous goods, international work concludes that it is considered neither reasonable nor sustainable to prohibit such transports in today's society. The strategy laid out in international consensus is instead to manage the risks associated with the transports using a regulatory framework. The purpose of the framework is to prevent, impede and restrict the transport of dangerous goods or unauthorized procedures with such goods, and by doing so reducing the harm caused to people the natural environment (e.g. fragile ecosystems) and/or damage property and infrastructure.

The national regulations governing safety requirements of transport of dangerous goods is based on the so called UN-recommendations, which cover classification, test methods, packaging requirements
etc. The recommendations are implemented in Swedish legislation mainly by law (1), ordinance (2) and regulations (4) ADR-S 2017 regarding transport of dangerous goods.

To reduce the probability and the consequences of a major transport accident, routing control is used to direct the transports to roads engineered to higher standards and to avoid transports through areas where an accident can cause major consequences. Routing control consists of recommended routes and local traffic regulations assigned by the County Administrative Board, which consist of mandatory restrictions or prohibitions. Within the local traffic regulation, prohibition of transport on certain roads is one option.

In addition ADR-S contains specific provisions concerning restrictions on the passage of vehicles carrying dangerous goods in road tunnels. The rules allow routing control for the transport of dangerous goods through tunnels, i.e. either passage is granted through the tunnel or the transport is referred to an alternative route. Routing control is based on that each tunnel is assigned to a tunnel category, A-E, the category regulates the types and the amount of goods to be allowed through the tunnel in order to limit the consequences of an accident regarding life-safety or the tunnel construction, see Table 1. The same tunnel may be assigned to more than one tunnel category, depending on e.g. the weekday and time of day. Tunnel restrictions and alternative routes are displayed on road signs and with alternating traffic signals.

The categorizing of tunnels are based on three main risks, which can cause fatalities or severe damage to the tunnel construction. These risks, or rather accident scenarios, consist of explosion, release of toxic substance and fire.

Table 1. Meaning of tunnel category A-E (4).

<table>
<thead>
<tr>
<th>Tunnel category</th>
<th>Restriction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>No restrictions for the carriage of dangerous goods.</td>
</tr>
<tr>
<td>B</td>
<td>Restrictions for the carriage of dangerous goods which may lead to a very large explosion.</td>
</tr>
<tr>
<td>C</td>
<td>Restrictions for the carriage of dangerous goods which may lead to a very large explosion, a large explosion or a large toxic release.</td>
</tr>
<tr>
<td>D</td>
<td>Restrictions for the carriage of dangerous goods which may lead to a very large explosion, a large explosion, a large toxic release or to a large fire.</td>
</tr>
<tr>
<td>E</td>
<td>Restriction for the carriage of all dangerous goods other than UN 2919, 3291, 3331, 3359 and 3373 and all other dangerous goods in accordance if the quantities carried exceed 8 tones total gross mass per transport unit.</td>
</tr>
</tbody>
</table>

Decisive for the restrictions on the transportation of dangerous goods are the properties of the goods, as well as the type of containment and transported amount. The ADR regulations sets out the considered classification codes, groups, packing groups and UN numbers to meet the criteria for each category (see ADR-S, chapter 1.9.5.2). However, the ADR regulations do not explicitly define the meaning of the terms very large explosion, large explosion, large toxic emissions, etc.

About categorization
Countries align to the international ADR agreement are responsible for categorizing their road tunnels in accordance with the ADR regulations. The regulations require that any restriction must follow the directives provided in the regulations, but sets no specific requirements on how to perform the categorization, or what criteria should be used to sort tunnels in different categories. The regulation does not state a criterion for acceptable risk.

International consensus regarding required basis for decisions or which criteria that are to separate each tunnel category are currently lacking. However, considering different countries having varying conditions regarding e.g. number of tunnels but also type of tunnels and their standards and safety
culture, this is understandable. Furthermore, the view on tunnel risks and safety systems is widely varying within the tunnel safety field.

Given this background and conditions, methods to categorize current road tunnels should have a national outset. However, it is expected to be a difference in the dangerous goods approach also within Sweden, and therefore flexibility is required when developing methods for categorizing.

In Sweden the competent authority assigning the tunnel category is the County Administrative Board in their role as decision-makers regarding local traffic regulations for dangerous goods. The formal role as infrastructure manager in charge of operation of the tunnel, e.g. The Swedish Transport Administration, consists of providing documentation for the facilities they are operating and managing so that the County Administrative Board can decide on the tunnel category for each tunnel.

Limitations
The methods for categorization presented in this paper focus on aspects related to risk and safety. Decisions regarding tunnel category must however also take into account other aspects, part from risk and safety matters. The occurrence, the character and the meaning of other aspects, e.g. political and economic, can vary a lot and therefore has to be assessed on a case-by-case basis. Access to an alternative route in case of planned and unplanned shutdown is also expected to be an aspect where special consideration is needed. The overall method for categorization presented here can also include other aspects if needed. Risk analysis and assessments based on the methods presented in this paper is to be considered as basis for decisions for the concerned decision-makers.

The methods presented provides assistance in the categorization process. The use of the methods does not in itself guarantee a high quality of either the risk analysis or the decision-making basis. Good practices and other recommendations regarding implementation of the risk analysis as a basis for decision-making, e.g. regarding competence and quality assurance, must be followed, documented and reported according to many standard risk analysis procedures. This also applies to the simplified risk analysis method.

Decisions regarding tunnel category are based, consciously and unconsciously, on what is perceived and considered an acceptable risk. This paper also use the abbreviation acceptable risk in several places. It is important to note that this does not mean a specific absolute or relative risk criterion is being specified, given that no such criteria is set in the Swedish legislation and no such criterion have been evaluated within this work. Instead, it is meant by risk assessment analysts and/or decision-makers to consider what acceptable risk is defined as in the specific case.

This paper assumes that a restriction against the passage of dangerous goods through road tunnels is only implemented to improve the tunnel safety, i.e. to reduce the level of risk for the people and objects protected in close vicinity to the tunnel, whose level of risk is directly affected by the location and configuration of the tunnel. This means that a tunnel restriction is not implemented to reduce the level of risk to people exposed, e.g. residents, or protected natural and cultural environments of value along other parts of the stretch of road involving a tunnel passage. This limitation applies to the case when an alternative route has been referred and it is relatively far away from the tunnel and its area of influence in regards to risk and safety.

In practice, this means that the road section including the tunnel passage also includes part of the surface road network. The road used for re-routing from the tunnel does not have to be the same as the alternative route. In the simplified risk analysis method, risk impact on the road used for re-routing used when the tunnel is shutdown is not included. However, the same method applied to the alternative route can be used to determine the risk exposure from the road used for re-routing, but aspects such as the amount of traffic and how often the road section is used, has to be considered.

COMPREHENSIVE METHOD FOR CATEGORIZATION
This section presents the comprehensive method for categorization of road tunnels in accordance to ADR 2017. The method is considered to be a logical decision model which, when followed, should lead to a well-supported basis for decision regarding the appropriate categorization. More detailed descriptions of suitable risk analysis methods that can be used within the comprehensive method is referred to within this section.
The categorizing of a tunnel is a complex decision where many aspects of objectives and prerequisites has to be considered. The fundamental issues to consider are:

- What tunnel category is suitable given the underlying risk and safety aspects? This includes the tunnel safety but also the safety of the transport of dangerous goods by road in general and on the surface road network.
- What tunnel category is desirable given the overall societal assessment taking into account every relevant aspects of the decision? Those aspects can consist of a socio-economic assessment, practical and political consideration etc.

Tunnel safety can simplified be described by the safety concept of the tunnel. A road tunnel’s safety concept consist of the technical and administrative actions intended to reduce the probability of an accident and/or reduce its consequences to an acceptable level. What is considered an acceptable risk level is often defined within a safety objective. A common safety objective is to meet the general qualitative requirements in the Swedish legislation. In general, the safety concept implies an acceptable risk level with respect to human life/health, natural environment and property. In developing the safety concept also considered is the resulting costs for society at large, e.g. costs for traffic disruptions and reconstruction.

A road tunnel’s risk level and its safety concept are in many ways dependent on the types and amounts of dangerous goods transported through the tunnel. There are many different categories of transports of dangerous good; transports that are not labeled (not classified as dangerous goods), mixed cargo groupage with small amounts of goods, combination packaging with different types of goods and larger transports of single substances.

The comprehensive method for categorization should be useful and provide support irrespective of the objectives and prerequisites associated with an individual decision on categorization. This means that the method has to be general in terms of its ability to give suitable advice on any tunnel and can include different standpoints and preferences. The method is therefore focusing on giving advice about the decision-making process and what aspects must be considered, instead of focusing on what is a right or wrong decision in regards to a specific category for a tunnel. The method includes steps where it may be appropriate to introduce risk mitigating measures. The possibility to make different considerations for existing and new tunnels is therefore given as well.

With support from the comprehensive method, the required basis for a decision about a suitable category range can be obtained. Depending on what tunnel that is to be categorized, the basis for the decision will be different, especially regarding the access to information and documentation. This also means that how the basis for a decision is to be obtained depends on different aspects, e.g. the available time for collecting information and making the assessment. Possible ways to obtain the basis for a decision is mainly by investigation (risk analysis) or expert judgement. The method does not specify in detail what is required in the basis for decisions or how this is to be obtained, however recommendations are given. Risk analyzes can generally be conducted in a variety of ways and with different levels of detail, but must address the correct aspects of risk and answer the right questions.

A simplified process of how a decision about a categorization is made can be described with three options, permitting all, part of, or no dangerous goods transports to go through the tunnel. If part of or no dangerous goods are permitted through the tunnel, the transports are instead referred to an alternative stretch of road.

Figure 1 shows how the transport of dangerous goods can be made from a point X to a point Y on the road section though the tunnel and/or on an alternative road section. If a tunnel is categorized with category A all goods are permitted through the tunnel, meaning no risk impact on any alternative road section. However, if the tunnel is given a restriction, i.e. category B-E, the transports redirected on the alternative road section will expose the surroundings to an increased level of risk.

The implementation of a restriction therefore must be based on an evaluation and possibly a comparison of both the road section with the tunnel and the alternative road section.
Scope of work for risk analysis in accordance with ADR

The extent and content of risk analysis required in different contexts is generally based on why the risk analysis is established and what it intends to highlight, that is to say its purpose and objective. One common purpose is that the risk analysis should form a part of the basis for a decision, which can vary in terms of scope and content depending on the governing regulations. In this case, the regulation ADR-2017 is governing and its purpose and objective is decisive for the scope and the content of the risk analysis. The regulations' scope and objective can be described as:

- reduce the level of risk associated with transport of dangerous goods to human life and health, natural environment and property,
- prevent and limit accidents (with following fire, explosion or dispersion of toxic substance) in tunnels leading to a many fatalities and/or severe damage to the tunnel construction, and
- guide transports to roads engineered to higher standard and avoid transports through areas with valuable natural and cultural environments (residential areas, vulnerable ecosystems, critical societal functions etc.)

Given the purpose and the objective of the regulations, risk analysis for categorization should take into account the impact of accidents in tunnels on people and tunnel construction, i.e. what is often referred to as tunnel safety, and also, the impact on the surroundings (human life/health, natural environment and property) along the roads where dangerous goods are transported. What types of accidents should be included is clearly presented in the regulations regarding categorization, fire, explosion and release of toxic gas and volatile toxic liquids or substances. All types of dangerous goods transported, or that can be transported in a vehicle on the given road section are expected to lead to an inherent risk of accidents and should be included in the risk analysis. To decide where the transport of dangerous goods is most suitable to minimize the risks, it is not enough to only take into account the safety in the tunnel.

The risk exposure to humans, natural environment and property along the surface roads also has to be considered. Depending on if all transports will go through the tunnel or if a restriction means that some transports will be guided to the surface road network, the level of risk for the given road section has to be compared for different individual groups (passengers, people in the surroundings and other valuable objects or environment), before a decision can be made about where and how the transports will take place.

Altogether the following aspects are considered central to obtain the purpose and objective of the regulation:

- All relevant classes of dangerous goods has been considered.
- The impact of accidents on objects required to be safe-guarded in the tunnel (human life and health and tunnel construction) has been considered.
• The impact of the accidents on object worthy of protection in the surroundings (human, natural environment and property) has been considered.

Work flow

The comprehensive method for categorization is presented as a flow chart and shows in what order each step in the method is to be carried out, see Figure 2.

Figure 2. A comprehensive method for categorization as a flow chart, describing the workflow of the method. The numbering in the figure shows in what principal order each step is to be carried out.
1. Categorization is initiated, i.e. a decision is made for a specific tunnel that it should be categorized to a tunnel category. The underlying basis for the decisions should be stated and included in this step, e.g.:
   a. Whom is the competent authority assigning the tunnel category?
   b. What organizations should be included in the decision through consultation and referral procedure?
   c. Economical limits?
   d. Timeframes?
   e. Who is to carry out the risk analysis?
   f. Etc.

2. When the underlying basis for decisions have been stated, information about the tunnel and its surroundings is obtained. The information can consist of technical information regarding e.g. tunnel characteristics and safety, drawings, assessments, risk analysis, safety documentation, fire safety documents etc.

3. Based on the risk characteristics of the tunnel, the highest possible tunnel category, given that risk for human life and health and tunnel construction is acceptable, is analyzed. The risk along the alternative route in case of a shutdown is also included. It is recommended that the risk analysis regarding transport of dangerous goods in the tunnel is made in accordance with the simplified risk analysis (level 1) and if necessary in accordance with the in-depth risk analysis (level 2) described later on or other similar method. An expert assessment should only be used when level 1 or level 2 for any reason cannot be applied.

4. If the tunnel, according to the risk analysis, can be categorized as an A-tunnel, no further assessment is needed. It is assumed that the decision-maker prefers the tunnel category without restrictions if possible, i.e. A is the preferred category. In case the tunnel, according to the risk analysis, is categorized as an A-tunnel, but this category by any reason does not reflect the requests and preferences of the decision-maker, an analysis of an alternative route is needed. In this case, move to the overall method, step 11.

5. If the risk analysis shows that the tunnel and/or its alternative route should be subject to a restriction, i.e. categorized as and B-, C-, D-, or E-tunnel, the next step depends on if the proposed category can be accepted by the decisions-makers.

6. The risk analysis propose a tunnel category equivalent to the decisions-maker’s requests.

7. If the risk analysis propose a tunnel category not equivalent to the decision-makers request, the result (and category) of an in-depth, or other, analysis should be compared with the first result and category, see section about level 1-3 in step 3 above. If the new analysis does not result in a different category, decisions has to be made about either introducing further safety precautions to reduce the risk and enable the desired category, or to accept a higher risk level in the tunnel and/or along the alternative route.

8. If further safety precautions are introduced to enable the desired category, an adjustment is made to the prerequisites of the initial risk analysis. Move back to the overall method step 2.

9. If a higher risk level is accepted in the tunnel and/or along the alternative route, the next step depends on what category is desirable.

10. If the tunnel is to be categorized as an A-tunnel, no further assessment is needed. See the overall method step 4.

11. If the tunnel is to be categorized as a B-, C-, D- or E-tunnel, the risk level has to be acceptable along an alternative route. An alternative route is chosen for further analysis. In case there are more than one possible route sections, these are assessed separately with the same method. The same assessment is repeated for each road section. When the tunnel is the only connection and if by any reason there are no alternative routes, the tunnel is handled separately.
12. Collection of information regarding the alternative route. Relevant information is for example road- and traffic standard, traffic situation, transport of dangerous goods, protected regions of cultural heritage or environment value and sensitive hazardous installations, property or infrastructure and other objects of protection along the route section.

13. Based on the risk prerequisites, the possible category is analyzed based on the assumption that the risk for human life and health, natural environment and property should be acceptable. The risk analysis can be obtained with different methods, levels of detail etc.

14. This category is proposed if the risk analysis concludes that the risk level of the alternative route is acceptable for the given category B-E.

15. If the risk analysis instead concludes that the risk level not acceptable, the increased risk level has to be accepted or not.

16. If an increased risk level is accepted along the alternative route for the desired category, no further assessment is needed.

17. If an increased risk level is not accepted along the alternative route, risk mitigation measures are to be introduced in the tunnel and/or along the alternative route.

18. If further safety precautions are introduced in the tunnel and/or along the alternative route to enable the desired category, an adjustment is made to the prerequisites of the initial risk analysis. Move back to the overall method step 2.

19. By introducing further precautions along the alternative route, the risk level may be reduced and enable the desired category. This is verified by new analysis in accordance with step 12 and forth from there.

**Categorization of new tunnels**

Both the Planning and Building Act (4) and The Swedish Environmental Act (5) specify that risks for e.g. human health and the natural environment must be considered when a new area is planned, including the planning and designing of roads and road tunnels. The planning process for a new road consists of three stages; initial study, feasibility study and road plan (including preliminary design). This is followed by a detailed designing process resulting in construction documents. The need for risk analysis varies depending on the different stages. The planning process and its stages for e.g. road projects and the need for risk analysis is described in (6).

A new road tunnel and its safety concept shall, part from the above legislation, also fulfill the Road Act (7), The act on safety in road tunnels (8), The Civil Protection Act (9) and Transport of Dangerous Goods Act (2). It is important to be aware that all laws are independent and each tunnel has to consider and fulfill all legal requirements (11). The most detailed requirements and guidelines regarding safety measurements are found in the Act on Safety in Road Tunnels (8) and the requirements 2016:0231 (13) and recommendations 2016:0232 (13) from the Swedish Transport Administration. The two last ones applies to all tunnels belonging to The Swedish Transport Administration, no matter what length, and tunnels managed and maintained by others made out of steal or concrete when the length exceeds 100 m.

Decision regarding the categorization of road tunnels should not be made formally until all relevant prerequisites are known. Examples of those prerequisites are knowledge about the safety concept and traffic situation. For new tunnels, this means that the decision can not formally be made until the tunnel is ready to put into use, i.e. in a late stage of the planning process.

Prerequisites regarding the transport of dangerous goods, e.g. restrictions, are important aspects when designing a tunnel’s safety concept. Given this, it should be possible to implement a restriction of dangerous goods as part of the safety concept, when needed. Therefore, it is important that a categorization decision is predictable and can be agreed upon among all involved parties during the planning process. Given this, it is noted that the basis for a decision regarding tunnel category has to be obtained during the planning and designing of new tunnels and this should be coordinated with other risk management in the specific project.
The risk analyses required and carried out in the planning process in Sweden today are expected to meet the requirements of a risk analysis needed to categorize a tunnel. However, an earlier study (15) states that the risk analyses carried out until today’s date, do not meet the requirements of the basis for decisions regarding tunnel categories for existing tunnels. The costs to update and adjust the analyses to the required standard are, however, expected to be very small, given that the analyses contain the correct information and answer the correct questions.

In this context, it is important to say that a decision regarding tunnel category and dangerous goods restrictions is an administrative measurement, and has to be able to vary over time depending on future conditions. The reasons to reconsider a decision can be many, e.g. a new traffic situation or settlements. These new conditions can change either during the planning process or during operation.

Categorization of existing tunnels
An earlier study (15) states that the risk analyses carried out until today’s date, do not meet the requirements of the basis for decisions regarding tunnel categories for existing tunnels. The identified deficiencies mainly consist of:

- The risk analysis does not include all current classes of dangerous goods, only focusing on transport of flammable liquids (class 3).
- Alternative routes are not assessed.

Although a risk analysis does not represent a complete basis for decision, it can still be used as part of a bigger basis for decision. When no earlier risk analysis is present, or when the quality is too low, a new analysis is to be obtained. The categorization of existing tunnels can be made in accordance with the method and recommendations presented in this paper.

Documentation of decisions
The categorization decision of road tunnels can, and is recommended to, be based on risk analysis, including relevant risk and safety aspects. In societal planning as a whole, many other aspects also need to be considered. Regardless of how, when, where, by whom, why and on what grounds and the available basis, the decision has to be documented. The documentation enable the decision to be evaluated and, when needed in the future, reconsidered.

LEVEL 1 – SIMPLIFIED RISK ANALYSIS METHOD
This section presents a simplified risk analysis method that can be used when categorizing existing and new road tunnels, with a risk-based approach. The simplified risk analysis method is recommended to represent the first step, here called level 1, in a risk analysis regarding transportation of dangerous goods in tunnels when choosing appropriate tunnel category in accordance with the comprehensive method. In the simplified method, the technical prerequisites and other conditions in the specific tunnel and its surroundings are considered to decide the highest tunnel category (i.e. with the least restrictions) that results in an acceptable risk level for people in the tunnel and its construction. Note that the risk impact from a possible alternative route used in case of a shutdown is not included in the method. The same method as the one presented further down in this article can be used for this purpose, but has not been developed further within this scope of work.

The method takes into account the required safety measurements in the Act on Safety in Road Tunnels (8) and Tunnel 16 (13) (13), which is the requirements and recommendations from the Swedish Transport Administration. The intention is that the method shall describe relevant requirements on existing and new tunnels in a correct way.

The method is based on the approach that a few risk parameters can be linked in a relative simple way to a suitable safety concept and an expected risk level, and therefore also a suitable tunnel category for each object. The method is presented as a checklist with specific tunnel characteristics and is carried out step by step. By answering the questions in the checklist, the method leads to a proposed highest tunnel category. If the checklist results in a category A-tunnel, the risk analysis can be used as a basis for decision when deciding on the tunnel category. Otherwise (tunnel category B-E), the risk
level for the alternative route has to be assessed and can be accepted in regards to human life and health, natural environment and property.

**Step 1 – Verification of general conditions**

In this step, a few general conditions are verified in accordance with what is normally expected in a road tunnel context. If one or more of the listed general conditions for the specific tunnel are not met, the tunnel should continue to be categorized as an E-tunnel, unless the results of an assessment in accordance with risk analysis level 2 or 3 shows something else.

All general conditions listed below shall be met to move to the simplified risk analysis method step 2:

1. Traffic and road standard, i.e. vertical and horizontal alignment (inclination), reference speed, number of lanes etc., shall for new tunnels be in accordance with “high standard” in the Swedish Association of Local Authorities and Regions and The Swedish Transport Administration’s requirements for road design, VGU (16). For existing tunnels, the traffic and road standard in all relevant aspects meet these requirements, with few exceptions. If a deviation is reasonable it has to be decided on a case-by-case basis.

2. There are no reversible lanes in the tunnel.

3. The rescue service’s capacity to perform a rescue mission in the specific object is expected to be satisfactory. The following aspects should be central for the assessment of the rescue capacity:
   - evacuation strategy (normally consisting of self evacuation),
   - resource availability,
   - time of arrival (normally less than 10 minutes),
   - equipment availability,
   - level of education/competence,
   - tactical knowledge and preparation (including training), and
   - the characteristics of the access roads.

4. The traffic situation/possible traffic jams (daily or seasonal): The risk of traffic jam and/or slow moving traffic should be low. Busy tunnels and/or city tunnels should normally, without taking into account traffic management measurements be associated with a high risk for traffic jam and congestion. Other indicators of risk of traffic jam can be when the traffic flow is in level with the capacity the road/tunnel is designed for, lack of capacity on surrounding road network, inadequate traffic or signal controlling, pedestrian crossings or bridge openings. Non busy and/or tunnels in rural areas should normally be associated with low risk of traffic jams.

5. The potential consequences of an accident are not big, i.e. the tunnel is not situated under water and not immediately under buildings or just next to other densely populated areas. The tunnel is not situated next to important societal services, e.g. a central power line.
The traffic flow in this instance means the designed annual average daily traffic per tunnel tube. If the amount of heavy trucks exceeds 15% of the ÅDT_DIM, the traffic flow used should be increased in accordance with the following formula: $0.6 \times (\text{percentage of heavy traffic} - 15)$ (16).

The tunnel length means the length of the tunnel including covered road outside the tunnel, e.g. light shields. Single tube tunnels with a partition is seen as a double tube tunnel.

Step 3 – Technical standard
Step 3 describes the technical standard, beyond the overall prerequisites, needed in the safety concept for each category and highest suitable category for 1a – 3d.

Note that the safety concept is based on today’s safety requirements on tunnels. These requirements should also apply to existing tunnels; however, the plausibility of the existing tunnels to fully meet the requirements has to be taken into account. An assessment of whether the tunnel in all relevant aspects meet the technical and administrative requirements or not should be made.

Every category in Figure 3 cannot be described in detail due to length restrictions, but the technical requirements are to be found in the reference documents and are developed further in (17).

Step 4 – Risk based categorization
A tunnel, whose safety concept includes the technical and administrative requirements in accordance with the specified risk category 1a, 1b, 2a, 2b, 3a, 3b, 3c or 3d can, with no further risk assessments, be categorized as a C-tunnel (or D or E). The same tunnel can, with no further risk assessment, be categorized as an A-tunnel (or B) if the following requirements are met:

Risk of fire and explosion has been considered in particular, and necessary safety precautions have been implemented. The need for implementing more preventive measures have been evaluated, and if
it is reasonable to implement these. A selection of suitable precautions to implement is presented below:

- Rigorous requirements regarding the protection of load bearing structures in case of a fire.
- Increased requirements regarding separating components explosion load absorption capacity.
- Installation of a fixed extinguishing system.
- Special precautions to minimize the risks with some or all vehicles transporting dangerous goods, e.g. declaration before entering the tunnel, convoy transportation escorted by a vehicle, the shutdown of other traffic or to control the traffic to specific times (the tunnel’s category vary with time of day).

For tunnels in risk category X (see Figure 3), the risk is so complex that the tunnel, regardless of the technical standard, must be further investigated. Without investigation, the tunnel should be regarded as an E-tunnel.

Note that the presented tunnel categories are based on risk and safety aspects, in accordance with the comprehensive method for categorization. There are also other aspects that has to be considered as part of the category decision.

The level for what is considered enough safety precautions is not clearly specified. To some extent, it is possible to make a decision based on other basis than a risk analysis. If there is not enough experience and basis for a decision, it is necessary to obtain a risk analysis in accordance with level 2 or 3 in this method, to be able to motivate a decision of a tunnel category A (or B).

**LEVEL 2 – EXTENSIVE TUNNEL RISK ANALYSIS**

This section describes risk analysis of road tunnels and tunnel safety, in accordance with the comprehensive method for categorization. It is recommended that such a risk analysis, herein referred to as level 2, is used as a second step when the simplified risk analysis (level 1) for some reason, e.g. the tunnels complexity or expected risk level, does not result in the desired tunnel category. The focus in the descriptions of the level 2 risk analysis is on the overall aspects that need to be considered within the analysis. The exact form of the risk analysis, e.g. types of methods, level of detail etc., has to be based on the requirements of the specific object.

**Introduction to risk analysis as a basis for decision**

Risk analysis is used as a tool to identify, assess and evaluate risks in a systematic way, with the purpose to, when needed, implement suitable risk reduction measurements, e.g. restrictions on the transportation of dangerous goods. Risk analysis is not in itself a solution to a safety issue, but facilitates risk identification and analysis. The practical value in a risk analysis consists of the decisions based on said analysis. These decisions are inevitably inherently affected by the decisions maker’s values, e.g. the decision makers might be risk averse or the opposite. There is not a specified acceptance value or acceptance criteria for risks related to the transportation of dangerous goods in Sweden. To be able to use the risk analysis as a basis for decision, it is crucial to present the values (safety targets), value criteria and acceptance criteria resulting in the analysis’s result. Value and acceptance criteria simplifies the communication of relevant risks between involved parties. It is important that the risk analysis’s level of detail, its method and limitations are chosen in a way that relates to the chosen criteria.

Given the lack of value and acceptance criteria, it is practically impossible to, via risk analysis, show or verify that a specific tunnel design results in an acceptable risk level in accordance with current legislation.

Suitable literature to learn more about risk analysis as a basis for decisions are for example Handbok för riskanalyser (18), Olycksrisker och MKB (15) and Värdering av risk (20).

**Risks with dangerous goods in road tunnels compared to the surface road network**

Accidents involving dangerous goods in road tunnels are associated with other prerequisites compared to if the same accident happened on the surface road network. These prerequisites can be positive in the sense that the consequence might be lessened by them, e.g. the possibility to evacuate the hazard...
area (passengers) is sometimes easier and the protection of third person (people in surrounding
buildings) is in many cases better. In other instances the prerequisites work in the opposite way, e.g.
the potential consequences in case of a fire are bigger. However, one cannot draw general conclusions
when comparing the risks of transporting dangerous goods in tunnels with transports on the surface
road network, there are too many uncertainties within each scenario. All roads are associated with a
specific, unique design and different goods and amounts are transported, and is therefore associated
with specific, unique prerequisites and risks. In addition, the surroundings, e.g. the design of buildings
in the vicinity of the road, can be more or less suitable to limit the consequences of an accident
involving dangerous goods. Further examples of such specific conditions are if a road tunnel is
situated close to a densely populated area and/or a decking-type construction is located on top of the
tunnel. These examples of conditions result in that no general conclusions can be made regarding a
comparison of the risks with dangerous goods in road tunnels and on the surface road network.

**Prerequisites to consider for a risk analysis regarding tunnel safety**

The measurements needed as part of a tunnels safety concept depends on the following overall
prerequisites, which together determine the expected risk: the physical design of the tunnel, the
geographical location of the tunnel (surrounding aspects), type of traffic (cars, trucks and dangerous
goods transports), the amount of traffic and the conditions for rescue operations. Risk analysis
conducted with the purpose to act as a basis for decision for categorization in accordance with ADR-
2017, should include these overall aspects.

The Ordinance on Safety in Road Tunnels (16) specifies what risk factors should be included in the
risk analysis when it is acting as a basis for the safety concept. The ordinance regulates in the 2:nd
chapter. 1 § that, the safety precautions in the tunnel should be based on a systematical assessment of
all the relevant system aspects, i.e. infrastructure, operation, passengers and vehicles. The legislation
specify the following risk factors/parameters to be included in such an assessment: tunnel length,
number of pipes, number of traffic lanes and their width, the tunnel’s cross section geometry, vertical
and horizontal alignment, one way or two way traffic, traffic flow in relation to time of day, speed,
risk of traffic jam (daily or seasonal), percentage of heavy trucks, percentage and type of dangerous
goods, the tunnel’s type of construction, time for the rescue service to reach the tunnel and their
capacity to conduct a rescue mission, the characteristics of the roads used by the fire service and the
geographical and metrological prerequisites.

If a tunnel has a particular design given certain risk factors (length etc.), the ordinance states that a
risk analysis should be made to determine if more safety precautions or extra equipment is needed to
determine if the safety level in the tunnel is acceptable or not.

In the requirements on safety in road tunnels (16) it is stated that the safety measures taken for tunnels
should be the result of an overall assessment. The assessment should take into account for example
proportion and type of transport of dangerous goods.

Advisable suitable measurements to minimize the risks can for example be declaration before entering
the tunnel, transport in a convoy escorted by a vehicle, shut down of all other traffic or to control the
traffic to certain hours. These operational measurements can also be implemented in accordance with
the ADR-regulation and shall therefore be considered in a risk analysis acting as a basis for decision
for categorization.

It is also important that, when categorizing a tunnel, temporary and permanent as well as planned and
unplanned shutdowns of the tunnel and how unique transport, e.g. those transported with a
dispensation, are considered.

Suitable literature to learn more about risk analysis for road tunnels are: Integrated Approach to Road
Tunnel Safety (21), Combined Qualitative and Quantitative Fire Risk Analysis – Complex Urban
Tunnels (21), Veileder for risikoanalyser av vegtunnlar (revidert) (22), Riskanalysmetoder (23),
Riskvärdering (25), Tunnel 16 (13) (13), Towards Development of a Risk Management Approach
(26), Risk Analysis for Road Tunnels (27), and Current Practice for Risk Evaluation for Road Tunnels
(28).
There is also useful information in the documentation from the two research projects UPTUN (Upgrading of existing tunnels) and FIT (Fire in tunnels) and at the PIARC: website for tunnel safety.

**Risk analysis for categorization of road tunnels**

There are many methods, both in Sweden and internationally, for risk analysis whose purpose in particular is to assess risks associated with transportation of dangerous goods in road tunnels and/or to categorize road tunnels in accordance with the ADR-regulations. However, there are no international agreements on how these risk analyses should be carried out, but there is a large amount of information and material that can be used from these methods, e.g. from project reports such as The Nothern Link in Stockholm (15) where an extensive event-tree analysis is used.

The risk analysis method named DG-QRAM ((Dangerous Goods – Quantitative Risk Assessment Model) should be mentioned in particular. It was developed in parallel with the new EU-directives and should act as a support when categorizing tunnels with dangerous goods.

DG-QRAM is a software developed by INERIS (France) and WS Atkins (UK) in a cooperation with the Institute of Risk Research from University of Waterloo (Canada). The work has been supervised and followed up by a coordination committee formed by OECD (Organization for Economic Co-operation and Development) and PIARC (World Road Association). The purpose of DG-QRAM is to calculate the risks with transport of dangerous good on the surface road network and/or in road tunnels and should be used to compare different solutions or as a comparison of acceptance criteria.

The model is only studying the extra risk inherent in dangerous goods transports. Risk associated with “normal” traffic accidents on the surface road network or in tunnels are excluded. The model is based on 13 predefined scenarios. The first two covers fires in trucks (no dangerous goods), The rest covers accidents with dangerous goods class 2 (flammable and toxic gas) and class 3 (flammable liquid). Other dangerous goods classes are not included. Additional development of software for tunnel risk analysis has been financed by The Norwegian Public Road Administration which has resulted in the model Transit (28) but it is not publicly available at the moment.

As a support for categorization on level 2 extensive literature regarding certain aspects are available and can be incorporated in the framework presented here. The following documents are international guidance documents based on risk analysis to categorize road tunnels: Safe in tunnels – Transport of dangerous goods through road tunnels (28), Verfahren zur Kategorisierung von Straßentunneln gemäß ADR 2007 (29) (freely translated: Method for categorizing road tunnels in accordance with ADR 2007), Risk analysis relating to dangerous goods transport (32), Current practice for risk evaluation for road tunnels (28), Guide to Road Tunnel Safety Documentation (31) and Methodological Approaches for Tunnel Classification According to ADR Agreement (33).

### Pre-defined scenarios in DG-QRAM

1. Heavy Goods Vehicle fire with no dangerous goods (20 MW)
2. Heavy Goods Vehicle fire with no dangerous goods (100 MW)
3. Boiling Liquid Expanding Vapour Explosion (BLEVE) of Liquid Petroleum Gas (LPG) in cylinders
4. Pool fire of motor spirit in bulk
5. Vapour Cloud Explosion (VCE) of motor spirit in bulk
6. Release of chlorine in bulk
7. BLEVE of LPG in bulk
8. VCE of LPG in bulk
9. Torch fire of LPG in bulk
10. Release of ammonia in bulk
11. Release of acrolein in bulk
12. Release of acrolein in cylinders
13. BLEVE of carbon dioxide in bulk (not including toxic effects)

**LEVEL 3 – EXPERT ASSESSMENT**

This section gives an overall expert assessment method for risk based categorization. The expert assessment regarding suitable tunnel category should only be used when the other methods for some reason cannot be used.

The Expert Assessment means an assessment based on experience and is qualitative. The expert assessment is a subjective assessment carried out by one or several persons with relevant knowledge about the subject. It is important to note that all risk analyses contain subjective elements, i.e. elements of expert assessments. The expert assessment described here refers to a more straightforward...
expert assessment, without support from an explicit risk analysis method, e.g. leve 1 or level 2 approach.

The advantages of using an expert assessment compared to a risk analysis method are that it is usually a fairly simple process and it requires less resources. However, the disadvantages are many. For example it is difficult to carry out the assessment in a systematical way and present the facts behind the assessment. To document an expert assessment is also therefore important, some examples of what the documentation may include are: The compositions of the expert group, the purpose and target of the assessment and the available facts. It is crucial that the expert group have the necessary knowledge about the tunnel and its surroundings, and the competence to perform the assessment.

**RISK ASSESSMENT FOR SURFACE ROAD NETWORK**

All cases with a restriction on transport of dangerous goods in tunnels, i.e. categories B-E, needs documentation as a basis for the decision of a category. The documentation regarding the category decision should include an assessment of risk level for the surroundings and along the alternative road used for goods not allowed in the tunnel. The alternative road is here assumed to be a surface road, which should be the normal case.

This guiding document does not include further development or descriptions of specific risk assessment methods to assess the risk exposure from an alternative surface network. However, this section gives an orientation of the aspects needed to be included in any such risk analysis. The corresponding method should be useful when studying the risk impact from the road used for re-routing when the tunnel is shut down, even if the prerequisites can be different.

The current legislation’s requirements on risk management, e.g. who is to be protected and area specific conditions regarding for example objects and environment required to be safe-guarded, risk objects, risk sources etc. mainly determine the scope and the level of detail of the risk assessment covering the surface road network acting as the alternative road section.

**Scope of work**

The applicable legislation is, in this case, the Act of Transport of Dangerous Gods (1). The purpose of the legislation is to increase the safety when transporting dangerous goods, by minimizing the probability of an accident and to limit the consequences for human life and health, natural environment and property. One way of acquiring knowledge about the probability of, and consequences of an accident on the alternative road section, is to, in a systematical way with help from a risk analysis method, identify, assess and evaluate the risk impact from the redirected transports on adjacent protective objects, i.e. human life and health, environment and property.

To be able to use the risk assessment as a suitable basis for decision, it is important that it covers the risk objects, risk sources and objects worthy of protection, that are covered in the legislation.

**Choice of method and level of detail**

As for the assessment of the tunnel safety, the choice of method and the level of detail in a risk assessment for the surrounding along the alternative road section has to be adjusted to every specific case. An important factor is the assessment’s overall purpose, e.g. if it is to act as a basis for the evaluation between different road sections or if it should determine the need for measurements along the section. Likewise, the complexity of the current risk is an aspect to consider when choosing the method and level of detail. Whatever method and level of detail the assessment should, in a well-supported way, answer the questions described above in the scope of work section of this paper. If the alternative road section runs through unpopulated areas, it may be enough to state that the accidents have little to no effect on the people in the surroundings and to document why it can be considered an acceptable risk when diverting the dangerous goods transports. If the location of the tunnels is adjacent to a protected region of environmental or cultural value, or a highly populated area, this may lead to the need of a more detailed risk assessment, to determine the need of measurements or a different location.

**Risk assessment in spatial/land-use planning**

It is common to address the risk impact along roads with dangerous goods, when assessing the risks in the land-use planning process, where the transports on road often represents the risk object. Risk
assessments in land-use planning usually only covers how accidents involving dangerous goods may affect a limited part of the area along the road section, i.e. along a specific detailed development plan. In these risk assessments, carried out for different local plans, it is ensured that enough consideration is taken regarding risks for the planned land use from adjacent roads and other risk sources. This is done by implementing different risk mitigating measurements regarding e.g. configuration of the detailed development plan or the design of the buildings. For older buildings, there are usually no such risk consideration.

A number of guiding documents are carried out for these risk analyses, in which requirements of content and quality are described, to approve as basis for decision. Documents of general character and specific documents for the planning and development of new buildings are listed below. It is important to note the difference in scope depending on what legislation or what requirements are governing in different situations. Therefore, the documents should only act as guiding in each specific case.

Examples on guiding documents regarding risk management in land-use planning: Riskanalyser som beslutsunderlag (32), Handledning – Riskanalys vald vägsträcka (36), Fördjupning – Riskanalys vald vägsträcka (34), Riktlinjer för riskhänsyn i samhällsplaneringen – Bebyggelseplanering intill väg och järnväg för transport av farligt gods (36), Riskhantering i detaljplaneprocessen. Riskpolicy för markanvändning intill transportleder för farligt gods (39), Riskanalyser i detaljplaneprocessen – vem, vad, när & hur? (37), Riskhantering vid ny bebyggelse intill vägar och järnvägar med transport av farligt gods och bensinstationer (38), samt Säkerhetshöjande åtgärder i detaljplaner (39).

CONCLUSIONS
Categorization is a complex process where it is necessary to address the risks in the tunnel, the risks along the alternative route for transports considered to be restricted from the tunnel and what risk reducing measures that are practically applicable. The decision regarding categorization can be structured with a decision model in which risk analysis plays a central part. The risk analysis model can be executed with different level of complexity depending on the prerequisites for both the analysis, the risk reducing measures possible to apply and the level of conservatism that is applicable. Independently of the method chosen the documentation of the method and the prerequisites together with the quality of the assessment carried out is very important.

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The Art of Refurbishment of In-Service Tunnels

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ABSTRACT

Many old road tunnels in Europe have reached their initial design life time. Additionally, the legislation and requirements for tunnel safety have changed considerably in the last decade. Therefore, refurbishment and upgrade projects have been carried out in many tunnels or will be carried out in the near future. In these projects the desired safety level will often be based on the current legislation and requirements where possible. The constraints of the existing situation and choices from the past, poses challenges for the refurbishment and upgrade projects. In this paper refurbishment and upgrade projects of Dutch road tunnels carried out in recent years are described. The major challenges encountered, and lessons learned are discussed, mainly based on our experience with the refurbishment of the IJ-tunnel [1] in Amsterdam (finalised in 2016) and the Maastunnel in Rotterdam (planned to start from medio 2017), which are both tunnels operated by the respective cities.

KEYWORDS: Refurbishment, tunnel safety, operation, legislation.

INTRODUCTION

During the last decades, the knowledge level on tunnel fires and tunnel fire safety has increased considerably due to tunnel fires in the Alps around the year 2000 and e.g. the UPTUN research program [2]. The main findings are that fires in heavy goods vehicles with common goods can already lead to high heat release rates and high temperatures, much higher than anticipated up to that moment. This eventually impacts the desired safety level for tunnels and the legislation of the member states of the European Union, e.g. via the implementation of the European Directive 2004/54/EC [3]. The modification of the safety concept and the directly related design fire size and escape routes as well as new requirements on compartmentation and structural safety have the largest impact for in-service tunnels as the existing civil structure limits the design freedom.

Refurbishment projects on various in-service road tunnels have been carried out since the introduction of the Dutch Tunnel Law in 2006, for instance the IJ-tunnel in Amsterdam (2012-2016) and the listed Maastunnel (2017-2019) in Rotterdam. More refurbishment and upgrade projects will be carried out in the near future. The main reasons for this are ageing tunnel equipment and road surfaces and the limited smoke control capacity of the old ventilation systems. In these projects the desired safety level will often be based on the current legislation and requirements where possible. The constraints of the existing situation and choices from the past, poses challenges for the refurbishment and structural upgrades.

STRUCTURAL UPGRADES

The motivation for structural upgrades can be twofold. On the one hand there is doubt regarding the fire resistance of the load bearing structure. The commonly used fire curves and the knowledge on spalling of concrete have evolved in the last decades. The topic of designing fire resistance for existing structures has been covered before [4].

On the other hand, there are issues with the fire compartmentation of old road tunnels, especially the compartmentation of the escape routes. In the Netherlands, it is common to have an escape gallery in
between the two tunnel tubes when possible, alternatively cross-connections are constructed between the tunnel tubes. Especially in older, in-service tunnels like the IJ-tunnel, it is required to limit the leakage between each tunnel tube and the escape gallery to be able to provide pressurisation of the escape routes.

**UPGRADE OF SAFETY SYSTEMS – TUNNEL VENTILATION**

**Increase of design fire size**
The tunnel fires in the Alps as well as the results of the UPTUN fire tests [5] have shown that heavy goods vehicles with rather ordinary goods can already reach high heat release rates and temperatures. Therefore, design fire sizes of 100MW or 200MW are common nowadays in the design for new tunnels. In many in-service tunnels the ventilation systems were originally not designed for fire sizes of 100MW or more, which applies specifically for the IJ-tunnel and Maastunnel designed over 60 years ago and equipped with transverse ventilation systems to control the vehicle emissions. The transverse ventilation systems of both tunnels consist of supply and extraction ducts for different tunnel sections and tunnel tubes to supply fresh air and extract polluted air from the tunnel through the tunnel ventilation buildings equipped with fans.

**Maastunnel – From transverse ventilation system to longitudinal ventilation**
The Maastunnel is an in-service river tunnel in the municipality of Rotterdam being operated since 1942. The Maastunnel is still a vital part of the road network in the city. In July 2017 an extensive refurbishment and upgrade project was started with the purpose to realise 1) a safe motorway tunnel compliant with the Dutch Tunnel Act and Building Codes, 2) to restore the concrete construction and apply state-of-the-art technical installations and 3) to do justice to the listed status of the Maastunnel and bring back a time sense of 1942.

Before the renovation, the Maastunnel the transverse ventilation system consisted of an ingeniously designed system of supply and exhaust ducts for the different sections and tunnel tubes of the tunnel which enter the tunnel through the two ventilation buildings between the river tunnel and land tunnel. The air flow is distributed over the length of a tunnel section by varying the dimensions of slits between the extraction duct and the tunnel. A drawing and picture of one of the ventilation building of the Maastunnel is shown in Figure 1.

![Figure 1 Maastunnel: Original ventilation building between river and land tunnel with supply and exhaust (Photo: Municipality of Rotterdam).](image)

The Maastunnel, including the ventilation buildings, is a national heritage site as it is one of the oldest immersed tunnel in the Netherlands and one of the first rectangular immersed tunnels in the world.

For the Maastunnel, the supply and extraction ducts in the land tunnel section could only locally be
removed above the traffic tube to install one cluster of jet fans near each of the (4) portals. The transverse ventilation system is not used for emergency ventilation. So, the emergency ventilation consists of the newly installed jet fans composing the longitudinal ventilation system, where in the original situation only transverse ventilation was present.

**IJ-tunnel – From transverse ventilation system to hybrid ventilation system**

The IJ-tunnel (commissioned in 1968) is a river tunnel with a length of 1140 m under the IJ which connects the centre of Amsterdam with the Amsterdam Noord district. It is an old in-service tunnel where relatively a lot of bus transport passes through. In addition, the safety concept differs from most recent tunnels. A feature of the IJ-tunnel is a hybrid ventilation system that consists of a combination of longitudinal ventilation and cross-ventilation.

For the IJ-tunnel, the supply and extraction ducts in the land tunnel section above the traffic tube were removed to enlarge the tunnel cross-section and enable the mounting of multiple clusters of jet fans and therefore longitudinal ventilation. In addition, the extraction ventilation of the original transverse ventilation system is still used when downstream of the detected fire location as this effectively increases the ventilation velocity in the tunnel as the available mounting space was not sufficient to achieve a fully longitudinal ventilation system with jet fans only.

The IJ-tunnel is divided in different section and the fire detection system is equipped to detect in which of these sections the fire is located. Additionally, traffic data is used to determine whether traffic at low speed is present downstream (traffic jam) of the detected fire location. Depending on the presence of traffic downstream and the detected fire location, a combination of jet fans and extraction is switched on in the accident tube (and in the non-accident to prevent the recirculation of smoke) as shown in Figure 2.

![Figure 2 IJ-tunnel: Hybrid ventilation system with a combination of jet fans and smoke extraction. In the original situation only transversal ventilation was present.](image)

By ventilation a safe zone will be created upstream from the accident location. The evacuation will be prepared: evacuation lighting is switched on, maximum lighting in the accident tube is switched on, traffic lights on both sides of the tunnel will be put on red and the emergency barriers will be closed to prevent vehicles entering the tunnel.
An escape gallery is present between the two traffic tubes, see Figure 3. In the southern part of the IJ-tunnel the escape gallery is used for the evacuation of road users. In the middle and northern part, the escape doors lead to the safe tube via a closed central portal (located in the escape gallery which is inaccessible).

Figure 3 shows that both tubes have eight escape doors. At five locations, these escape doors are situated close to an increased inspection path in both tubes. Stairs are provided on both sides of the emergency door, which allows the door to be reached by the evacuees. Some of the escape doors are directly accessible from the road surface level.

In the non-accident tube the ventilation will be activated to create overpressure for a safe escape route. The emergency door contour lighting will be switched on and the sound beacons at the emergency door will be activated. Escape instruction are provided by the speakers and also broadcasted via the radio.

The non-accident tube will be closed for traffic and emptied. It is noted that evacuees in the northern part will initially reach the (increased) inspection path in the non-accident tube and not directly on the road. Evacuees in the southern part of the tunnel, between the south tunnel portal and the escape doors O3/W3 will use the escape gallery without having to enter the non-accident tube.

Upgrade of ventilation capacity

The capacity of the full transverse ventilation systems for both tunnels before the refurbishments to handle a fire was rather limited as these were designed for emission control. Analyses carried out to determine the maximum fire size that could be handled with the original transverse systems was much lower than 100MW and could even be as low as 10MW depending on the position in the tunnel (e.g. grade) and the position of the supply and extraction openings.

Given the limited existing ventilation capacity, it can generally be quite a challenge to upgrade the tunnel ventilation system as the existing (immersed) tunnels poses severe civil constraints: the extraction ducts cannot easily be enlarged, because the total immersed tunnel size is fixed, the required duct size to handle the current design fire sizes would be huge and the expected ability of these ducts to withstand high smoke temperatures is limited. Therefore, changing the ventilation concept to hybrid or longitudinal ventilation is to be considered, keeping in mind that longitudinal ventilation is only suitable for tubes with unidirectional traffic per tube and not suitable if the probability of traffic jams in the tunnel is high.

In the specific case of the IJ-tunnel and Maastunnel, the cross-section of the tunnels and the heights of the tunnels are rather limited, so jet fans cannot be mounted without reducing the clearance of the tunnel and therefore posing limitations to the usage of the tunnel by HGV and buses. Additionally, the
required ventilation capacity is too large to use jet fans at the entrances of the tubes only. Saccardo nozzles could be possible, but need to fit in the existing construction (and the land use above the tunnel). In another tunnel in The Netherlands, the Velsertunnel, the interior height of the tunnel was increased during the refurbishment by lowering the road surface, still preventing floating of the tunnel. For the IJ-tunnel and Maastunnel it was not possible to increase the interior height over the full tunnel length as the extraction and supply ducts are not always above or below the tunnel along the length: in the immersed part the ducts are located below the tunnel and in the land tunnel part the ducts are above the tunnel (see also the longitudinal cross-section of the IJ-tunnel in Figure 3.

So summarizing, for in-service tunnels with transverse ventilation a design to meet the current requirements can be found by going through the following steps, shown in Figure 4, to end up with different design options to be evaluated in more detail:

1. Is the capacity of the existing transverse ventilation system sufficient (given the duct size and design fire size)?
2. Is it possible to increase the capacity of the existing transverse ventilation sufficiently (given the structural constraints)?
3. Is it possible to apply longitudinal ventilation (given the tunnel operation constraints: unidirectional traffic)?
   a) Do jet fans fit in the existing cross-section of the tunnel (given the clearance)?
   b) Is it possible to apply longitudinal ventilation with modifications near the tunnel portals only (jet fans or Saccardo)?
   c) Is it possible to increase the existing cross-section of the tunnel (to include jet fans without reducing the clearance)?
      i) Is it possible to remove existing ventilation ducts?
         (1) Locally: to provide space for a ventilation cluster?
         (2) Over a longer distance (section): to provide space for multiple ventilation clusters?
      ii) Is it possible to lower the road surface?

Figure 4  Step-wise approach to analyse design options for the upgrade of an existing transversal ventilation system.

**UPGRADE OF SAFETY SYSTEMS – PRESSURIZATION OF ESCAPE ROUTES**

In many in-service tunnels, separate escape routes are present that can be pressurized to prevent smoke distribution in the escape route. Most Dutch tunnels have an escape gallery in between the two tunnel tubes, which serves as escape route. Over the years, the insights regarding escape route pressurization and the design requirements have changed considerably. Design requirements include the number of simultaneously opened escape doors and the minimum and maximum flow velocities in the escape gallery and the opened doors.
The main lessons learned are:

- **Tunnel ventilation:** The design of the tunnel ventilation system affects the requirements for the pressurization of the escape routes as the pressure distribution in the tunnel tube affects the flows from escape route to the tunnel and vice versa through open escape doors. As the tunnel ventilation is refurbished, the pressurization needs to be refurbished as well.

- **Leakage:** It is observed that the control of the leakage of air through connections between the pressurised escape route and other compartments like the tunnel tube through segment connections, escape doors, cable penetrations etc. is very important in older in-service tunnels.

### SAFE TUNNEL OPERATION DURING REFURBISHMENT PROJECTS

**Refurbishment and operation of in-service road tunnels**

Another issue during refurbishment projects is the availability of the tunnel system. Non-availability of the road infrastructure is considered as inconvenience for road users and becoming less and less accepted. For instance, the increasing pressure on the existing space in Amsterdam and Rotterdam would lead to disruption in traffic flow after a the IJ-tunnel or the Maastunnel would be taken out of service. For this reason, many road tunnels are only partly closed for traffic during refurbishment works. To guarantee safe operation during each phase of the works, Dutch tunnel managers are responsible for a Phasing Plan for Safe Operation (PPSO). A PPSO describes the agreements on temporary measures for safe operation during the works between the tunnel manager, the project delivery manager and the contractor.

To better understand the complexity to follow the procedures in the PPSO, the evacuation concept after finishing the refurbishment work is outlined for the Maastunnel. Then, in the next section the evacuation concept during the works of the Maastunnel is explained.

**Evacuation concept after commissioning the refurbished Maastunnel in 2019**

The evacuation concept in the Maastunnel (see Figure 5) differs from the IJ-tunnel. In case of a fire longitudinal ventilation will be switched on full power to spread the smoke in the driving direction.

In this way a safe zone will be created upstream from the accident location. The evacuation will be prepared: the evacuation lighting is switched on, the maximum lighting in the tube is switched on, traffic lights on both sides of the tunnel will be put on red and the emergency barriers will be closed.

In the non-accident tube the ventilation will be activated in the driving direction to create an overpressure in the non-accident tube. The emergency door contour lighting will be switched on and the sound beacons at the escape doors will be activated. Escape instructions are provided by the speakers and also broadcasted via the radio.

Tunnel users will escape via unfoldable stairs that are positioned in the inspection path. Escape doors are present in the wall between the traffic tubes to escape from the accident to the non-accident tube. These escape doors are elevated so the evacuees first have to climb an unfoldable stairway onto the
inspection path before using the doors (see Figure 6). Then, the evacuees will reach the inspection path of the non-accident tube and return to the road surface via the stairs and then exit the tunnel. After the last evacuee has left the tunnel, the evacuation is complete.

The key points in the evacuation concept are:
1. Controlled enhanced staircases in the inspection path.
2. Emergency signs and clear lighted or illuminating indications of the escape doors;
3. Clear marking of escape doors via led lighting.
4. Ventilation in the driving direction of the accident-tube to prevent smoke to lay-back to the people upstream of the accident.
5. Ventilation in the non-accident tube in the same direction as in the accident tube via reversible ventilation to prevent smoke recirculation from the accident tube and to create overpressure in the accident tube.
6. An adaptive Traffic Jam Management System: this system consists of a speed discrimination system that traces the traffic speed. For too low a traffic speed the systems controls the out and in flow of traffic to prevent traffic jams in the tunnel.

Evacuation concept during refurbishment of the Maastunnel (2017-2019)
The construction period of the Maastunnel is divided in two phases. During construction phase 1 (2017 – 2018) the west tube is being refurbished and the east tube is in operation for traffic in south north direction only. After the end of construction phase 1 a new west tube is commissioned, and the east tube will be refurbished in construction phase 2 (2018 – 2019).

During the refurbishment work fires may occur in the operating tube or a fire in the work tube. In both cases people have to be evacuated from the accident tube via the non-accident tube to a safe zone as will be outlined in the following.

Fires in the operating tube
During a fire in the operational tube self-rescue (egress) and emergency response are crucial when it
comes to life safety and reducing the consequences of a fire.

The prerequisites for egress of road users have been translated by the contractor into safety measures to safely escape from the operating tube via the work tube. The most important adjustments to the escape route are explained below.

In phase 1.1 the demolition of the driving deck of the west tube is being prepared.

The escape route from the east operating tube leads through a new climbing niche with a temporary staircase to the inspection path through the escape doors. And then from the inspection path in the work tube via a temporary staircase type A to the floor (see Figure 7).

Figure 6 Maastunnel: lateral view (above) and top (below) view of inspection paths and elevated escape doors (yellow) in the wall between the tubes.

Figure 7 Escape route during phase 1.1.
All evacuees walk to the southern tunnel portal over the driving floor and the mobile temporary reversible building ventilation to control the air quality of the workers is stopped by an instructed employee. The escape route over the building traffic route for building traffic is shown in Figure 8. The building traffic that travels from south to north is stopped, in such a way that the escape route is not blocked.

In the work tube during the various sub phases until the moment where new asphalt is applied, the building traffic route is marked by a (white) alignment. Within this marked route, a (green) alignment is placed to mark the escape route in the work tube to the south side. The width of this escape route is at least 1.2 m.

During Phases 1.2 (Driving deck removal), Phase 1.3 (Floor repair) and Phase 1.4 (New driving deck) in the river tunnel the escape route leads from the operating tube via a new climbing niche with a temporary staircase to the inspection path through the escape doors (see Figure 9). Then, the existing inspection path is widened from 0.7 m to 1.2 m and fitted with a robust handrail. At the transition from river to land tunnel, the evacuees are led via a type B staircase to the driving floor and further to the southern tunnel portal (see Figure 9). In case of accidents, the building ventilation is stopped by an instructed employee. Again, the traffic that travels in and out from both sides of the work tube is stopped so that the escape route is not blocked.

In the land tunnel the escape route leads from the operating tube via a new climbing niche with a temporary staircase to the inspection path through the escape doors (see Figure 10). And then, from the inspection path in the work tube via a type A staircase to the floor.

All evacuees walk over the driving floor to the southern tunnel portal and the evacuees in the land tunnel north are led via a staircase to the widened inspection path of the river tunnel and move in the same way as described at the river tunnel section above.

During Phase 1.5 (Completion and prepare testing) the escape route in the whole tunnel leads from the operating tube via a new climbing niche with a temporary staircase to the inspection path through the escape doors. And then, from the inspection path in the work tube via a type A staircase to the floor. All evacuees walk over the driving floor to the southern tunnel portal.
During Phase 1.6 (Testing and detailed completion) in the whole tunnel the escape route leads from the operating tube via a new climbing niche with a temporary staircase to the inspection path through the escape doors. And then from the inspection path in the work tube via the final unfoldable staircase in the unfolded mode (see Figure 11). All evacuees walk over the driving floor to the southern tunnel portal.

During Phase 1.7 (End Site Integration Test) both tubes are closed for traffic.

During normal operation, the work tube and in particular the inspection path will be used as a working area. Only in case of a fire in the operating tube the work tube serves as an escape route and safe zone (smoke and dust free) for evacuees in case of a fire in the operating tube (see Figure 8). The escape route extends over the building site to the adjacent ground level on the south side. Hereto, it is of paramount importance that the safe zone is a real safe zone, in the sense that people will not harm or injure themselves because of building activities.

The PPSO for the Maastunnel describes the procedures how to ensure that a safe escape route for road users and personnel is maintained in the work tube. The following procedures are followed:

1. **Obstacle free escape route**: In case of an evacuation in the operating tube, the personnel of the contractor will leave the inspection path with all equipment obstructing the escape route within one minute. The escape route on the driving deck (see Figure 8) is made free of obstacles within
two minutes.

2. **Unrecognizable escape doors.** The escape doors shall not be opened by the contractor from the work tube except for (fire) accidents in the work tube. An emergency door that is being worked on is not suitable for road users to escape and therefore it is rendered unrecognizable by the tunnel management staff in the operating tube. Also, the inspection path and the evacuation signposting are adjusted by the tunnel management staff. An unrecognizable emergency door is also unusable, or not suitable for flight, in case of accidents in the work tube.

3. **Dust free and available escape doors.** The escape doors shall be reliable to open. Hereto, it must be prevented that dust and dirt from building activities hamper the operation of the escape doors. Therefore, the escape doors and made dust free by the contractor on a daily basis.

**Fires in the work tube**
The contractor has provided an evacuation system which aims to alert its employees in case of a fire accident in the work tube, after which they will leave the work tube via the operating tube. The system consists of a so-called slow-whoop system (sound) and a visual system (red light signal). This system can be activated at each emergency door in the work tube. Activation is done by pressing a button by the observer of the fire. The sound and the light signal are noticed by anyone, including the door man at the south entrance. The door man will call the tunnel operator and inform him to close the operating tube. After the traffic has left the operating tube it will function as a safe zone for the workers (see Figure 12).

![Figure 12 Evacuation system (button to activate slow whoop and red lights) for the work tube.](image)

The evacuation from the work tube in the river tunnel during the period that the old driving deck has been destructed will be for some workers via a ladder and movable handrail.

**Emergency response**
In case of a fire in the operating tube the access route for the fire brigade always runs through the operating tube. Temporary longitudinal ventilation is applied at the southern entrance of the traffic tunnel (east). This ventilation ensures that the fire brigade can use the operating tube to drive smoke free, in the driving direction. Two temporary ventilation fans are also provided at the southern entrance of the work tube for the purpose of a smoke free escape route in the work tube and to preventing smoke reversal at the northern tunnel exit.

In the event of a fire, the longitudinal ventilation is started in both tubes in the driving direction. The ventilation ensures that the fire brigade can access the accident location in a smoke-free way.

Since the work tube is a building area, it is not fit for the purpose as a supporting tube for the fire brigade to approach and fight the fire. Therefore, a dedicated Tunnel Response Team is positioned at a portacabin at the southern entrance of the operating tube with the purpose to compensate the absence of a supporting tube with a fast intervention aimed at “keeping a small fire small”.
The Tunnel Response Team is operational during the traffic peak hours (working days from 06.00 to 22.00 hour and in the weekends from 11.00 to 19.00 hour). When the Tunnel Response Team is absent, the traffic is directed via only one traffic lane. The other free lane is red-crossed and reserved for the regular fire brigade. In this way each accident can be approached with normal rescue vehicles supported by ventilation to create smoke free approach conditions.

Safety levels before and after refurbishment of the Maastunnel

Article 6 of the Dutch Tunnel Act states with respect to the QRA safety test that the societal risk shall not exceed $0.1/N^2$ per kilometre tunnel tube annually, where $N$ is the number of fatalities for $N > 10$. The QRA methodology is prescribed by the same act that unfortunately does not provide rules for a phased renovation, during which one tunnel tube is being operated. Strictly speaking, each construction phase would be a change in Maastunnel use, which requires compliance with the Dutch Tunnel Act including a societal risk profile that meets the test criterion before and after the changes in the Maastunnel system. This would mean that formally at the start of the renovation a commissioning permit must be granted. However, during the renovation it is not possible to meet the safety criterion (which was one of the reasons to start the project), which would lead to a situation where the administrative authority would not grant a commissioning permit.

Therefore, the tunnel manager and the administrative authority have designed a tailor-made safety decision process because of the cruciality of a south-north connection during the works for all traffic including the emergency services. It was agreed that in each construction phase the safety level is compared with the actual safety level. The societal risk profile in the next phase shall not be lower than in the actual safety level. Also, the safety processes traffic flow, accident control, egress and emergency response are included in the safety assessment.

The additional safety measures to guarantee the safety level in each phase are:

- To limit the distances between the escape staircases and the escape doors;
- To apply (temporary) longitudinal ventilation in the operating tube and the work tube;
- To minimise the probability of a traffic jam to reduce the potential number of fatalities during a fire;
- To temporary close a traffic lane during works on escape doors or absence of the Tunnel Response Team to reduce the potential number of fatalities during a fire;
- To create an escape route in the work tube that can be made free of obstacles within 2 minutes.

Besides, the fire brigade has posed some requirements for a safe and adequate emergency response during the for the construction phase:

- It must be possible to safely approach the fire accident;
- It must be possible to fight the fire;
• In case of an escalation the fire brigade shall be able to escape timely.

To warrant and take measures and the conditions for a safe emergency response are stored in the tunnel safety file. The tunnel safety file is the central location where all safety decisions and the actual safety performance of the Maastunnel can be found.

SUMMARY AND CONCLUSION

In this paper the different lessons learned regarding the upgrade of existing tunnels are summarized.

First of all, the design of the tunnel ventilation system affects the requirements for the pressurization of the escape routes as the pressure distribution in the tunnel tube affects the flows from escape route to the tunnel and vice versa through open escape doors. As the tunnel ventilation is refurbished, the pressurization needs to be refurbished as well. In in older in-service tunnels the control of the leakage of air through connections between the pressurised escape route and other compartments is very important.

Secondly, when improving the safety of an old tunnel to the required level of safety, a tailor-made safety decision processes might be needed. In the case of the Maastunnel, the tunnel manager and the administrative authority had to find a way to put the safety level in each construction phase to the test. During each construction phase a new mode of operation of the tunnel is introduced, which would require a commissioning procedure that would lead to failure of the societal risk profile test in the first construction phase. Therefore, the tunnel manager and the administrative authority agreed that a gradual enhancement (stand still principle) of the safety in each construction phase of the renovation project would be sufficient to proceed.

And last but not least all the extra procedures required by the tube-after-tube approach need extra training and education for all parties involved. During the response to an accident not only the tunnel operator and emergency services are involved, but also the contractor that is responsible for the safety of his personnel. This paper has focussed on the evacuation of travellers via the work tube. However, a fire accident in the work tube is imaginable and then the traffic has to be stopped to create a safe escape route for the personnel. Therefore, multi-disciplinary training at the beginning of the renovation and frequently repeated has appeared to be crucial for ensuring a safe operation of the Maastunnel.

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Simulation of Fire Propagation in Cable Tray Installations for Particle Accelerator Facility Tunnels

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ABSTRACT
In this paper, it is demonstrated that the simulation of fire propagation in cable tray installations, with the Fire Dynamics Simulator (FDS), version 6.3.2, can be achieved. A material parameter set allowing to estimate the fire spread, depending on environmental conditions close to the fire seat, was generated. The parameters are determined by utilisation of an evolutionary algorithm, in an inverse modelling framework, based on experimental data from Cone Calorimeter tests. As a further step, the performance of the parameter set is compared between the FDS versions 6.3.2 and 6.5.3.

The foundation of this work are experimental results of the CHRISTIFIRE campaign. The inverse modelling approach is inspired by and based on Anna Matala’s and Chris Lautenberger’s work. A material parameter set generated by the evolutionary algorithm is then used in a real scale cable tray fire simulation to predict the fire propagation. The total heat release rate (HRR) of the cable tray simulation and the respective experiment are compared and are in good agreement. The major features in the HRR plot of the experimental data are visible in the simulation results, but slightly shifted in time. Thus, predicting the fire propagation in a simulation, based on data of small-scale experiments, seems possible with FDS.

However, the parameters used in this work are model specific and very sensitive to changes in the model, like grid resolution and FDS version.

KEYWORD: FDS, pyrolysis, CHRISTIFIRE, cone calorimeter, cable tray fire, inverse modelling, evolutionary algorithm, genetic algorithm, SCE-UA, particle accelerator;

INTRODUCTION
The European Organization for Nuclear Research (CERN) is one of the largest particle research laboratories in the world, situated north of Geneva in Switzerland and France. The Organisation’s facilities are very divers and encompass a variety of surface buildings, ranging from office buildings, restaurants and hotels to computing centres, large storage facilities, workshops and experimental halls. Furthermore, extensive underground facilities house particle accelerators, which are connected via transfer tunnels between one another, and are directly connected to multi-storey experimental caverns. Combined they have a length of about 76 km [1]. The so-called accelerator chain (Figure 1) starts from a linear accelerator (LINAC 2) where protons are injected into the chain. They are accelerated close to the speed of light, before they are used in various experiments. During this process, the protons travel through different accelerators: the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) into the Large Hadron Collider (LHC). The accelerators LINAC 2, PSB and PS are housed in surface buildings. The facilities of SPS and LHC are deeper underground between 30 to 150 m. Access is provided via vertical shafts, some of which contain elevators and staircases, whilst others are clear of obstructions to allow for equipment and material transport, using cranes. The tunnel cross section diameters are between 4.5 m to 6.2 m. This allows for the movement of material and personnel. Distances between the access shafts range from 150 m for the PS up to about 3 km for the LHC. Since the accelerators are ring-shaped, the accelerator...
tunnels are also used as ventilation ducts. Parts of the facilities are relatively old. For example, the PS has been in operation for nearly six decades now. Furthermore, plans for new accelerators are studied. One of which is the Future Circular Collider (FCC) study to design requirements for the FCC. This accelerator is envisioned to be housed in an 80 km to 100 km long, ring-shaped tunnel, up to 400 m below the earth’s surface, with a tunnel diameter of about 6.2 m and distances between the access shafts of about 10 km. During operation of the accelerators, the tunnels and experimental caverns, as well as the equipment installed therein, are subjected to radiation. Over time, this leads to parts of the equipment becoming activated (radioactive). The radiation levels depend on the location along the accelerator, with the highest radiation levels occurring at the beam dumps, the experimental caverns and kicker magnets. Thus, design fires for particle accelerators need to be carefully evaluated, when radiological release in case of fire has to be estimated.

![Schematic overview over the particle accelerator facilities at CERN](image)

**Figure 1: Schematic overview over the particle accelerator facilities at CERN [2].**

The accelerator facilities contain a huge amount of electrical cables used for power supply, machine control and data transfer from the experiments to the data centres. Cables constitute one of the major hazards with respect to fire safety inside particle accelerator facilities. A cable fire can lead to the spread of smoke and heat within the facility, jeopardising people and equipment. Due to their unique layout and purpose, statistical data is scarce. Thus, other means to define the design fire need to be established.

Cables are a major fire load not only for CERN, but also in facilities like telecommunication data centres or nuclear power plants. In 2012, the United States Nuclear Regulatory Commission (U.S.NRC) published a report on an extensive cable fire test campaign which had been conducted in the previous years, titled “Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE)” [3].
Given the rigid nature of design fires, different options are investigated to achieve a more detailed representation of fire and smoke spread simulation. Part of the ongoing research deals with the modelling of the pyrolysis reaction of a material, since it is an important factor when it comes to fire propagation. It determines how much combustible gas will be released based on the solid’s temperature, thus determines the fire development. Often pyrolysis models are based on an Arrhenius equation because it allows to describe the results of small scale fire tests, which focus on pyrolysis like micro-combustion calorimetry (MCC), well. On an international level, different groups put effort into understanding pyrolysis and how to simulate this phenomenon properly. For example within the ongoing research, focus has been put on Latin-Hypercube sampling [4] [5], evolutionary algorithms [6] [7] or statistical methods like Bayesian updating [8]. It is of great interest for the fire safety community to have a reliable process which generates material parameter sets based on small scale experiments, that are able to replicate the fire behaviour within a simulation.

In this paper, it is demonstrated that the simulation of fire propagation in cable tray installations, with the Fire Dynamics Simulator (FDS), version 6.3.2 [9], can be achieved if appropriate input data can be obtained in combination with limited experimental testing work. A material parameter set was generated that allows to estimate the fire spread depending on the environmental conditions close to the fire seat. The parameters are determined by utilisation of an evolutionary algorithm, in an inverse modelling setup, based on experimental data from Cone Calorimeter tests.

MATERIALS AND METHODS

In the CHRISTIFIRE program, cable fire tests ranged from small-scale tests of the cable components with MCC, bench-scale tests with tube furnace and Cone Calorimeter to real-scale tests with cable tray arrangements in the open, in mock-up corridors and vertical shafts. This wide variety of tests makes the CHRISTIFIRE campaign a valuable source for the creation of design fires and the validation of simulation results. Out of the tested cables, cable #219 was chosen for this work, because it was one of the cables that was tested in a cable tray arrangement, where all trays were filled with this specific cable. Also, its behaviour during the Cone Calorimeter tests was very similar across all repetitions, while repeatability for other cables was not as good.

Focus was set on three different fire tests: MCC, Cone Calorimeter and cable tray installations in open space. The MCC tests have been performed by using a Pyrolysis Combustion Flow Calorimeter [10]. The MCC was used to determine reaction kinetics parameters of the pyrolysis reaction of the cable components jacket and insulator. Their pyrolysis has been modelled by utilising an Arrhenius equation during the CHRISTIFIRE campaign and the respective parameters are provided in the campaign’s report. The results of the MCC tests and the Arrhenius model are reproduced in Figure 4. Furthermore, the heat release rates (HRR), production rates of residue and heat of combustion are provided in the report as well.

Cone Calorimeter tests were performed on cable pieces, which were neatly ordered in one layer in the sample holder. Incident heat fluxes were set to 25 kW/m², 50 kW/m² and 75 kW/m². Three repetitions were performed for each of the first two incident fluxes, one repetition for 75 kW/m². The results of the Cone Calorimeter tests are reproduced in Figures 5 and 6. Since the repeated tests for 25 kW/m² and 50 kW/m² yielded similar results, they are summarised by a grey area in the plots.

Cable tray installations (Multiple Tray Tests – MT) were tested in different sizes under a large hood, up to seven trays were stacked upon each other. The width of the trays was 0.45 m, vertical distance between the trays was 0.3 m while the tray length varied. Two different approaches were used to determine the total HRR, by oxygen consumption and mass loss. For the simulation of cable #219, focus was set on the HRR measurement based on oxygen consumption. The chosen test was MT-3, which consisted of three trays.

Within the CHRISTIFIRE framework, a simple fire propagation model for cable trays was developed, called FLASH-CAT (Flame Spread over Horizontal Cable Trays) [3]. It distinguishes between thermoset and thermoplastic cable insulation material, in terms of fire propagation. For CERN the FLASH-CAT approach has been adopted to create design fires to perform assessments of the smoke management within its facilities.

On the simulation side of things, the Fire Dynamics Simulator (FDS) [9] was used. FDS is a three-dimensional computational fluid dynamics software, which numerically solves a low mach number...
specialisation of the Navier-Stokes equation. The computational domain needs to be divided into small rectangular cells creating a mesh. Within this mesh, the transport of fire-driven gas flow and heat transfer is then simulated.

In FDS, objects are defined by their geometry and the material properties. The geometry is built out of box-shaped obstructions (FDS: OBST) that influence the flow field. Surfaces (FDS: SURF) are then attached to the sides of the obstructions, which contain the respective material information (FDS: MATL). MATL describes the material properties like density, thermal conductivity or heat of combustion, while the SURF contains information of its application. It does not need to be homogeneous, but can consist of layers of different (homogeneous) materials.

FDS provides different ways to model fire propagation, e.g. when the surface temperature reaches a specified threshold, a prescribed mass flow is initiated. A more sophisticated method is based on an Arrhenius model for the pyrolysis reaction kinetics of a solid material [9]. Parameters for the Arrhenius model are the activation energy $E$, the pre-exponential factor $A$ and the reaction order $n$. The same parameters as provided in the CHRISTIFIRE report. During the pyrolysis process, one or more new gaseous and solid species are generated and the original material is consumed. If a sufficient amount of combustible gas is generated, and combustion is possible, a flame can develop. The temperature of the material is used to control its degradation, which is in turn controlled by the energy transfer to the solid, e.g. by flame radiation, its emissivity and heat transfer within the solid.

Four different simulation setups for FDS were created to simulate the different fire tests: MCC, Simple Cone, Coarse Cone and MT-3.

The simulation setups of MCC and Simple Cone are basically the same, where no gas phase reactions are simulated and were based on suggestions in the FDS user’s guide [9] and in the work of Anna Matala [6]. The focus was solely on the pyrolysis reactions, with the aim to reduce the demand for computational resources to a minimum.

The simulation setup of the MCC consists of four cells in each direction. The temperature of the whole domain was linearly increased over time to simulate the behaviour of the real MCC test. The Simple Cone simulation setup (Figure 2a) was based on [6]. Its computational domain was divided into cube-shaped cells with an edge length of 10 cm and a total extension of 30 x 30 x 40 cm$^3$. The sides and the top of the mesh were given an “open” boundary condition, while the bottom surface was closed. The layered SURF was attached to the bottom boundary of the central cell, to represent the cable sample. Due to the poor resolution in this setup, the incident heat flux to the cable sample was prescribed, using the FDS parameter EXTERNAL_FLUX on the SURF.
It was later found that suppressing the gas phase reactions (flame) was too much of a simplification. Mainly, because it neglected a significant amount of heat, radiated from the flame to the sample surface [11]. Attempts were made to prescribe an extra amount of heat flux and add it directly to the value for EXTERNAL_FLUX. The specific amount was determined by a simulation of higher fidelity (Figure 2b). However, it was realised that the external flux became a limiting factor during the inverse modelling process (IMP), which is covered later.

To assess the sensitivity of the material parameter sets of cable #219, in terms of mesh and flame resolution, a coarse replication of the Cone Calorimeter was created in FDS. The Coarse Cone was set up in a 7.5 mm cube-shaped mesh, where the radiative heat flux is generated by a hot, conical-shaped surface (Figure 2b). Within the Course Cone simulation setup, the parameter sets were subjected to heat fluxes as during the CHRISTIFIRE experiments (25 kW/m², 50 kW/m² and 75 kW/m²).

Furthermore, a representation of Multiple Tray Test 3 (MT-3) from CHRISTIFIRE Phase 1 was created in FDS (Figure 3). The simulation setup of MT-3 was based on a mesh with 5 cm cube-shaped cells. Due to the resolution, the geometry of the tray racks themselves has been neglected. The cable layers in each tray were modelled as obstructions of 0.4 m width and a length of 3.1 m. The thickness of each cable layer was of one cell size (5 cm). This enables FDS to calculate the heat transfer in the solid while taking the temperature of the opposite surface into account, due to software limitations. However, this thickness is only of importance for the flow field. For the heat transfer in the cable material a thickness of about 1 cm was prescribed via the SURF, depending on the specific parameter set coming from the IMP. A vertical distance of 0.3 m was kept between the three trays, measured bottom to bottom. Some obstructions were put on the bottom of the simulation domain to mimic the supporting structure of the tray racks, which can be observed on the photographs in the CHRISTIFIRE report. A Propane gas burner, 0.3 m edge length, was located 0.2 m below the lowest tray and provided 40 kW for the first 600 s of the simulation.

It was briefly mentioned above, that the Simple Cone simulation setup was used with supressed gas phase reactions, which was later changed. The reason is, that the amount of combustible gas released determines how large the flames will be, which in turn determines the mass release, as well as the amount of radiation sent back to the sample surface [11]. Therefore, prescribed flame fluxes lead to inaccurate burning behaviour during the IMP. As proposed by Anna Matala [6], gas phase reactions were allowed again, even though the cell resolution in the simplified Cone Calorimeter simulation setup was very coarse (10 cm cube-shaped cells). With higher resolution, tall flames were observed, which are in line with observations of real Cone Calorimeter tests (Figure 2b and Figure 4). This behaviour could not be covered with the coarse grid, but it still allowed to cover parts of the flame’s radiation influence. Methane was used as surrogate fuel for the combustion process.
Before the inverse modelling, attempts were made to use reaction kinetics parameters accompanied by the information on residue formation and heats of combustion provided in the CHRISTIFIRE report, directly for the materials in FDS. The remaining thermo-physical parameters were based on the example cases provided with FDS and literature values. However, performance was not satisfactory, except for the simulation of the micro-combustion calorimetry (MCC). Thus, focus was shifted to an inverse modelling approach.

Material and reaction kinetic parameters have been determined by utilising the global optimisation method SCE-UA (short for: shuffled complex evolution method developed at The University of Arizona) [12] in an inverse modelling approach. The IMP was controlled by a self-developed script, utilising the scripting language Python, version 2.7 and the Python package “Statistical Parameter Optimization Tool for Python” (SPOTPY) [13]. This script worked basically as the interface, handling communication between the SCE-UA and FDS.

First an input file for FDS is created and set up as a template. Markers in the template allow the input file to be parsed and the markers to be swapped to the specific parameter values. Another file contains the experimental results that are used as target information. A setup script provides input data for the optimisation process, as defined by SPOTPY. Each parameter was given a lower and an upper value, to limit the search space and to avoid to receive unrealistic values. However, the values are somewhat artificial. The limiting values are basically guess values, loosely based on literature values. For instance, the heat of combustion values got a range of ± 20% around the CHRISTIFIRE values, and were expanded when the algorithm got “stuck” at one of the limits during the search.

Table 1: Overview of which parameters were used during the IMP. The ‘x’ denotes individual parameters that the optimization algorithm had access to.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Jacket reaction A</th>
<th>Jacket reaction B</th>
<th>Jacket residue</th>
<th>Insulator reaction A</th>
<th>Insulator reaction B</th>
<th>Insulator residue</th>
<th>Copper conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>Same for reaction A and B</td>
<td>x</td>
<td>Same for reaction A and B</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emissivity</td>
<td>Same for reaction A and B</td>
<td>x</td>
<td>Same for reaction A and B</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>Same for reaction A and B</td>
<td>x</td>
<td>Same for reaction A and B</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific heat</td>
<td>Same for reaction A and B</td>
<td>x</td>
<td>Same for reaction A and B</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E$</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat of combustion</td>
<td>Same for reaction A and B</td>
<td></td>
<td>Same for reaction A and B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat of reaction</td>
<td>Same for reaction A and B</td>
<td></td>
<td>Same for reaction A and B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer thickness</td>
<td>Same for reaction A and B</td>
<td></td>
<td>Same for reaction A and B</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Per generation the number of complexes has been the number of parameters $n_{\text{para}}$ plus 1. Each complex contained two times the number of parameters $n_{\text{para}}$ plus 1. Thus, the number of individuals (parameter sets) per generation $n_{\text{gen}}$ can be described as:

$$n_{\text{gen}} = (n_{\text{para}} + 1) \times (2 \times n_{\text{para}} + 1)$$

Which is the default setup for SPOTPY. After the parameter sets have been created by SPOTPY, they were written into the FDS file, and the simulation was performed. From each simulation only the time and HRR data was kept, the rest was deleted to save hard drive space. The root mean squared error (RMSE), calculated between the experimental and the simulation results, was considered as the fitness value. Parameter sets which had RMSE values closest to zero were rated best. After all parameter sets of a generation had been assessed, they got ranked, shuffled and the new generation was generated.
The shuffling is aimed to prevent the optimisation algorithm getting stuck at a local optimum instead of finding the global optimum of the search space. The process was terminated when either a specified number of simulations had been performed, about 100k, or the fitness value did not improve less then $1 \times 10^{-6}$ % over the course of the previous 100 evolution loops (also SPOTPY default).

The SCE-UA was used on the Simple Cone simulation setup, with the experimental results from CHRISTIFIRE as target. Specifically, only one repetition of the 50 kW/m² Cone Calorimeter results was chosen as target for the IMP.

The cables were simplified as a SURF with three layers (jacket – insulator – jacket), to account for the assembled nature of electrical cables. By using the EXTERNAL_FLUX parameter, the conditions of Cone Calorimeter tests could be replicated easily. This approach was regarded to be sufficient for the demonstration purpose, thus reducing the computational costs of the IMP significantly.

In total 34 parameters were used for the optimisation algorithm to work on. Those are the thicknesses of the different layers, reaction kinetics parameters and thermo-physical parameters for each cable component, as well as thermo-physical parameters of the residues. In the beginning, the copper conductor was implemented as well, but only its layer thickness was accessible for the IMP. During every run of the IMP the thickness of this copper layer was reduced to its lower limit, thus it was removed completely. This behaviour is also in line with findings reported by Anna Matala [6]. An overview of the parameters used during the IMP is provided in Table 1.

As mentioned above, each cable component was divided into two materials (MATL) to cover the two pyrolysis reactions, (reaction A and reaction B). Both MATL of a cable component yield surrogate fuel and a residue. The yields were taken from the MCC results of the CHRISTIFIRE report. The IMP was provided with the heat release rate data (HRR) of one repetition of the 50 kW/m² Cone Calorimeter experiment as the target data.

The different parameter sets were then used within the MT-3 simulation setup to assess their performance in predicting the fire propagation in a cable tray installation.

RESULTS

In Figure 5 the results of MCC tests from CHRISTIFIRE and simulations are shown. The results from the simulations with the parameters provided in the CHRISTIFIRE report match the experimental
results very well. The results out of the IMP show significantly different behaviour. Cone Calorimeter data for irradiance levels of 25 kW/m² and 50 kW/m² are provided in Figure 6, for 75 kW/m² in Figure 7. Note that the SCE-UA worked with the Simple Cone simulation setup at 50 kW/m² external heat flux. For this case, experimental and simulation results match relatively well, as expected.

The main features of the experimental results are visible in the simulation results, but slightly off. For 75 kW/m² the results are still similar to the experiment, however at 25 kW/m² the behaviour is significantly different. Increased cell resolution in the Coarse Cone setup improves the results for 25 kW/m² and 75 kW/m² but largely overestimates the results in the 50 kW/m² case. In general the direct transfer of the CHRISTIFIRE parameters is only able to cover the first peak at 50 kW/m² and 75 kW/m² but shows significantly different behaviour in all other cases.

During the CHRISTIFIRE experiments the HRR of the cable tray arrangements was estimated by the oxygen consumption method, as well as based on the mass loss rate. The results of the oxygen consumption method was chosen to compare them against the simulation results. For simulations of the tray setup it proved to be difficult to achieve fire propagation. In most of the simulations, the fire extinguished on its own, shortly after the burner was switched off. The parameter set based directly on the CHRISTIFIRE results showed only a small contribution to the total HRR of the fire, close to 10 kW.

The parameter set from the IMP showed a contribution of around three times the burner’s input. After the burner was switched off, the HRR dropped by 40 kW recovered slightly (~10 kW) and then decayed slowly, similar as the FDS 6.5.3 results (Figure 8). Following the assumption that the material and reaction kinetics parameters are determined reasonably well during the IMP, focus was shifted to the heat transfer to the cable.

Three parameters were looked at, for the investigation of the influence on the radiative heat transfer: radiative fraction of the flame, soot yield and the surface temperature of the burner. After the investigation, the surrogate fuel was changed from methane to toluene, both are pre-tabulated in FDS. Thus, the radiative fraction of the flame changed from one of the lowest (0.2) to one of the highest (0.45) pre-tabulated values. Soot yield was set to 0.178 g/g based on textbook values for toluene [14]. The surface temperature of the burner was set to 410 °C with a slow decay rate, after the burner was turned off. Specifically the burner temperature was of greater importance as expected at first glance.
Thus, satisfactory fire propagation could be achieved in the simulated cable tray installation. It is important to note that the parameter set was adjusted after the IMP was finished, to achieve fire propagation. Furthermore, comparison of the two FDS versions, 6.3.2 and 6.5.3 shows nearly the same results for the MCC and Cone Calorimeter simulations. When comparing simulation results of the tray arrangement a significant difference is notable after the burner is switched off.

**DISCUSSION**

As a proof of concept, it was demonstrated that the simulation of fire propagation in cable tray arrangements is feasible within FDS. The set up IMP is able to generate parameter sets that are able to predict the general fire behaviour within a real-scale simulation setup, based on small scale experimental data. However, the parameter set performs relatively well only within a tight frame.
Furthermore, it is important to note that the user needs to be careful when attempting to transfer the material parameters between different versions of the simulation software. Specifically in the presented case, the parameters are model specific, also depending on the FDS version. Additionally, the demonstrated process, to obtain a material parameter set for fire simulations, could possibly be used for all solid combustible materials. Cables are used as a specific example in this work.

The ability to predict the fire development, based on material parameters and environmental conditions near the fire, enables the user to create better assessments of possible fire and smoke spread, specifically in non-standard facilities. This is of interest, for example, within the (accelerator) tunnel and technical gallery infrastructure at CERN. Cables as a fire load, spread over long distances, from tens of meters up to kilometres. Narrow cross sections may lead to long stretches of cables being pre-heated which will promote the firespread, the extent of which is to be investigated in the future with the outcomes of this work. Obviously, this is not only limited to CERN, but of interest for all cases where cables are installed inside technical galleries, like data centres or power plants. It is also of interest, how much material may be involved and turned into smoke during a fire incident. In the event of a fire in a particle accelerator tunnel, large parts of the accelerators would be contaminated with fire products, which are possibly activated. Soot, mainly carbon, could lead to short circuits. Substances like halogens form corrosive solutions with the humidity of the air and would lead to damage to the sensitive electronics of the accelerators and detectors. Cleaning the accelerators would most likely be performed manually and extremely expensive, also considering the possible long down time of the whole accelerator complex. Furthermore, smoke production and movement is important to assess evacuation strategies in CERN’s tunnel network. In some cases, egress routes can become quite long and useful compartementalisation strategies need to be defined.

Currently, the overall process is being revised and improved and some aspects of the envisioned improvements are presented in this paragraph.

One severe limitation has been the use of the result of only one experiment as target information. This has been changed to incorporate all repetitions of the Cone Calorimeter experiments with their respective incident heat fluxes as simulation setup for the upcoming optimisation runs. In the beginning, the assumption has been that methane could serve as surrogate fuel, together with the given material parameters. However, after the IMP the surrogate fuel and the soot yield needed to be changed to achieve the desired fire propagation behaviour. For the upcoming runs of the IMP, the surrogate fuel and the soot yield will be set to the values of toluene right from the beginning.

The simplified simulation setup of the Cone Calorimeter contains some inaccuracies, like a very coarse mesh, the missing exhaust gas flow and a slightly large edge length. Those points will be addressed for future runs. Specifically smaller mesh cells, despite being costly in terms of computational resources, are desirable in order to better cover the interaction between sample surface and flame. Furthermore, it can be seen in Figure 5 that the chosen parameters, by the IMP, diverge significantly from the experimental data of the MCC. It is important to emphasis that the IMP was was working with material parameters, that were used in the simplified Cone Calorimeter environment with a model representing assembled cables. This means, in the MCC tests were performed on a tiny, homogenous material sample, under conditions that are aimed to specifically test the material behaviour and reduce influences from other sources. Those sources could be, for example, the geometry which could lead to an inhomogeneous heat up, thus an inhomogeneous pyrolysis. By using the configuration of a relatively large furnace with a tiny sample, the main factor for material pyrolysis can assumed to be the samples temperature, while others can be neglected. Due to limitations in FDS however, the representation of the circular cross section of cables is difficult. The chosen model, to represent the cables in the simplified Cone Calorimeter simulation, is inaccurate by using flat layers of material that are stacked upon each other. Therefore, the bumpy structure of the cables, that could be observed when multiple cables lie next to each other, is lost. This should affect the heating up of the cable model in comparison to the real experiment. Furthermore, in the real experiment, the degrading cable material may undergo chemical reactions that are not known here and
are not modelled. Thus, it might be necessary to use artificial parameters for reaction kinetics to account for model inaccuracies, and is also expected to some degree. Still, it needs to be investigated if the optimisation algorithm shall have free reign over the reaction kinetics parameters or if it requires some constraints.

With the revised process, more of the CHRISTIFIRE cables will be treated. Followed by non-halogenated cables, which have been tested, within the framework of the FCC Fire Safety Collaboration, at Lund University, Sweden.

In addition, the implications of the changes in the radiation and solid heat transfer models between the FDS versions 6.3.2 and 6.5.3 need to be further assessed. Furthermore, the Python scripts are also in an improvement process to set them up in a more general way. This will allow faster changes in the setups to be investigated. A small group of people came together at the University of Wuppertal, Germany, and started the creation of a flexible Python framework to tackle similar inverse modelling problems (working title: propti).

Note: Part of the data used for creating this paper, is publically available on the Zenodo data base under the following DOI: 10.5281/zenodo.1145947

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Within the study project of the Future Circular Collider, a fire safety engineering collaboration with other particle laboratories was established. Members of this group are some of the major particle accelerator facilities (CERN, DESY, ESS, FNAL and MAX IV) and Lund University. It is aimed towards a better understanding of smoke production and movement in one-of-a-kind underground research facilities, e.g. such as particle accelerators, benefitting life, environment and asset protection. The authors are thankful for all the discussions and advice coming out of this collaboration.

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REFERENCES


Fire Safety Engineering Method Evaluation
Based on a Real Tunnel Fire Case

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ABSTRACT

Fire safety engineering is more and more used for tunnel safety measures design. Such studies are
based on both fire modelling, which different types of software (1D or 3D mainly), and people
behavior hypothesis. One of the main important issues in such studies consists in having a relevant
approach for both fire source and human impact. Those two aspects are highly coupled in the sense
that the evaluation of human consequences depends on both temperature, visibility and toxicity
evaluated from fire source term and human displacement.

While the beginning of such approach consists in using a validated numerical tool, the human
behavior and the evaluation of fire impact on human being is not so obvious. To meet the safety
objective, different standards are proposed at both national and international level. Those documents
provide some information regarding the human walking velocity in case of fire, commonly based on
visibility, and the methodology to evaluate the toxic and thermal impact.

A theoretical analysis of those documents shows some major differences between existing
approaches, toxic gases to be accounted for in the toxic effect evaluation, the temperature threshold or
the walking velocity are two examples. On top of that, some recent publications propose a relation
between all those quantities, making a link between human walking velocity and the whole fire
impact, temperature, toxicity and visibility.

Because of the lack of experimental data, evaluating the relevance of those different methods requires
an analysis of existing fires. Among the different fires occurred in tunnels during the last decades, the
Gudvanga tunnel fire in August 2013 should be the most interesting one for such an evaluation.
During this fire, 67 persons were trapped in smoke and escapes through the smoke during more than
one hour. The paper proposes a numerical reproduction of this fire, based on available accidental
analysis reports. Based on these numerical results, the different human behavior methods are
compared to evaluate whether or not their conclusions are in accordance with the fire consequences.
This comparison shows the quite good accordance, for this situation, with what prediction could have
been and real consequences.

KEYWORD: smoke toxicity consequence, evacuation in tunnel, real fire analysis

INTRODUCTION

Assuming that numerical models are able to predict realistics values, one of the main problem fire
engineers have to face off is the human behaviour and human consequences evaluation. Because
nothing is less predictable than human behaviour in fire, strong hypothesis has to be made regarding
their reaction, as demonstrated in each fire analysis. The evaluation of consequences, in terms of
evacuation capability loss, non reversible effects or lethality, is also a key issue considering not all
human being will react in the same manner to toxic gases or temperature increase. In order to provide
tools for fire consequences modelling, the ISO 13571 standard provide some elements for evaluating
consequences on people in terms of evacuation capability including toxic and thermal effects.

It is obvious that such a theory is not so easy to be compared to real cases because this requires
knowing both people position along time and physical quantities, temperature and gas concentration.
After a brief description of the ISO 13571 model, this paper proposes a fire safety study of a real fire
that occurred in Norway, the 2013 Gudvanga tunnel fire. The fire analysis was achieved using both a
simple hand calculation and CFD computation to evaluate fire consequences in terms of physical values, toxic gas concentrations and temperature. Those values were then used to estimate consequences on people using the ISO 13571 approach.

**BRIEF DESCRIPTION OF THE 13571 ISO STANDARD**

**General context and objectives of the 13571 ISO standard**

Human behaviour in fire is a key issue for fire engineers because of large variety of possible reactions to alarm and effects on human beings of toxicity, temperature and visibility. The ISO 13571 [1] standard give some elements regarding the second aspect. Regarding toxicity, this standard proposes to evaluate consequences considering two different types of gases in terms of physiological effects are distinguished in this document, asphyxiant and irritant gases. For thermal aspect, it proposes to account for both radiative and convective consequences. It should be highlighted that this standard is dedicated to the evaluation of self evacuation capability loss and does not consider non reversible or lethal effect. The most important aspects of this standard are summarised hereafter.

**The asphyxiant gases**

Asphyxiant gases are mainly carbon monoxide (CO) and hydrogen cyanide (HCN). Those gases lead to incapacitation according a time concentration integral law, named the X\text{FED}, defined as follow:

$$
X_{\text{FED}} = \int_{t_1}^{t_2} \frac{\varphi_{\text{CO}}}{35000} \, dt + \int_{t_1}^{t_2} \frac{\exp\left(\varphi_{\text{HCN}} / 43\right)}{220} \, dt
$$

In this equation $\varphi_{\text{CO}}$ is the carbon monoxide concentration, in µl/l, $\varphi_{\text{HCN}}$ is the hydrogen cyanide concentration, also in µl/l and dt is the time interval in minutes. Concentration in this equation should be modified to take account for CO$_2$-driven hyperventilation factor expressed as:

$$
\varphi_{\text{CO}_2} = \exp\left(\frac{\varphi_{\text{CO}_2}}{5}\right)
$$

$\varphi_{\text{CO}_2}$ is the carbon dioxide concentration.

**The irritant gases**

Irritant gases are mainly acid gases as hydrogen chloride, hydrogen fluorine or hydrogen bromide but also sulfur and nitrogen dioxides. They are considered, in terms of impact on human beings through a threshold value using the $X_{\text{FEC}}$ (Fractionnal Effective Concentration) defined as follow:

$$
X_{\text{FEC}} = \frac{\varphi_{\text{HCl}}}{F_{\text{HCl}}} + \frac{\varphi_{\text{HF}}}{F_{\text{HF}}} + \frac{\varphi_{\text{HBr}}}{F_{\text{HBr}}} + \frac{\varphi_{\text{SO}_2}}{F_{\text{SO}_2}} + \frac{\varphi_{\text{NO}_2}}{F_{\text{NO}_2}} + \sum \frac{\varphi_{\text{irritant}}}{F_{\text{irritant}}}
$$

In this equation $\varphi$ is the subscript mentioned gas concentration in µl/l and F is the concentration of each irritant gas that is expected to seriously compromise self evacuation capability, also expressed in µl/l. Values to be considered for F are given in Table 1. Among other gases, formaldehyde or acrolein should be considered when relevant.

<table>
<thead>
<tr>
<th>$F_{\text{HCl}}$ = 1 000 µl/l</th>
<th>$F_{\text{NO}_2}$ = 250 µl/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{\text{HF}}$ = 500 µl/l</td>
<td>$F_{\text{CO}_2}$ = 250 µl/l</td>
</tr>
<tr>
<td>$F_{\text{HBr}}$ = 1 000 µl/l</td>
<td>$F_{\text{HBr}}$ = 1 000 µl/l</td>
</tr>
<tr>
<td>$F_{\text{SO}_2}$ = 150 µl/l</td>
<td>$F_{\text{SO}_2}$ = 150 µl/l</td>
</tr>
</tbody>
</table>

*Table 1: Threshold values for irritant gases, from [1].*

**Thermal consequences**

To take into account the thermal consequences on the people evacuation capability, a thermal FED is defined as follow:
In this equation, $t_{\text{rad}}$ corresponds to the time limit, expressed in minutes, to second burning of skin due to radiant heat. It is defined by:
\[ t_{\text{rad}} = 6.9q^{-1.56} \]  
(5)

In this equation, $q$ is the incident thermal radiative flux, in kW/m². Following the same approach, the time limit, in minutes, to experiencing pain due to convective effect, $t_{\text{conv}}$, is defined, for fully clothed people, by:
\[ t_{\text{conv}} = (4.8 \times 10^8)T^{-3.61} \]  
(6)

In this equation, $T$ is the temperature expressed in °C.

It is important to note that, in this approach, the thermal effect on the respiratory tract is not evaluated considering that, for evacuation capacity loss, the first criteria is the skin burning and that toxic effect commonly occur before breathing apparatus burning. This obviously depends on the water concentration in the air.

**Relation with physical consequences prediction**

Independantly of the numerical model used, the evaluation of the people evacuation capability based on the ISO 13571 standard requires evaluating both $X_{\text{FED}}$, $X_{\text{FEC}}$ and $X_{\text{FED}}^{th}$. It is clear that those different quantities cannot be evaluated as a same manner. While $X_{\text{FEC}}$ can be computed directly as an output of the model by summing the different species local concentrations divided by the corresponding threshold, evaluating $X_{\text{FED}}$ and $X_{\text{FED}}^{th}$ requires a dedicated model to compute the time integral while accounting for people displacement during the evacuation process. Such a model has to account for people initial position, reaction time and walking velocity.

An additional hypothesis is required for 3D models because people are able to move in two directions: transversely or longitudinally. For all the 3D results presented in this paper, people are supposed to be close to the tunnel right side during the evacuation process. Some words about the meaning of the $X_{\text{FED}}$ and $X_{\text{FEC}}$ should then be given. The 13571 standard was developed considering a human population of healthy and young adults. A value of 1 for those quantities corresponds to the median value of a log-normal distribution of responses, with safe evacuation for approximatively 50% of human beings. Using a 0.3 limit value corresponds to safety conditions for 90% of human beings.

**THE GUDVANGA FIRE**

**Description of the tunnel**
The Gudvanga tunnel is a 11.4 km long single bore two way tunnel located on the E16 between Aurland and Voss in Norway. The tunnel cross-section is represented on Figure 1. The cross-section is about 75 m².
It presents a 300 m height difference between portals due to a 3.5% rise from Gudvangen to Aurland. This tunnel is not equipped with dedicated evacuation routes and people are supposed to evacuate using portals. The ventilation system is based on a longitudinal strategy using 92 fans distributed along the tunnel. This bidirectional tunnel was not equipped with any monitoring system to estimate and locate cars inside.

The 2013 fire event description
In 2013, August the 13th an empty heavy goods vehicle caught fire 8 km after entering to the tunnel from the Gudvangen portal. A detail description of this fire case is provided in [2]. Only relevant elements are reported in the present paper.

The fire occurs around 12 o’clock 3 km upstream the Aurland portal. When the fire starts, the natural ventilation and some fans generated an air flow with a 2.9 m/s characteristic velocity from Gudvangen to Aurland portal, this means in the driving direction of the truck. Some minutes after fire detection, the fire ventilation started and induced an airflow in the opposite direction, from the Aurland portal to the Gudvangen one, this means to the longest part of the tunnel. Because of the lack of monitoring system to locate vehicles inside the tunnel, it was not possible to evaluate whether this solution was relevant or not.

During this fire, 67 persons were trapped in the smoke and had to walk to the Gudvangen Portal up to 8 km long with a maximum walking duration in smoke of about 1.5 h. Only 28 people were admitted to hospital for injuries. It is important to highlight that, when this fire occurred, no alarm system was installed inside the tunnel, this means that people had to evacuate based on their own feeling.

Data from the fire investigation
An evaluation of the heat release rate (HRR) from the fire was achieved by SINTEF [3]. The HRR peak value was estimated to 25 MW. Such a value is in quite good accordance with expected HRR for an empty heavy goods vehicle based on available data [4][5]. The fire growth was also evaluated in [3] with 15 minutes of linear growth before reaching the peak value, a steady state HRR along 15 minutes and a total fire duration of 50 minutes with an estimated linear decrease.

Applying the ISO 13571 methodology requires not only the HRR but also an evaluation of the toxic gas emissions. So, based on the HRR curve and on previously published data regarding emissions from fire [6][7], the toxic gas source terms were estimated.

CONSEQUENCES MODELLING
Based on above described consequences evaluation methods, incapacitation could be predicted during the Gudvanga fire evacuation process. This requires evaluating toxic gas concentrations and temperature on both sides of the fire. This was achieved using two different approaches. The first is a
simple approach based on an homogeneous gas concentrations hypothesis, the second uses a CFD (Computational Fluids Dynamics) tunnel modelling. Using both approaches also enables to evaluate the importance of the stratification in the tunnel having in mind that, even for such a ventilation velocity, the mixing process is not instantaneous.

A first global approach
Before going any further in terms of consequences modelling and considering uncertainties exist regarding the fire characteristics, one can use a global approach to evaluate the ISO 13571 results. Such a global approach consists in considering the emission rates for the toxic products and evaluate the FED and FEC values. Such a simple approach obviously does not allow to consider smoke displacement or stratification but could provide first informations.

Then, considering a 25 MW fire, the peak HRR estimated for the Gudvanga fire, led to a CO₂ production rate of 1.3 kg/s considering [7], based on experimental CO/CO₂ ratio, the CO emission rate could then be estimated to 29 g/s. For this simple global approach, the fire ventilation velocity of 2.5 m/s and considering the 75 m² tunnel section shall be considered for evaluating the fresh air flow. Assuming then a perfect mixing of gases indicates a CO₂ concentration around 0.4% of the volume and a CO one of 130 ppm. It is important to note that HCN could also be produced and following data available in [7], the concentration is estimated to 1.7 ppm. An evaluation of the available time for people trapped in such a smoke before loosing their evacuation capabilities gives about 120 minutes, i.e. longer than the walking duration, considering a FED value of 1, this mean that half of people might not lost their evacuation capability. It is however important to keep in mind that smoke is moving in the tunnel during the evacuation. Without considering HCN, the available duration becomes 270 min highlighting the major effect of HCN consideration for the FED evaluation. Regarding the different formulation that exist in the litterature for the HCN effect on global toxicity, this aspect could be considered as a key issue in terms of the FED evaluation.

The peak concentration values, for the above mentionned fresh air flow rate lead to a maximum FEC lower than 0.1. This means that no physiological impact of irritant gases has to be considered. A similar approach can be used for the thermal consequences first evaluation. Considering then a 25 MW fire and a convective fraction of 2/3 gives an average temperature downstream the fire of about 90°C and consequently, for the only convective effect, a corresponding tenability duration of 30 min using equation (x). It is important to note that such an approach does not take into account the thermal losses due to wall exchanges and consequently overestimates gases temperature.

The visibility can also be evaluated, based on the same global approach using [5]. Considering the CO₂ concentration and the temperature downstream the fire, the visibility distance is estimated to 0.5 m that appears in great accordance with the feeling of people trapped into the smoke [2]. It is interesting to point out here that, during the evacuation process, probably since the visibility reduction, people escaped in both directions, including people initially in the same car.

Before the detailed analysis based on CFD modelling presented hereafter, one can note that it seems that thermal effect is more important than toxic ones.

Using FDS for predicting consequences
In the present paper, the CFD (computational Fluid dynamic) code FDS v6 [8] (Fire Dynamics Simulator) was used to model fire consequences. This code was previously validated for different fire configurations [9] and especially evaluated for tunnel applications [10].

Even if this code is dedicated to fire modelling, particular attention must be paid on some specific aspects. First of all, obviously, meshing is of primary importance for predicting fire development and consequences. Because of the length of the tunnel, using a mesh as fine as requested on the entire domain is clearly not realistic. Consequently choice was made to model only 500 m between the fire and the Aurland portal and 2500 m between the fire and the Gudvangen portal. This leads to a 3 000 m long numerical domain. The mesh is finer in the fire region than in other parts. The fire region consists in a 100 m long block, 50 m each side. In that part, cells characteristic length is 0.25 m in each direction. Between 50 m and 250 m both side of the fire, the characteristic cell size is increased to 0.5 in each direction. Finally, in the rest of the numerical domain, the characteristic
length is rise up to 1 m while other dimensions are kept to 0.5 m. Then, as described in [10] consists in the heat transfer through the wall and the necessity of accounted for the real material of it. In the present case, the wall is made of concrete whose thermal characteristics are introduced into the numerical model.

The next point is crucial for the present case, the CO emission rate has to be introduced into the fire description through a CO yield. For a truck fire, configuration was assumed to be quite close to car fire with an averaged heat of combustion of 36.8 MJ/kg, which means, for the peak HRR value, a combustion rate around 650 g/s, this means a CO production rate of 29 g/s or 44 mg/gfuel [7]. Assuming a C₆H₁₂ equivalent fuel, this leads to a CO₂ production rate around 1 500 g/gfuel which is in correct agreement with expected values for such a fire [7]. Then, it appears obviously that a single-step chemistry model cannot be representative of the complex chemical mechanisms that occur during a fire and cannot model the release of other toxic gases. Considering a constant ratio between those gases production rate and CO and CO₂ ones, it is however possible to determine all gases concentration based on CO and CO₂ distribution. Concerning HCl for example, the average production rate is about 13% of the CO one, the one for HF is about 3%. Then, in the following, those ratio will be considered as constant along time but also in space, which means that pollutant dispersion process is assumed to be the same for all gases.

Finally, it must be indicated that the HRR is distributed over the entire external surface of the truck, excepted on the bottom and that the gap between the ground and the bottom of the truck is modeled.

**General results and comparison with available data**

Before going into details of the people evacuation conditions and the incapacitation prediction using ISO 13571, it is important to evaluate whether or not the numerical model gives a quite correct prediction of the fire development and consequences. First of all, it is important to evaluate whether the smoke behaviour is in accordance with the ventilation strategy. Pictures on Figure 2 shows the smoke position at different time step, the current ventilation direction is also schemed in these pictures.

![Figure 2: Some pictures to show the smoke behavior along time. Gudvangen portal in on the left, Aurland one on the right.](image)

This first series of pictures shows that, the smoke behavior is in good accordance with what is expected, in a physical meaning. The ventilation velocity kinetics used for such a modelling is coming from the accident analysis report [2]. The first information coming from these pictures is that, in the first minutes after the fire ignition, people located between Gudvangen portal and the fire could feel safe considering downstream position of the smoke. 5 minutes after ignition, the ventilation was reversed and then the smoke is quickly pushed in the opposite direction with a velocity higher than 3 m/s, i.e. about 3 times faster than people moving’s speed.

The toxic concentrations should then be analysed regarding the stratification phenomena to evaluate the mixing length. CFD results show that toxic gas concentrations are quite stratified in the vicinity of
the fire, Figure 3, and become more homogeneous hundreds meters downstream the fire.

**Figure 3: CO concentration in the vicinity of the fire.**

The conclusions regarding FED and FEC concepts are then not strongly modified considering people will first be in a region with lower CO concentration near the ground and then a quite constant concentration after the full mixing process. As far as temperature is concerned, the CFD model enables taking into account the thermal exchange process with wall, that was not considered in the first global approach. The CFD computation shows that, as for toxic gases, a stratification process in the vicinity of the fire, and a transition to an homogenous temperature after the mixing process. The temperature is plotted on Figure 4, 800 s after ignition.

**Figure 4: Temperature in the vicinity of the fire 800 seconds after fire start.**

ISO 13571 standard application to the Gudvanga

**Evaluation of the FEC**

To evaluate human escape capability according to the ISO 13571 standard, several parameters must be considered. The simplest evaluation is the $X_{FEC}$ that is just a local sum of concentration divided by the corresponding threshold. As detailed in the model description, not all gases were introduced explicitly into the model but all are taken into consideration in the $X_{FEC}$ evaluation through the relative emission factor. Because no all gases transport was modelled in the CFD simulation, $X_{FEC}$ is computed using carbon monoxide fraction and respective ratio for each gases. The FEC is then computed based on the emission ratio for each relevant toxic gas. The resulting FEC is presented for different times, using 2D slice, 1.8 m above ground, that corresponds to the breathing heigh for people during the evacuation process, Figure 5. This instantaneous value must be considered at different times.
These graphs enable confirming ventilation kinetics consequences with a first period with smoke pushing downstream the fire, in the direction of the shortest part of the tunnel and a second period with a reversed flow and smoke fulfilling the longest part of the tunnel.

**Evaluation of the FED**

The second relevant quantity to be estimated is the $X_{FED}$. This quantity however has to be attached to a displacement path considering an initial position, a reaction time before starting to walk and a walking velocity. To evaluate the influence of the initial position, different starting points were considered, between 100 m and 1500 m from the fire. The $X_{FED}$ evaluation was achieved on both sides of the fire to evaluate the consequences of the ventilation strategy on the people evacuation capability in both directions. Regarding the reaction time, several elements must be considered. During the 2013 fire in the Gudvanga tunnel, this tunnel was not equipped with a fire alarm and people has to alarm themselves. It was then considered here that people start evacuating 30 s after the occurrence of one of the following events:

- they can see the smoke above themselves,
- they are informed by other people that smoke is arriving and evacuation is required.

Then, based on existing data[5][11], the evacuation velocity is assumed to be:

- 1 m/s when visibility is sufficient, greater than 20 m,
- reduced to 0.5 m/s when visibility is lower than 20 m but larger than 5 m,
- reduced to 0.3 m/s when visibility is lower than 5 m.

Based on those hypothesis, the $X_{FED}$ curves can be built for asphyxiant gases consequences for different initial positions.

The graph hereafter shows the evolution of the FED for two initial positions of people. The first individual is located just downstream the fire, in the shortest part of the tunnel with the hypothesis...
that he left his car and walked towards the tunnel portal. The second is located upstream the fire, in the longest part of the tunnel, and the hypothesis is made, i.e. he left his car and walked towards the corresponding tunnel portal. The FED computation plotted here includes the CO$_2$ concentration and the HCN effect. For each situation, the maximum concentration in the lateral position, at 2 m above ground was considered for computation.

Figure 6: Evolution of the FED for different initial positions and people behaviours.

As discussed earlier using the homogeneous model, toxic consequences evaluated using FED are in quite good accordance with observation, the rate of incapacitated people is quite low.

Evaluation of the FEC$_{th}$

The assessment of the $X_{FED}^{th}$ was done based on the same assumptions than the $X_{FED}$ associated to evacuation process. A focus on the radiative fluxes is however required first. In case of a fire in tunnel, the radiative effects are mainly located in the vicinity of the fire because of the flame radiation. Farther than the immediate fire neighboring, let’s say 10 m, the radiative flux can be neglected, in the present evaluation. The $X_{FEC}^{th}$ was then computed only based on the convective part using equation 4. To evaluate whether this parameter could affect people or not, the time to experiencing pain is plotted as a function of temperature,
This graph shows that temperature should exceed about 80°C for seriously reducing the tenability duration. The temperature distribution at different time after ignition, Figure 8, indicates that, 2 m above ground, this temperature level is reached below 100 m each side of the fire field.

Those temperature distributions, compared with the time to experiencing pain, clearly show that the value of $\lambda_{FED}$ is low enough to be considered in the present situation, the people will rapidly be out of the thermal potential effect area.
CONCLUSIONS
The evaluation of real consequences of fire on people is the most difficult part of Fire Safety Engineering to validate. So, using a real fire with people trapped into the smoke and achieving afterward the fire safety engineering study appears as an interesting step in this long and complex validation process. Having in mind that a unique comparison cannot be considered as a validation, the present paper relative to the Gudvanga 2013 tunnel fire provides a contribution to this complex process.

The objective was to evaluate whether the ISO 13571 standard formulae to estimate the people evacuation capability provides results in quite good accordance with real consequences or not. Before using those consequences estimation formulae, physical quantities should be computed. This was achieved following two different methods. The first is a simple global homogeneous one, the second uses CFD. The validation of those approaches is not considered in the present paper that mainly focus on the consequences model evaluation.

Whatever the approach used for physical quantity prediction, the result regarding toxicity is identical, no major toxic impact is predicted regarding the people incapacitation. This means that, even the very low visibility in the tunnel for the studied case and the irritant physiological effect of smoke, the toxic gas concentration were not important enough to induce people major injuries with evacuation capability loss. It is important to remind that ISO 13571 formulae do not consider non-reversible effects that are still possible even if evacuation capability was not lost. The comparison of both homogeneous model and CFD computation also shows that, as a first quick approach, the homogeneous model enables providing a first relevant evaluation. In the present case, such a model leads to very long tenability duration for the asphyxiant gases and no effect of irritant on the evacuation capability, that is fully confirmed by CFD approach. The CFD model also shows that, even the ventilation velocity is important, a stratification phenomena appears, this means that concentrations near the ground are lower than homogenous model results. Regarding temperature however, such an homogeneous model is not relevant because thermal exchanges, mainly with walls, were not considered.

Finally, this comparison shows that ISO 13571 standards are able to accurately predict the first physiological effects.

REFERENCES
[10] BHR-G FDS vs EGSISTES
Hot Smoke Tests for Smoke Propagation Investigations in Long Rail Tunnels

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ABSTRACT
Smoke propagation in an enclosed facility is always a matter of concern whenever the evacuation of people is necessary. The construction of long rail tunnels has made evacuation an even greater challenge. Long rail tunnels are equipped with emergency stop stations so that evacuation may still occur even when trains are on fire and incapable of leaving the tunnel. However, should a train breakdown occur between the portal and the emergency station, passenger evacuation has to be performed via cross passages and into the non-affected (safe) tube. This requires a balanced pressure regime between the two tunnel tubes and/or across the cross passages. The paper describes field tests which were performed in order to investigate smoke propagation in tunnel tubes and over cross passages in the event of severe fires. Fire tests up to 21 MW peak heat release rate were performed, and smoke propagation was monitored, with a strong focus on the situation at cross passages.

INTRODUCTION
Smoke propagation in tunnels and especially smoke transport via cross passages into safe areas are of considerable interest in emergency cases in long tunnels. In Austria, three quite long high-speed road tunnels are under construction. These are the Koralmtunnel with a length of 33 km, the Semmering Base Tunnel with a length of 27 km and the Brenner Base Tunnel (together with Italy) with a length of 55 km. All these tunnels have emergency stop stations for emergency passenger evacuation. However, the possibility of a train breakdown in the tunnel between portal and emergency station can never be ruled out. In such cases the evacuation of passengers has to be performed via the cross passages into the non-affected (safe) tube. In the case of a fire the safe tube is normally set under overpressure. This therefore raises the question as to which type of equipment has to be installed in the cross passages to maintain this pressure balance and to avoid smoke penetration into the cross passage. Additional ventilation equipment might be needed to maintain the overpressure and to supply clean air.

In order to assess the extent to which installation and maintenance costs might be minimized, full scale tests were performed in an existing and separately ventilated section of the Koralmtunnel. Fire tests were performed in order to monitor smoke propagation in the tunnel, and in the region of the cross passages. These tests entailed a max. heat release rate of up to 21 MW. The tests were performed with and without active water mist systems in order to estimate the influence on visibility inside the smoke-covered region downstream of the fire location. The parameters investigated concerned heat, air velocity in the tunnel, and pressure differences between the tubes etc. Smoke propagation was investigated on basis of image processing of the video data. A precise quantification of the smoke volume flow rate was intended but failed due to imprecise information from video images.
TEST LOCATION AND TEST SET-UP

The tests were performed in the Koralm Tunnel in the south of Austria. The tunnel has a length of 33 km and a maximum overburden of up to 1,200 m. Figure 1 shows a sketch of the tunnel, and of the test section in the east, KAT 1. The section has a length of roughly 3.5 km and covers the stretch between the east portal and the ventilation shaft at Leibenfeld. Within the test section, 5 cross passages connect the two tunnel tubes. As tunnel excavation and construction activities were (and are) still in progress, a clear separation of the test section from the rest of the tunnel was required.

A detailed description of the test location and the measurement procedures can be found in reference [1]. The following gives a short overview of the most important items. Figure 2 shows the test section. The air flow was provided by two axial fans installed in the brattice at the east portal of the north tube.

Air was brought into the tunnel via the east portal of the south tube. The cross passage 3 (QS03) acted as a bypass to bring the air into the north tube. Hence, there was a U-shaped flow, with air flowing in via the south tube and being expelled via the north tube. The fans in the two brattices separating the test section KAT 1 from the remaining tunnel (KAT 2 and KAT3) were rarely used as they provided only little air. Hence, these fans acted mainly as a fall-back provision in case of a break-down of the main fans during fire tests.

The fact that both air streams, the fresh one via the south tube, and the polluted one via the north tube, were exchanged via the east portal resulted in some problems concerning air re-circulation. Although
between the two portals a quite a long separation wall is erected, under extreme meteorological conditions it happened that that smoke exiting the north tube was recirculated into the south tube. This resulted in increased safety provisions being provided, such as a pressurized rescue train close to the fire location in the south tube, etc.

Figure 3 provides an illustration of the fans at the brattice and also provides the most important fan parameters. The fans were capable of producing air flows of up to 150 m³/s. However, the prevailing complexity of the aerodynamic system meant that it was impossible to adjust any steady state conditions of the air flow in the test region. There was always a quite noticeable oscillation of the air speed in the whole system. Both fans were speed controlled.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impeller diameter</td>
<td>[mm]</td>
<td>1,600</td>
</tr>
<tr>
<td>Volume flow rate</td>
<td>[m³/s]</td>
<td>46 to 74</td>
</tr>
<tr>
<td>Total pressure increase</td>
<td>[Pa]</td>
<td>2,750 - 820</td>
</tr>
<tr>
<td>Shaft power</td>
<td>[kW]</td>
<td>160</td>
</tr>
<tr>
<td>Number of fans</td>
<td>#</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 3: Axial fans and fan parameters

Air speed was monitored by ultrasonic path-averaged measurement equipment at various locations in the tunnel (see Figure 4) and temperature by PT100 sensors (Platine sensor with a resistance of 100 Ω) along the tunnel and over various heights at the measurement locations (see Figure 5). Smoke movement was monitored by video cameras. The attempted usage of smoke (opacity) sensors failed, due to their limited measurement range (in fact they quickly exceeded their measurement range as the smoke was really dense). At downstream locations, where the smoke already filled the tunnel from roughly 1 m above road surface level, visibility was in most cases in the range of 1 to 4 m. Measurements of the pressure difference between the tubes at QS02 complemented the measurement set-up.

Figure 4: Measurement set-up for air velocity (LG0x), video monitoring (VC0y) and pressure difference between the tubes at the closed cross passage
Two different types of doors were installed in the cross passage used for the investigations. While one side was closed with a sliding door, a swing door was used on the other side (see Figure 6).

**FIRE SITE AND HEAT RELEASE RATE**

Pools with an area of 1 m² were used as fire sources. Variation of the heat release rate (HRR) was achieved by varying the number of pools. A mixture of 20 l diesel and 5 l gasoline per pool [2] was used as heat and smoke source. The heat release rate was derived from high quality measurements of the fuel mass loss. A set of four pools were placed on a platform, weighing the loss of fuel mass. The recording was done on a 1 Hz basis. The heat release rate was calculated from the loss in fuel mass and a calorific value of 44.4 MJ/kg fuel. Figure 7 shows, by way of example, the course of the fuel mass values in the pools. The scales were calibrated several times during the various experiments.

**Table 1: Test parameters**

<table>
<thead>
<tr>
<th>Test</th>
<th>No. of pools</th>
<th>HRR average</th>
<th>HRR maximum</th>
<th>Duration</th>
<th>Air velocity at start</th>
<th>Air velocity average</th>
</tr>
</thead>
<tbody>
<tr>
<td>BV 1</td>
<td>2</td>
<td>2.3</td>
<td>4</td>
<td>00:15</td>
<td>1.54</td>
<td>1.3</td>
</tr>
<tr>
<td>BV 2</td>
<td>4</td>
<td>5.5</td>
<td>8</td>
<td>00:13</td>
<td>1.12</td>
<td>1.75</td>
</tr>
<tr>
<td>BV 3</td>
<td>2</td>
<td>2.3</td>
<td>4</td>
<td>00:16</td>
<td>0.6</td>
<td>1.22</td>
</tr>
</tbody>
</table>
Due to the fact that the inner tunnel lining had already been fitted in the test section KAT1, damage to the existing surface had to be avoided. Hence, it was necessary to construct a 5m x 5m x 20 m fire box in order to prevent temperatures exceeding 120 °C at the concrete surface. The box consisted of two layers of fire protection boards. These can withstand surface temperatures above 600°C without any problem (Figure 8).
Two tests were performed applying a high pressure water mist system (HPWMS). The original purpose of this system was to act as an additional protection device in situations where the acceptable temperature levels for concrete were exceeded. The parameters of the water mist system were: water pressure, 30 bar; water volume flow rate 400 l/min; the area covered by the HPWMS was the full box plus one meter upstream, resulting in a water droplet density of 0.8 l/min/m³.

The prevailing conditions meant that the HPWMS could not be mounted and activated as it would be in the case of a real fire. Normally in such a system the zone upstream of the fire site is already activated. However, as this zone didn’t exist in the experiments the water mist was released directly above the fire and only within a zone of 20 m in length.

RESULTS

The tests were performed between December 2016 and February 2017. In total, 14 tests were performed and the respective data recorded. The data concerned mainly temperature profiles, air velocities and images of the visibility and smoke propagation. The original intention to measure the extent of the backlayering had to be abandoned due to problems with the distance measurement upstream of the fire location. As a result, only a rough estimation can be given concerning the length and thickness of the backlayer in the individual cases.

Most of the data processing, especially that concerning dependency of the backlayer length on heat release rate and parameters of the upstream air (air velocity, temperature and humidity) is still ongoing.

Figure 9 shows as an example the profile of the temperature curves at various distances downstream of the fire box and at various times during the test. As can be seen, there is strong layering of the smoke/air over height. Figure 10 gives a closer look at the single locations. At MP6, 15 m downstream of the fire box (i.e. roughly 30 m downstream of the last pool), the fire produced, at the most elevated sensor, air/smoke temperatures of up to 260 °C as soon as 150 s after ignition. During the course of the fire temperatures were in most cases between 180°C and 240°C. As soon as the majority of the fuel was burnt the temperature dropped rapidly. It has to be mentioned that the burning behaviour of the fuel in the individual pools varied. In most cases the pools most downstream were the first to be empty. This is probably due to some extent to the higher temperature of the air streaming over the pools enhancing fuel evaporation, and therefore directly related to the external flame radiation. On top of that, the high turbulence generated by the flames of the upstream pool additionally enhanced the burning process. Another reason is the incident heat radiation towards the fuel surface, as it increases downstream the fire. Whatever the exact case, the amount of oxygen was always sufficient to burn the fuel in the pools further downstream without any problem.
Figure 9: Fire test #13, 10 pools, max. HRR 21 MW, av. HRR 9 MW
In the lower regions (~5 m below the highest point) temperature rarely exceeded 40 °C. This is approximately the height of the head of an adult. However, it has to be mentioned that heat radiation at that location can be very high. The further downstream the temperature profile is measured, the less pronounced the profile.

In the course of test #14 the HPWMS was activated roughly 4 minutes after the start of the fire. As Figure 11 shows, temperature at MP 6 drops immediately after the activation, but mainly at the upper layers. Due to the mixing of hotter air and steam the lower layers even experience a small increase in temperatures. It took the water mist roughly five minutes to reduce the HRR effectively and bring the temperatures down to below 35°C on average. Figure 12 shows some images of the test before, during, and after the activation of the HPWMS.
Figure 12: Images from test #14 with HPWMS, w/o activation (left), with activation (middle), activation turned off (right)

Figure 13 shows the development of the temperature profiles along the tunnel at two distinct time steps. The first one is at 100 s after ignition, without activation of the HPWMS, while the second one, at 350s, has already experienced the active HPWMS. The interesting thing is, that at 15 m downstream of the fire box, the positive effect in terms of temperature reduction is clearly visible, but at 30 m downstream the effect diminishes, or is not visible at all.

Figure 13: Temperature profiles from test #14 with HPWMS

Figure 11 shows clearly the positive effects of an active HPWMS. However, one also has to note that visibility at a height of 1 m above the floor dropped from a few meters at the location of MP6 to almost zero. Hence, for the case of the pool fire the positive effect of the temperature reduction was counteracted by the negative effects of the full loss in visibility. As the velocity of the air on the upstream side (cold) was well below critical velocity, a backlayer of considerable length was established. However, in contrast to test #13, which was performed without activation of the HPWMS, the backlayer was much thicker due to the high content of moisture in this smoke-filled layer. Hence, even upstream of the fire, visibility at head height was reduced. It has to be mentioned that those findings were derived for pool fires and the results might be different for solid fuel fires. In addition it has to be mentioned, that for demonstration purposes the activation of the HWPMS was very late. Hence the fire had time to grow and to produce a thick smoke layer. It is well known, that one of the major benefits of any kind of fixed fire fighting systems (FFFS) is to keep the fire small, but therefore a very quick activation is required.
CONCLUSIONS

The tests performed in the Koralm tunnel were designed to monitor the smoke propagation within the tunnel and through cross passages in the case of fire. The tests performed covered various heat release rates, starting small, and ending at 21 MW (maximum). A HRR in that range represents the typical HRR employed for passenger trains in the ventilation design process. Although the tests were finished in February 2017, data processing is still ongoing. However, the following qualitative results can already be stated:

- The tests with more than 6 pool fires (max. HRR > 10 MW) resulted in quite severe smoke production rates and strong restrictions in visibility downstream of the fire. However, visibility downstream of the fire was in all cases sufficient for persons to see the nearest escape signs, except in those cases with active FFFS.
- Temperature at a height of some 1.5 m to 2 m above floor level (height of head) never exceeded 30°C to 40°C.
- As the air velocities upstream of the fire never exceeded 2.5 m/s, backlayering was apparent. For smaller fires (< 10 MW) the smoke layer was stable and stayed at heights posing no problem whatsoever for people underneath. For bigger fires, the smoke layer upstream grew strongly in depth – not so much in length. For example, during the 20 MW tests (10 pools), the smoke layer extended down from the ceiling to some 1.5 m above the floor.
- The application of the HPWMS resulted in a clear decrease in downstream temperature and in HRR. However, visibility downstream of the fire was strongly restricted (note: the activation of the HPWMS started 6 minutes after the fully developed fire and the installation set-up was not as it would be in reality).
- Full data sets concerning the main parameters of the individual tests have been produced for model validation. These data are available for research purposes (e.g. model validation) on request.

Acknowledgements

The project was funded by the research department of the Austrian railway corporation ÖBB. The authors want to thank the companies PROMAT GmbH, for providing the passive fire protection boards and SICK GmbH for providing air velocity measuring instruments. Special thanks to DI. Matthias Kager and Mag. Susanne Fehleisen, ÖBB Infra, for on-site support.

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Applying the FDS Pyrolysis Model to Predict Heat Release Rate in Small-Scale Forced Ventilation Tunnel Experiments

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Christchurch, New Zealand
³Olsson Fire & Risk, Manchester, UK
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ABSTRACT

The pyrolysis model in Fire Dynamics Simulator version 6.3.1 (FDS6) is applied to simulate a series of small-scale tunnel experiments under varied forced ventilation velocities, where cribs made of medium density fireboard (MDF) are used as the fuel source. Prior to the simulations the material properties of MDF are investigated in order to effectively describe the decomposition behaviour in FDS6 and to develop optimised values. In the tunnel simulations, the effect of the burning duration of the ignition source, the heat of combustion of the MDF in the presence of the forced ventilation, the assumed fuel mass and the modelling domain set-up on the prediction of heat release rate are examined. It is found that the cribs take longer to ignite than that in the experiment; the available burning mass is affected by the assumed thickness of the crib sticks and the available surface area; and a limited domain size can result in not all of the fuel burning. Efforts are made to obtain an equivalent burning mass to the experiments and to account for the influence of the forced ventilation on the burning efficiency by manually specifying the heat of combustion to improve the predictions of heat release rate and consumption of fuel mass.

KEYWORDS: FDS pyrolysis model, small-scale tunnel experiments, heat release rate

INTRODUCTION

One of the most important parameters in the selection of design fire scenarios for tunnels is the heat release rate (HRR). This input provides information for the evaluation of fire hazard severity, the tenability conditions for occupants and tunnel ventilation design parameters, etc. Various tunnel fire safety standards and guidance provide design fire HRR values. Cheong [1] compared NFPA 502 (2004 and 2008), BD78/99, PIARC and CETU in which the values are generally obtained from different large-scale fire experiments. The peak fire size in these documents for passenger cars, buses and vans usually ranges from 5 to 30 MW and can exceed 200 MW for goods vehicles. However, the use of these recommended design fires has limitations when representing different tunnel fire scenarios where a range of vehicles may be involved and the influences on the fire from the tunnel size and ventilation conditions may be different to those in the original experiments. Even though valuable results can be obtained through large-scale tunnel experiments using them to measure the fire sizes for different circumstances is not a practical approach due to the complexity and high costs involved.

In order to have a cost-effective approach to obtain the HRR for tunnel fires in different scenarios Cheong [2] proposed the use of the Fire Dynamics Simulator (FDS) as a predictive tool. One of the
experiments in the Runehamar heavy goods vehicle (HGV) programme [3] was modelled by dividing up the surface into individual elements each with a defined ignition temperature and burning rate history in order to predict the HRR. A peak value similar to the experimental result was obtained where the spread of fire was fully dependent on the pre-described surface element properties.

Another potential approach to predict the HRR of tunnel fires using FDS is to apply its kinetic pyrolysis model. This approach uses the decomposition reactions of materials and one-dimensional heat transfer to predict the mass loss rate for solid fuels and further to predict the HRR of the fire using the FDS combustion model. The influences on the decomposition reactions from environmental conditions such as ventilation effects, tunnel geometry and suppression systems can be assessed so that theoretically a more realistic fire can be obtained by using the pyrolysis model approach. Currently the main applications of the pyrolysis model are for material- and bench-scale experiments where the heat transfer can be simply modelled in one-dimension [4, 5]. The use of the pyrolysis model to simulate large-scale fires has not been widely studied although Li [6] notes that the accuracy of the HRR prediction from the FDS pyrolysis model is limited due to the assumptions it contains. However, it is still useful to investigate the predictive capability of the pyrolysis model for large-scale fire scenarios and to investigate where its limits may be.

In this paper the pyrolysis model in FDS version 6 is adopted to simulate a series of small-scale tunnel experiments and compare the predicted HRR with measured values. The paper briefly describes a series of small-scale tunnel experiments in which cribs constructed of medium density fireboard (MDF) were burnt under a range of forced ventilation velocities. The paper describes the derivation of the MDF material properties which have been evaluated with a series of cone calorimeter experiments. The modelling of the source used to ignite the crib is described and finally the simulations of the tunnel experiments are presented from which HRR results have been obtained.

SMALL-SCALE TUNNEL EXPERIMENTS

The small-scale tunnel experiments were conducted in the medium-scale fire laboratory at the University of Canterbury. The tunnel was 0.365 m (W) × 0.26 m (H) × 11.9 m (L). The downstream end of the tunnel was connected to a circular duct for the measurement of the flue gases to obtain the HRR using oxygen consumption calorimetry. Longitudinal ventilation at different velocities was provided by a speed controlled fan that was installed 2.58 m upstream of the fire location. The main tunnel body was constructed of 0.9 mm thick SS304 sheets with 5 mm thick insulation blanket. The section in which the fuel source was located was 1.22 m in length and had fire resistant glazing along the front side for observation purposes. An insulated platform raised up 50 mm above tunnel floor was used to locate the fuel source and the platform was connected to a load cell so that the mass loss could be measured.

![Figure 1](a) Tunnel dimensions, (b) crib geometry.)
Cribs made of MDF were used as fuel (the average weight for the cribs was 1.44 ± 0.05 kg). The cribs were constructed with five layers of 15 mm thick sticks comprised of three 375 mm long-sticks and six 100 mm short-sticks equally spaced. The crib porosity is 0.8 mm. Figure 1 shows the overall view of the small-scale tunnel geometry and the crib geometry. A more detailed description of the small-scale tunnel and fuel arrangement is given by Wang et al. [7].

Results and analysis of the experiments [7] found that the forced ventilation affected the fire spread as well as burning efficiency of the crib, and further affected the HRR. Figure 2 presents the measured effective heat of combustion for the MDF cribs at different forced ventilation velocities. When the air velocity was less than ~ 0.6 m/s the effective heat of combustion is found to be 12 MJ/kg which is the same as that obtained from the cone calorimeter experiments discussed later. Thereafter an increase in air velocity up to 1.2 m/s gradually increases the burning efficiency; however the burning efficiency then falls when the velocity exceeds 1.2 m/s.

Figure 2 Effective heat of combustion at different forced ventilation velocities [7].

### DETERMINATION OF MDF PROPERTIES

#### Thermal properties

The thermal properties of MDF required in the pyrolysis model are density, specific heat and thermal conductivity. Li et al. [8] have carried out a series of studies on the same MDF adopted in the small-scale tunnel experiments. In Li et al.’s [8] study, the specific heat and thermal conductivity for both virgin and charred MDF have been investigated as functions of temperature (T) and moisture content (MC) with the results shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Thermal properties for virgin MDF and char MDF [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDF, specific heat (J/kg/K)</td>
<td>( c_{p}^{(\text{dry})} = 2.5T + 1080 )</td>
</tr>
<tr>
<td>MDF, thermal conductivity (W/m/K)</td>
<td>( k_{0}^{30} = 4.86 \times 10^{-8} \rho^{2} + 4.63 \times 10^{-5} \rho + 4.38 \times 10^{-2} )</td>
</tr>
<tr>
<td></td>
<td>( \Delta k = 4.9 \times 10^{-3} MC \times 100 + (1.1 \times 10^{-4} \rho + 4.3 \times 10^{-5} MC \times 100)(T - 30) )</td>
</tr>
<tr>
<td></td>
<td>( k = k_{0}^{30} + \Delta k )</td>
</tr>
<tr>
<td>Char, specific heat (J/kg/K)</td>
<td>( c_{\text{char}}^{(\text{dry})} = 3.7T + 547.86 )</td>
</tr>
<tr>
<td>Char, thermal conductivity (W/m/K)</td>
<td>0.09 W/m/K at ambient temperature and 7% increase per 10 K</td>
</tr>
</tbody>
</table>

Note: All symbols shown in equations can be found in the Nomenclature
**Kinetic properties**

In the work of Li et al. [9], the kinetic properties (activation energy \( E \), pre-exponential factor \( A \) and reaction order \( n \)) of MDF have been analysed through an advanced computational searching method. They used four components to correspond to resin, hemicellulose, cellulose and lignin to represent MDF. The kinetic properties of each component were derived inversely from three differentiated thermogravimetric (DTG) curves at heating rates of 5, 20 and 60 K/min. However, the suitability of these kinetic properties to model decomposition behaviour in FDS was not part of the original research. In this study, the kinetic properties of the MDF are re-analysed by using a hand calculation method developed by Wang et al. [10] using the DTG experimental curves for the application of these properties to FDS modelling. This analysis consists of two steps: the first step adopts the Kissinger analysis method [11] to obtain a linear relationship based on Eq. (1) to derive \( E \) and \( A \).

\[
\ln \left( \frac{\beta}{T_{i,p}^2} \right) = -\frac{E_i}{RT_{i,p}} + \ln \left( \frac{A_i R}{E_i} \right)
\]  

(1)

The same four-component scheme proposed by Li et al. [9] is adopted for this analysis. According to the relationships of \( \ln(\beta/T_{i,p}^2) \) and \( 1/T_{i,p} \) for each component in Figure 3, the value of \( E \) and \( A \) for each component can be calculated based on the slope and the intercept of each line.

![Figure 3](image)

*Figure 3*  **Linear relationships of \( \ln(\beta/T_{i,p}^2) \) and \( 1/T_{i,p} \) for each component in MDF [9].**

The second step is to develop a mathematical model according to the decomposition rate presented in Eq. (2) in order to depict the reaction rate curves at different heating rates.

\[
r_{i,j} = \sum_{j=0}^{N_{i,j}} (1 - v_{i,j}) c_j A_j \exp \left( -\frac{E_j}{RT_j} \right) \left( \frac{Y_{i,j}}{Y_j} \right)^n
\]  

(2)

The values of \( n_i \) and \( c_i \) can be determined through visual comparisons between the model and corresponding experimental results. In this analysis, an average of 20% residue for \( v_s \) based on the TG experiment data in Li et al. [9] is considered. Due to the different mathematical expressions for the decomposition rate between the hand calculation and the FDS pyrolysis model, a further modification on the pre-exponential factor obtained from the hand calculation method is required in order to apply it in FDS. The details of the correction process are introduced in Wang et al. [10]. Table 2 summarises the final results of the kinetic properties for the four components of MDF for the application in the FDS6 pyrolysis model.

<table>
<thead>
<tr>
<th>Component</th>
<th>( y = )</th>
<th>( R^2 = )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemicellulose</td>
<td>(-18885x + 18.083)</td>
<td>1</td>
</tr>
<tr>
<td>Cellulose</td>
<td>(-23124x + 21.901)</td>
<td>0.9882</td>
</tr>
<tr>
<td>Lignin</td>
<td>(-23606x + 20.199)</td>
<td>0.9936</td>
</tr>
<tr>
<td>Resin</td>
<td>(-15660x + 17.505)</td>
<td>0.9463</td>
</tr>
</tbody>
</table>
Table 2  Kinetic properties for MDF.

<table>
<thead>
<tr>
<th>Components</th>
<th>$E_i$ (J/mol)</th>
<th>$A_i$ (s$^{-1}$)</th>
<th>$n_i$</th>
<th>$c_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin</td>
<td>1.30×10$^7$</td>
<td>6.24×10$^{15}$</td>
<td>5.0</td>
<td>0.10</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>1.57×10$^7$</td>
<td>7.64×10$^{12}$</td>
<td>3.0</td>
<td>0.42</td>
</tr>
<tr>
<td>Cellulose</td>
<td>1.92×10$^7$</td>
<td>6.78×10$^{13}$</td>
<td>0.9</td>
<td>0.36</td>
</tr>
<tr>
<td>Lignin</td>
<td>1.96×10$^7$</td>
<td>3.90×10$^{19}$</td>
<td>8.0</td>
<td>0.12</td>
</tr>
</tbody>
</table>

FDS6 simulations of the TG experiments at the heating rates of 5, 20 and 60 K/min have been conducted using the kinetic properties in Table 2 by applying the methods described in Wang et al. [10]. Figure 4 is the comparison of DTG curves obtained from the simulations and from the experiments. The predictions for the DTG curves indicate that the kinetic properties derived here can satisfactorily represent the decomposition behaviour of the MDF.

![Comparison of DTG curves between simulations and experiments.](image)

Evaluation through FDS cone calorimeter simulations

In the TG simulations the heat transfer within solids is not included. However, when using the pyrolysis model to simulate a fire, the thermal properties have a significant influence on the heat transfer results and consequently the HRR predictions will be affected. Therefore the thermal properties and the kinetic properties of the MDF are evaluated and optimised using FDS simulations of the cone calorimeter experiments.

Cone calorimeter ignition, mass loss and HRR results at incident heat fluxes of 25, 35 and 50 kW/m² are adopted in this analysis. In the experiments, conditioned samples with dimensions of 100 mm × 100 mm × 18 mm thick were used. The MDF samples were dried at 60 °C for 12 hours similar to the conditions used for the cribs in the small-scale tunnel experiments. Experimental procedures were based on AS/NZ 3837:1998 [12] and each experiment was repeated three times.

The average initial bulk density of the MDF samples was 710 kg/m³ and the remaining mass from the experiments gave an average bulk density of 180 kg/m³ for the char, i.e. 25% of the original mass remained similar to the 20% in Li et al. [9]. According to the measured HRR and mass loss data, the average effective of heat of combustion is 11 to 12 MJ/kg which is consistent with the value obtained from Li et al. [13].
To evaluate the MDF properties for the FDS predictions of HRR, simulations for the three cone calorimeter experiments at each incident heat flux have been conducted. The sample was represented by the top surface of a solid block (100 mm × 100 mm). The thermal conductivity and specific heat for the MDF and char were defined according to the values listed in Table 1 and the density as discussed previously. The back face was defined according to the properties of the insulation board used in the cone calorimeter experiments (density 336 kg/m³, thermal conductivity 0.07 W/m/K and specific heat 1.08 kJ/kg/K) and the side surfaces were defined as inert. The incident heat flux from the cone heater was specified as a constant external heat flux to the surface.
The corresponding predicted HRR curves from cone calorimeter simulation at the three incident heat fluxes are plotted in Figure 5 and are compared with the experimental results. The first peak HRR for all three fluxes occur at times comparable to the experiments and the predictions at 25 and 35 kW/m² showing similar magnitudes to the experimental results. All three predictions show comparable decay curves to the experimental curves. The values of the second peak HRR are comparable to the experimental values, while the predictions for the burning duration are not successful. The ignition in the simulations are much faster than the ignition in the experiments under the three heat fluxes. The total energy predictions for the simulations under different heat fluxes are approximately 1.18 ± 0.02 kW/m² are consistent to the averaged experimental values at different heat fluxes (0.99 ± 0.12 MJ for 25 kW/m², 1.02 ± 0.07 MJ for 35 kW/m² and 1.11 ± 0.03 MJ for 50 kW/m²). Although the simulation results cannot precisely match the experimental HRR curves, the FDS results shown in Figure 5 can still demonstrate the general burning behaviour in MDF cone calorimeter experiments with limited success.

**SMALL-SCALE TUNNEL EXPERIMENT SIMULATIONS**

**Basic settings**

According to the FDS user’s guide [14], the parameter $D^*$ can be obtained from Eq. (3), where $\dot{Q}$ is the heat release rate, and $\rho_0$, $c_{p,0}$, $T_0$ are the properties of ambient air.

$$D^* = \left(\frac{\dot{Q}}{\rho_0 c_{p,0} T_0 g} \right)^{2/5}$$

The maximum $\dot{Q}$ obtained in the small-scale tunnel experiments was less than 100 kW so that the corresponding $D^*$ is 0.383 m. As suggested by Li and Ingason [15], a cell size of 20 cm was a reasonable value for the simulation of tunnel fires and the number of cells spanning the characteristic fire diameter in their simulations was 13. Zhang et al. [16] adopted 20 mm cell size to simulate the behaviour of a wood crib fire in a confined space and the spanning-cell number was 20. With a uniform cell size of 15 mm adopted for the simulations in this work, gives 25 cells spanning the characteristic diameter of the fire.

After a series of sensitivity analyses using cell sizes of 15 mm, 7.5 mm and 3.75 mm, it was found that numerical instability occurred at ~100 s when the 7.5 mm and 3.75 mm cell sizes were applied. In order to achieve a numerically stable calculation within a reasonable computational time as well as to give sufficiently accurate predictions of the small-scale tunnel fire simulations, the cell size of 15 mm is adopted in this study. For the solid phase, a stretch factor of one and cell size factor of 0.5 are applied to have a more uniform and smaller cell size for the solid phase calculations based on the studies in the previous work [4, 17].

Since the dimensions of the small-scale tunnel is 360 mm (W) × 260 mm (H) × 11900 mm (L), a domain with dimensions of 420 mm (W) × 300 mm (H) × 12645 mm (L) was used in the simulations to ensure sufficient volume to represent the entire tunnel and to accommodate the 15 mm cell size set-up. In the simulations the insulated platform was represent as a solid block adjusted to a dimension of 300 mm (W) × 495 mm (L) × 45 mm (H) and the surfaces assigned the insulation material thermal properties. The tunnel walls were given the thermal properties of the insulation material used in the tunnel experiments and the thin steel sheets were omitted. The observation window glass was not specifically simulated due to the assumed minor thermal influence on the results.

The ventilation fan was represented by a supply air vent at 2585 mm upstream away from the fuel location. The circular duct for the collection of flue gases was not modelled, while the downstream end of the tunnel was initially modelled as being directly open to ambient conditions. A Smokeview image of the simulated tunnel is shown in Figure 6 (a).
In the simulations, the obstruction function in FDS was adopted to construct the crib. The dimensions of the crib were defined as those used in the experiments except that the length of the short stick was modified to 105 mm so it corresponded to the 15 mm cell size. The representation of the crib geometry in FDS is shown in Figure 6 (b).

For the application of the pyrolysis method, the decomposition reactions of the MDF had to be defined. A surface line in the FDS input file was defined to prescribe the boundary conditions for the obstructions that corresponded to the crib. The four different components (resin, hemicellulose, cellulose and lignin) were used to represent the fuel with the corresponding mass fraction of each component described in order to specify the kinetic properties, thermal properties and heat of combustion for each component. In FDS6, the burning efficiency can be controlled through the heat of combustion parameter. In order to investigate the influence of burning efficiency on HRR predictions, the heat of combustion of 12 MJ/kg based on the cone calorimeter results and the calculated heat of combustion obtained from the small-scale tunnel experiments [7] were applied to conduct corresponding simulations.

Another important parameter is the thickness for heat conduction and in FDS6 only one-dimensional heat transfer in solids is available. Therefore, the actual solid thickness could not be simply adopted to represent the thickness for the heat conduction calculation. In order to effectively characterise the heating conditions, an approximation was to use $\frac{1}{4}$ thickness of wood stick (3.75 mm) which represents a scenario in which the wood stick is heated evenly over all of the surfaces excluding the ends.

**Ignition source**

In the experiments 20 ml of methylated spirits was placed in an 80 mm diameter circular pan as the ignition source for the cribs. The burning of this fuel lasted for approximately 120 s. By using a density of 789 kg/m$^3$ and heat of combustion 26.8 MJ/kg [18] to 28.9 MJ/kg [19] for the fuel the corresponding steady-state heat release rate is calculated as 3.5 kW to 3.8 kW and the total energy content as 423 to 456 kJ.

In the simulations, the ignition source was simplified to a rectangular area with a dimension of 60 mm $\times$ 90 mm with a 3.8 kW maximum HRR obtained from a 700 kW/m$^2$ HRRPUA. To represent the burning of the methylated spirits the ignition source was set to linearly growth to 3.8 kW over the first 10 s and the value was kept constant for a further 110 s. By using this specification, it was found that the ignition source would not ignite the crib over the 120 s duration. In order to investigate the ability to ignite the crib, different burning times of 120 s, 240 s, 360 s and 1500 s (the full simulation time) were used to simulate the ignition source for the tunnel scenario with a 0.23 m/s forced ventilation velocity. The ignition source in this experiment lasted for about 120 s and the experiment was stopped at 1500 s when the crib residue was at a smouldering stage. The corresponding simulation results are plotted in Figure 7.
From these results it can be seen that when the 120 s duration is used the HRR curve has an average value of 3.8 kW which lasts about 120 s and then it drops to zero, which suggests that the crib has not been ignited. When the ignition duration time is extended to 240 s, 360 s, 500 s and 1500 s, the crib is ignited so that the HRR values increase after the ignition source burns out. As seen in Figure 7 (a), the HRR for the 240 s duration ignition source is lower than the predicted results when longer ignition source durations are applied which indicates that the crib has not fully ignited in this case. For the cases of the 360 s, 500 s and 1500 s durations the predicted peak HRR values are similar while the burning period increases with the increase of ignition duration. Figure 7 (b) plots the mass consumption for the cases of the 360 s, 500 s and 1500 s ignition durations where the longer ignition duration, the more crib that is consumed.

In order to represent the results from the small-scale tunnel experiments the influence of the ignition source on the crib needs to be minimised. Simulations found that a 360 s ignition source duration can effectively ignite the crib under different forced ventilation conditions from 0.23 m/s to 1.2 m/s when an effective heat of combustion ($\Delta H_e$) of 12 MJ/kg is used for the MDF, while the duration of ignition source needs to increase to 480 s for the 1.6 m/s scenario. However as discussed previously, different values of $\Delta H_e$ can be obtained when different forced ventilation velocities are applied. Simulations found that a 240 s ignition source duration is sufficient to ignite the crib when the correspondingly higher values of $\Delta H_e$ are applied. Table 3 gives the ignition source duration times for the different forced ventilation conditions when a heat of combustion of 12 MJ/kg (referred to as Fixed HoC) is used and the revised durations (referred to as Modified HoC) when the modified heat of combustion values are applied.

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Fixed HoC</th>
<th>Modified HoC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta H_e$ (MJ/kg)</td>
<td>Duration (s)</td>
</tr>
<tr>
<td>0.23</td>
<td>12</td>
<td>360</td>
</tr>
<tr>
<td>0.40</td>
<td>12</td>
<td>360</td>
</tr>
<tr>
<td>0.68</td>
<td>12</td>
<td>360</td>
</tr>
<tr>
<td>0.90</td>
<td>12</td>
<td>360</td>
</tr>
<tr>
<td>1.20</td>
<td>12</td>
<td>360</td>
</tr>
<tr>
<td>1.60</td>
<td>12</td>
<td>480</td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSION

HRR Predictions
The HRR predictions for the Fixed HoC and the Modified HoC groups and the corresponding experimental curves at different forced ventilation velocities are plotted in Figure 8 where the HRR generated from the ignition source has been subtracted from the HRR curves. The heat of combustion values calculated from the predicted values of HRR and mass loss rate are consistent with the set-up values in the FDS data file. The consistent heat of combustion results indicate that all of the available fuel is burned in the domain.

![Image of HRR curves at different velocities using different values of heat of combustion.]

Figure 8 Predictions of HRR curves at different velocities using different values of heat of combustion.

For the simulations using the fixed heat of combustion conditions, as the forced ventilation velocity changes from 0.23 m/s to 0.4 m/s, the burning duration reduces from 800 s to about 650 s and the peak HRR increases from 18 kW to 27 kW. However, the predicted HRR curves demonstrate similar...
burning behaviour in terms of burning duration and peak HRR when the 0.4 m/s, 0.68 m/s, 0.9 m/s
and 1.2 m/s forced ventilation velocities are examined. When the velocity increases to 1.6 m/s, the
burning duration and the peak HRR are both less than those predictions at the 0.4 m/s to 1.2 m/s
forced ventilation velocities. In general the predicted peak HRR value for each scenario are noticeably
less than the results from the experiments.

As shown in Figure 8, when the values for the heat of combustion are modified, the predicted HRR
values largely improve when compared with the fixed value simulations. The predicted peak HRR
values are similar to the experimental values at the 0.68 m/s, 0.9 m/s and 1.2 m/s forced ventilation
velocities. However, the predictions of the fire growth and the entire burning duration at each forced
ventilation velocity are unsatisfactory when compared to the experimental results.

When the total energy release results are considered, there are significant differences between the
experiments and simulations. As shown in Figure 9, less than half of the energy is predicted in the
simulations for each forced ventilation scenario compared with the energy released in the
corresponding experiment.

![Figure 9](image)

**Figure 9** Measured and predicted total energy released at different forced ventilation velocities
based on different simulation set-ups.

**Improvements to predictions**

In order to improve the predictions from FDS an investigation into the mass and energy consumption
is carried out for the 0.68 m/s forced ventilation velocity scenario. In the experiment, the initial mass
of the crib was measured as 1.4 kg and the remaining mass of the residue material (char and ash
mixture) after burning was measured as ≈ 0.2 kg, which was about 14% of the original fuel mass.

When the crib with the geometrical form was applied to the simulations, the available fuel surface for
burning could not be as large as in the experiments due to the overlapping sections of the sticks. FDS
uses the surface properties of one side obstruction only when two obstructions overlap each other
[14]. As a result of the available surface area (0.51 m²), thickness (3.75 mm) and density (710 kg/m³)
applied in the simulations, the available mass was 1.36 kg rather than 1.40 kg. In addition, 20% of
MDF was set to covert to char in the simulations, which means that no combustion reaction occurs for
this component proportion. Therefore the available burnable fuel mass in the simulations was less
than that in the experiments.

In order to obtain a comparable fuel mass between FDS and the experiments some modifications were
made to the 0.68 m/s forced ventilation simulation case to re-assess the results. The thickness of sticks
was increased from 3.75 mm to 3.90 mm to compensate for the ‘missing’ fuel mass due to the overlapping area and also in order to maintain the same fuel density and crib geometrical shape as the experiments. No residue was considered in this case, which means all of the exposed fuel was available to be consumed in the simulation. Thus a total of 1.4 kg of fuel was available as a result of these modifications. The revised simulation results are plotted in Figure 10 along with the experimental data and the previous simulation results using the 3.75 mm thickness.

As shown in Figure 10 (a), the predicted shapes of the fire growth curve are similar in both cases albeit with a delayed time shift when compared to the experiment. However, the increase in fuel mass improves the prediction of the peak HRR, where a value of 62 kW is obtained for the modified case (~60 kW was obtained in the experiment) compared with 47 kW with the previous case. The consumption of the fuel has improved from 46 % to 65 % in the mass loss curves shown in Figure 10(b). For the original mass loss curve there is still about 32 % remaining after subtracting the unavailable mass for burning and the mass that converts to char. This remaining mass indicates that the fuel is still not completely consumed in the simulation. The same as the revised mass loss curve, there is ~ 35 % fuel remaining for the modified case even though the fuel was set up to be fully consumed in this case. Based on the simulation results for the revised fuel mass, the predicted heat of combustion values (the predicted HRR / the predicted mass loss rate) obtained from this simulation are not fully consistent with the set-up value of 13 MJ/kg, which are plotted in Figure 11.

![Figure 10](image-url)  
*Simulation results with the modification of the available fuel mass for (a) HRR curves, (b) mass loss curves.*

![Figure 11](image-url)  
*Results for heat of combustion from the simulation for the 0.68 m/s forced ventilation velocity condition*
As seen, the values of heat of combustion obtained from the simulation with the revised fuel mass drop to about 11.5 to 12 MJ/kg between 280 s and 360 s, which indicates that the fuel is not effectively burnt in the simulation and some unburned fuel is lost out of domain. In order to overcome this, an extra mesh with 15 mm cell size was used at the end of the original mesh with sufficient height and length (as shown in Figure 12) to allow the unburned fuel to burn. The predicted heat of combustion values based on the extended domain is plotted in Figure 11 and the results of mass loss rate and HRR are plotted in Figure 10. The heat of combustion values over 280 s to 360 s are improved after the changes in the domain as shown in Figure 11. The HRR curve for the revised domain shown in Figure 10 (a) also demonstrates a higher peak HRR values over this time period, while no change is shown on the mass loss curve.

Figure 12  The modified domain with an extended mesh.

Based on the improvements obtained above, the modifications to the fuel mass and domain were applied to the other forced ventilation scenarios. The corresponding results are shown in Figure 13, which demonstrate a general improvement in the peak HRR and total energy predictions. Even though the simulation results have been improved after the increase of the available fuel mass, the predicted HRR curves at different velocities are still not ideal. The initial fire growth phase at each forced ventilation velocity is not improved, where significant ignition delays and slower fire growth rate are still found at 0.23 m/s, 0.4 m/s and 0.68 m/s and earlier ignition and faster fire growth rates are obtained for higher 1.2 m/s and 1.6 m/s forced ventilation velocities. It is noted that the cell size adopted in the simulations is relatively coarse in terms of the fuel dimensions. Due to the limits of resources, the simulations with a finer cell size are not carried out. However, the ignition delay might be improved with the use of a finer cell size. The predicted total energy is still less than the experimental value at each velocity based on the comparison of the area the under curve between the simulation and experimental result. The comparison is shown in Figure 9.

Overall, the predictions in HRR for the small-scale tunnel fires at different forced ventilation velocities through the application of the FDS6 pyrolysis model are limited. The assumption of one-dimensional heat conduction in the solid may limit the heat transfer and the increase in temperatures therefore hindering the pyrolysis reactions, slowing down the ignition of the fuel and so reducing the growth of the fire. Another reason for the limited predictions may be because the specified pyrolysis reactions are not wholly able to represent the decomposition reactions in the presence of air. The pyrolysis rate adopted in this study was under nitrogen environment, which represents the scenarios that decomposition reactions occur under flame without the presence of oxygen. When forced ventilation conditions are present the heat may be imposed on the downstream side of the fuel. Therefore, the fuel surface may be heated first without being covered with flame and the pyrolysates may mix with air before reacting.
CONCLUSIONS

This work applies the pyrolysis model in FDS to simulate a series of small-scale tunnel experiments under different forced ventilation velocities. The material properties of the MDF used in the small-scale tunnel experiments are investigated and evaluated through simulations of TG and cone calorimeter experiments. It is found that the kinetic properties for MDF obtained in this work can reasonably represent the decomposition behaviour in FDS. The results from simulations of the cone calorimeter are not perfectly comparable to the experimental results, however, predictions of peak HRR, burning periods and total energy release are able to reflect the burning behaviour of the MDF.
Based on the simulation results for the tunnel experiments, some factors are found to have significant influence on the predictions: the influence of the forced ventilation on the burning efficiency needs to be accounted for when using the pyrolysis model; the available fuel mass for burning is affected by the thickness of the crib sticks and the available surface area; the use of an appropriate domain is important in order to allow the unburned fuel to be completely consumed within the domain. However, even with these factors included, the match between the FDS predictions of HRR and the small-scale tunnel experiments has its limitations. As discussed, simulations with the application of finer cell sizes are suggested for future studies.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>pre-exponential factor (s$^{-1}$)</td>
</tr>
<tr>
<td>$c$</td>
<td>component mass fraction</td>
</tr>
<tr>
<td>$c_p$</td>
<td>specific heat (J g$^{-1}$ K$^{-1}$)</td>
</tr>
<tr>
<td>$D^*$</td>
<td>characteristic fire diameter (m)</td>
</tr>
<tr>
<td>$E$</td>
<td>activation energy (J mol$^{-1}$)</td>
</tr>
<tr>
<td>$ΔH_e$</td>
<td>effective heat of combustion (MJ kg$^{-1}$)</td>
</tr>
<tr>
<td>$k$</td>
<td>thermal conductivity (W m$^{-1}$ K$^{-1}$)</td>
</tr>
<tr>
<td>$k_{0}^{30}$</td>
<td>thermal conductivity alone the panel thickness at 30 °C (W m$^{-1}$ K$^{-1}$)</td>
</tr>
<tr>
<td>$Δk$</td>
<td>correction for $k_{0}^{30}$ (W m$^{-1}$ K$^{-1}$)</td>
</tr>
<tr>
<td>$n$</td>
<td>reaction order</td>
</tr>
<tr>
<td>$N$</td>
<td>number of components</td>
</tr>
<tr>
<td>$Q$</td>
<td>heat release rate (kW)</td>
</tr>
<tr>
<td>$r$</td>
<td>decomposition reaction rate (% K$^{-1}$)</td>
</tr>
<tr>
<td>$R$</td>
<td>universal gas constant, 8.314 (J K$^{-1}$ mol$^{-1}$)</td>
</tr>
<tr>
<td>$t$</td>
<td>time (s)</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature (K or °C)</td>
</tr>
<tr>
<td>$v$</td>
<td>yield of residue in solid phase reaction</td>
</tr>
<tr>
<td>$Y$</td>
<td>mass conversion fraction (-)</td>
</tr>
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</table>

**Greek symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$β$</td>
<td>heating rate (K min$^{-1}$)</td>
</tr>
<tr>
<td>$ρ$</td>
<td>density (kg m$^{-3}$)</td>
</tr>
</tbody>
</table>

**Subscripts**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>e</td>
<td>end of reactions</td>
</tr>
<tr>
<td>i</td>
<td>$i^{th}$ component</td>
</tr>
<tr>
<td>j</td>
<td>$j^{th}$ second</td>
</tr>
<tr>
<td>p</td>
<td>peak</td>
</tr>
</tbody>
</table>

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REFERENCES

The Experimental Approach to the Smoke Behaviour on Slope in Road Tunnel

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¹Hanshin Expressway Company Limited, Osaka, Japan
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ABSTRACT

In case of a fire occurrence in an urban road tunnel which has longitudinal ventilation system, it is important that the safe circumstance for evacuation is kept at very early stage of fire. While the smoke, which causes breathing difficulty, is most critical for evacuees, the smoke should be controlled with ventilation equipment to suppress the diffusion. This paper is focused on the smoke behaviour on a longitudinal slope in road tunnel and how the ventilation equipment should be controlled in case of fire.

KEYWORD: Model tests, Numerical analysis, Smoke behaviour, Tunnel section with a slope, Smoke control, Particle Image Velocimetry, Theory of Froude number similarity

NOMENCLATURE

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross section area of air flow, m²</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>Gravity acceleration, m/s²</td>
<td></td>
</tr>
<tr>
<td>Fb</td>
<td>Buoyancy force of air flow, N</td>
<td></td>
</tr>
<tr>
<td>Fi</td>
<td>Inertia force of air flow, N</td>
<td></td>
</tr>
<tr>
<td>Fr</td>
<td>Froude number, -</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Height of tunnel, m</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Characteristic length, m</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Pressure, Pa</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>Total Heat Release Rate (HRR), MW</td>
<td></td>
</tr>
<tr>
<td>q</td>
<td>Flow rate, m³/s</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>Gas constant, 287 J/kg K</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Temperature, K</td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>Time, s</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>Velocity of air flow, m/s</td>
<td></td>
</tr>
<tr>
<td>γ</td>
<td>Scale of the model tunnel, 18</td>
<td></td>
</tr>
<tr>
<td>ρ</td>
<td>Density, kg/m³</td>
<td></td>
</tr>
<tr>
<td>χ</td>
<td>Helium mixed ratio, -</td>
<td></td>
</tr>
<tr>
<td>Subscripts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>air</td>
<td>Air</td>
<td></td>
</tr>
<tr>
<td>He</td>
<td>Helium</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>Mixed gas with air and helium</td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>Smoke</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>ambient/standard conditions</td>
<td></td>
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</tbody>
</table>

INTRODUCTION

Recently the longitudinal ventilation system is often adopted even for urban road tunnels considering the advantage of tunnel construction cost; the longitudinal ventilation system needs no ducts like transverse ventilation system, and it means the cross section of tunnel can minimize. However the ventilation system has also disadvantage that polluted air as well as smoke cannot be removed from the room of motorway.

In case of fire ventilation equipment should primarily be controlled in early stages that the tunnel users does not be in smoke and can evacuate from the tunnel safely. The smoke produced by fire may cause degradation of tunnel user’s visibility as well as breathing difficulty, which lead to their lives being put in danger. However controlling the behaviour of smoke may be not always easy in urban road tunnels. A number of urban road tunnels have complex road alignments, i.e. ramps, sharp curves and sags between longitudinal slopes. Traffic congestions are often occurred at these sections and this
means it is essential to use different strategy of ventilation control depending on the traffic condition so as to keep the safe circumstance for evacuation at the very initial stage of fire. When vehicles are driven smoothly in front side of fire point, the smoke can be exhausted frontward by jet fans. In case that congestions exist in front of fire, the smoke must not be exhausted frontward but be kept in an injection point as possible by suppressing longitudinal air flow. If the fire occurs in a tunnel section with a slope, the behaviour of smoke on the both sides may not be symmetric. Much more smoke and plume may flow upward the slope, and cause the condition that the smoke fall to the road surface earlier on the upper side. Especially in case that there are evacuees on the both sides of the fire (e.g. fire in traffic congestion), evacuees on the upper side may suffer more risk of being trapped in smoke.

This paper presents experimental results regarding the behaviour of smoke on the slope which is carried out on a model tunnel. The study how to control ventilation equipment in order to retard the fall of smoke is also performed. The model scale is 1:18 and the smoke produced by the fire is represented by a mixed gas of air, helium and tracer particles for Particle Image Velocimetry, hereinafter called PIV. The main objectives of these experiments are; (1) to get a description of the smoke flow behaviour on slope, and (2) to identify the effect of longitudinal air flow on the smoke flow behaviour.

EXPERIMENTAL EQUIPMENT

General outline

The schematic view of the model tunnel with a scale of 1:18 is shown in Figure 1. The model tunnel consists of tunnel modules, base frames, a laser generator, a mixed gas supply system and a sCMOS camera for the PIV analysis. The tunnel modules, whose cross section shapes rectangular, are made from medium-density fibreboard (hereinafter called MDF) or acrylic glass. In principle, modules of the MDF are used for the experiment, although the acrylic glass modules are installed at the monitoring point of the mixed gas behaviour and also at downstream side from the ignition point. The cross sectional dimension of the module is determined by reference to both specifications of RQ10,5T regulated in the German directive for the equipment and operation of road tunnels (hereinafter called RABT: die Richtlinien für die Ausstattung und den Betrieb von Straßenrouten) \[1\] and the Japanese design guideline for Hanshin Expressway. Moreover the longitudinal slope is able to be adjusted by changing the height of each base frame. The smoke induced by fire in a real tunnel is simulated by the mixed gas in the model tunnel, which consists of air, helium and tracer particles for PIV. The both mass flow rates of the air and the helium are controlled by each flow controller. The tracer particles generated by the generator are mixed in the air, and subsequently the mixed gas is blown in the tunnel modules from the round shaped outlet. The appropriate mixture of the gas is calculated from the condition of a fire.

In this study there are some experimental cases in which the longitudinal airflow is needed. The longitudinal airflow was made by some fans from the outside of the model tunnel.

The concept of the Particle Image Velocimetry (PIV)

In order to analyse the condition of mixed gas, a measurement method is needed. The visualization of the behaviour of the mixed gas is done by the PIV in this study. PIV is the contactless measurement method for the velocity distribution of the airflow. The schematic view of PIV is shown in Figure 2. As mentioned above, the gas is seeded with tracer particles, and the flow of the mixed gas in the model tunnel is locally visualized by the illumination of the particles on a sheet of laser and by two pictures taken within a short interval $\Delta t = t_1 - t_0$ by sCMOS camera. Subsequently the local displacement factor $\Delta x$ is analysed with the cross correlation function by the two pictures, and the velocity distribution as well as the local velocity vector in the air flow is derived from the $\Delta t$ and $\Delta x$. In this experiment the tracer particles are generated with 2-ethylhexyl sebacate (DEHS) and its diameter is about 10 μm or less.
Figure 1 The schematic view of the model tunnel

(a) The schematic view from the portal and the cross section

(b) The overview and the component

The transverse slope of the road surface can be changed if needed.
THE EXPERIMENTAL CONDITION

The assumed fire scale

For simulating the case of fire in road tunnel, it is needed to determine the fire scale. Generally the total Heat Release Rate (hereinafter called HRR) is adopted as measure of fire scale. The situation is assumed that a fire is caused by a passenger vehicle and the value of the total HRR for it is set. The total HRR value of passenger car is set to 5MW in full scale value, which is derived from RABT.

The theory of hydrodynamic similarity

When the experiment is conducted with small-scale model, the flow specification in the model must be hydrodynamically similar to real tunnel as possible. There are several laws of similarity and non-dimensional numbers are defined in each law. However it is difficult in most cases to make a complete similarity, that is, to equalize all non-dimensional numbers between the both airflow. Therefore the approach to find out a dominant aspect and equalize the number associated with it is generally used.\[2]\[3]

In this study the critical force to the smoke is thought to be inertia force and buoyancy, hence it should be considered that the similarity with the Froude number is ensured. Froude number $Fr$ is represented by a ratio between inertia force $Fi$ and buoyancy $Fb$ acting on a flow, and in case of the airflow in a tunnel the $Fr$ is defined by

$$Fr = \frac{\sqrt{Fi}}{\sqrt{Fb}} = \frac{U}{\sqrt{gh}}$$
The both value of Fr of real- and model tunnel must be same.

\[
\frac{U_{\text{model}}}{\sqrt{gH_{\text{model}}}} = \frac{U_{\text{real}}}{\sqrt{gH_{\text{real}}}}
\]

\[
U_{\text{real}} = \sqrt{\frac{L_{\text{real}}}{L_{\text{model}}}} U_{\text{model}} = \sqrt{\gamma} U_{\text{model}}
\]

where \( \gamma \) is the scale of the model tunnel, namely 18 in this study.

On the other hand, the flow rate in the model tunnel is expressed and transformed below using the equation above;

\[
q_{\text{model}} = A_{\text{model}} \cdot U_{\text{model}} = L_{\text{model}} \cdot U_{\text{model}} = \gamma^{-2.5} L_{\text{real}} \cdot U_{\text{real}} = \gamma^{-2.5} q_{\text{real}}
\]

From this equation the flow rate in model tunnel should be set \( \gamma^{-2.5} \) times the value of real tunnel.

**Conversion of the characteristic of smoke in real tunnel to the mixed gas in model tunnel**

In this study the smoke behaviour in a real tunnel was simulated with the mixed gas in model tunnel. It means that the characteristic of the smoke should be converted to the mixed gas correctly. The characteristics of the mixed gas were determined from the smoke property induced by the fire of 5MW. The conversion procedure is shown in Figure 3.

At first the temperature and flow rate of smoke from the assumed total HRR were configured. The paper by Mégret et al.[4] indicates the relationship between the total HRR and the smoke temperature / flow rate produced by heptane pool fire. From these smoke characteristics the helium mixed ratio and mixed gas flow rate is able to be calculated using the equation of state and the equation above. Using the procedure shown in Figure 3, helium ratio \( \chi \) and flow rate \( q_m \) were calculated from the value of the total HRR, 5MW. The results are shown in Table 1.

* Ref[4]: Mégret O, Vanquelin O, A model to evaluate tunnel fire characteristics, Fire Safety Journal Vol 34, 2000

**Figure 3 Conversion procedure from a real tunnel to the model tunnel**

\[
\text{Theory of Froude number similarity} \quad q_{\text{in}} = \gamma^{-2.5} q_{\text{in}}
\]
Table 1 The characteristics of the mixed gas

<table>
<thead>
<tr>
<th>Fire type</th>
<th>Total HRR Q (MW)</th>
<th>Helium Ratio χ (−)</th>
<th>Flow rate qm (L / min)</th>
<th>Helium (L / min)</th>
<th>Air (L / min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger vehicle</td>
<td>5</td>
<td>0.62</td>
<td>780</td>
<td>483.6</td>
<td>296.4</td>
</tr>
</tbody>
</table>

Assumed conditions and the layout of measurement point

The experiments were conducted for the purpose of verifying the influence of the longitudinal airflow on the suppression of the gas on the slope section. The experimental conditions are shown in Table 2. RABT[1] regulates that the longitudinal gradient in tunnel is expected to be less than or equal to 3%. Similarly also the design guideline for Hanshin Expressway stipulates that the gradient should be 3% or less at tunnel sections in principle. From these regulations 3% of the longitudinal gradients were given for the tunnel. On the other hand there was no transverse gradient there. Variable longitudinal airflows were provided before the mixed gas was blown off in the sloped tunnel. It was assumed with this condition that the airflow was controlled with ventilation equipment before the serious smoke generation in case of fire.

Regarding the measurement points, the layout was decided them from the RABT; the standard interval of emergency exit is regulated 300m (16.8m in the model tunnel). In addition the measurement points were added at the 100m (5.6m), 200m (11.2m) from the ignition point. The layout of the measurement points is shown in Figure 4.

Table 2 Experimental conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Longitudinal gradient (%)</th>
<th>Airflow velocity (m/s)</th>
<th>Measurement point (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>3%</td>
<td>0 m/s, 0.12 m/s, 0.24 m/s</td>
<td>5.6m, 11.2m, 16.8m from the ignition point</td>
</tr>
</tbody>
</table>

Figure 4 The layout of the measurement point

§ The number in ( ) represents the adjusted value in real tunnel.
Conditions of evacuations

In this paper the situation is assumed that there is traffic congestion in front of the ignition point and therefore the evacuees exist on both side of the point. This means the smoke produced by fire cannot be exhausted frontward, but be suppressed spreading in the longitudinal direction as possible. Under this condition evacuees escape from the fire to the both side so as not to stay in the smoke. The assumed conditions are shown in Figure 5. The reaching time of the gas at each point was measured so as to compare with the position of evacuees. The time variation of the evacuees’ position was calculated on an assumption; tunnel users started to evacuate from the fire point in both direction with 0.31 m/s (1.3 m/s in a real tunnel) at the time of ignition. The adopted value is the travel speed of average pedestrians in normal situation[5]. The positional relationships between the gas and evacuees, which is important for the safety analysis, were evaluated with these obtained data.

EXPERIMENTAL RESULT

Suppression effect on the gas extent by longitudinal airflow

The experiments under the conditions shown in Table 2 were conducted in the model tunnel. The steady airflows were set, as described above, before the injection of mixed gas and the time to reach the gas on each measurement point had been measured. Moreover the position of an evacuee at upper side at each time was set by the condition shown in Figure 5. The results are shown in Figure 6. X-axis indicates the distance from the ignition point and positive direction is from down to upper side. Y-axis is the time from ignition. The green lines show the position of the evacuees at each time and blue dots indicate the reaching time of the gas at each measurement point obtained by experiments. The grey areas above the blue lines indicate the zone where the gas exists.

When there was no airflow, the lines of mixed gas and evacuees crossed at approx. 7.5m (equivalent to 135m in a real tunnel). This means the gas reached and overtook the evacuees. Under the condition of 0.12m/s and 0.24 m/s of the longitudinal airflow, each line did not cross each other. In this situation the evacuee can walk ahead of the tip of the gas layer. In addition it was confirmed that the evacuee can walk safely under the area of the stratified gas flow as the stratification of the upper side was maintained under the condition of up to 0.24m/s (equivalent to 1.0m/s in a real tunnel) as shown in Figure 7. These results indicate the longitudinal airflow prevents the mixed gas from spreading on the upper side well and make the safe circumstance there. Therefore controlling the gas with a moderate longitudinal airflow is more effective than the velocity of 0m/s in improving the circumstance during the evacuation on the upper side of the slope.
Figure 6 Experimental results

(a) Without airflow

(b) With airflow of 0.12 m/s (0.5 m/s in real tunnel)

(c) With airflow of 0.24 m/s (1.0 m/s in real tunnel)
(a) At 5.6m (equivalent to 100m) from the ignition point (Reaching time : 31.2s)

(b) At 11.2m (equivalent to 200m) from the ignition point (Reaching time : 48.6s)

(c) At 16.8m (equivalent to 300m) from the ignition point (Reaching time : 69.6s)

Figure 7: The tip of mixed gas under the condition of 0.24 m/s analysed by PIV
SIMULATION AND SAFETY ANALYSIS

Introduction and purpose of simulations

It was confirmed with the experimental results that the airflow could suppress the longitudinal diffusion of smoke effectively on the upper side. In order to ensure the safety for evaluation under the condition of congestion, the circumstance should be evaluated also at the down side because the evacuees exist on both sides of the ignition point. For the research of the relationship between smoke behaviour and the safety of evacuees, it is better that the tunnel has length more than the interval of emergency exit, i.e. 16.8m in both sides of the ignition point because the length enables a verification whether the evacuees are able to reach the next exits in a safe environment. However the length of the model tunnel is not able to be extended because the room of the laboratory for the model tunnel is limited. Hence simulations with the extended model tunnel were conducted in order to verify the safety not only on the upper side but also on the down side of the ignition point. At first the simulation results were compared with the experimental results for the validation of the simulation. In addition the results were compared also with the simulation results of the extended tunnel to confirm the influence of the length of the down side. And then the results of simulations were compared with the position of evacuees in order to clarify the most suitable airflow velocity, with which the ideal circumstance for the evacuee can be held as longer as possible on the slope. The simulation was computed with the Fire Dynamics Simulator (FDS) produced by NIST, National Institute of Standards and Technology of U.S. Department of Commerce.

Comparison of the experimental- and the simulation results

The analytical model for the simulation was developed which is same as the model tunnel shown in Figure 4. The cross sectional dimension is shown in Figure 1(a) and the analytical domain was divided into orthogonal grids of 1750*26*25. Simulations were conducted under each condition of longitudinal airflow and results were compared with the experimental results for the purpose of validation. Regarding simulations, the gas reaching time at each position was detected by the degradation of the density at the height by means of the lightness of helium. The comparison results are shown in Figure 8. The blue dots are experimental data shown in Figure 6, and red circles are data obtained by simulations. There are some differences between the data of the experiment and the simulation in the area away from the ignition point under the condition of 0.24m/s. The difference can be attributed to some disturbances on the experiment, for example, time variation of the airflow. Although it becomes obvious from the graphs that the results from the simulation is on average well consistent with the experiment on every condition.

(a) Without airflow
Comparison of the model tunnel and the extended tunnel

To verify the influence of the length of the down side in the model tunnel on the gas behaviour, the models of extended tunnel was also developed. The schematic view of the models is shown in Figure 9. The length of the down side was extended to 27.3 m, whose length was longer than the interval of emergency exit. 980 grids were also increased in this extended area. The longitudinal airflow was given at the tunnel portal on the upper side in the direction from upper to down side. The simulation results are shown in Figure 10. The red circles show the result with the model tunnel shown in Figure 4, and blue dots the result with the extended tunnel shown in Figure 9. It was confirmed that there was little influence of the tunnel length on the gas behaviour regardless of the airflow velocity.
Figure 10 Comparison of simulation results with the model- and the extended tunnel

(a) Without airflow

(b) With airflow of 0.12 m/s (0.5 m/s in real tunnel)

(c) With airflow of 0.24 m/s (1.0 m/s in real tunnel)
Comparison of gas behaviour and positions of evacuees

Simulation results shown in Figure 10 were compared with the position of evacuees in each time in order to identify the positional relationship between the gas and evacuees. It was assumed, described above, that tunnel users started to evacuate from the fire point in both direction with 0.31 m/s (1.3 m/s in a real tunnel) at the time of ignition. The simulation results are shown in Figure 11.

When there was no airflow in tunnel as shown in (a), the gas spreaded faster than the evacuee on the upper side. On the other hand the gas did not come over the evacuee on the down side. Under the condition with the longitudinal airflow of 0.12 m/s (0.5 m/s in a real tunnel) shown in (b) the gas diffused nearly symmetrically. However the green line was on or came into the gray area on both side of the fire point. In the longitudinal airflow of 0.24 m/s as shown in (c), the gas flowed more in the direction of down side and the evacuee on the down side was caught up with the gas. The evacuee on upper side was in safe circumstance under the condition. In fact the results was very similar to the evaluation results with the experimental data on the upper side, and on the down side, the results show a reverse trend of the upper side. These trends are caused because some gas on the upper side may be backlayered by the airflow.
With airflow of 0.24 m/s (1.0 m/s in a real tunnel)

**Figure 11** Comparisons of the gas behavior and the position of evacuees

For the more detailed evaluation the condition in the tunnel was examined with the contour obtained by the simulation. Figure 12 shows the contour of the gas density around the point of -5.8m at 16s in the condition of 0.12m/s. The yellow-green area indicates the low-density area, that is, the mixed gas. 16s is the time when the gas reached at the point of -5.8m in the airflow of 0.12m/s. From Figure 11 the gas was on the evacuee at -5.8m under the condition shown in Figure 12. However the condition may not be necessarily unsafe for the evacuee because the gas did not fall down to the evacuees yet. In order to verify the safe condition the positional relationship between the gas and evacuees was evaluated at the height of eye level of evacuees.

**Figure 12** The density contour around the point of -5.8m in 0.12m/s

Safety analysis on the height of evacuees

The evaluation height, where the reaching time of the gas is evaluated, should be decided for the safety analysis. It is critical for the evacuee whether they don’t have poor visibility or suffer breathing difficulty by the smoke. From these requirements the eye-level of the evacuees should be appropriate as the evaluation height. The height of 1.5m, which is equivalent to 0.083m in the model tunnel, from the road surface was assumed as the eye-level. The reaching times of the gas at 0.083m were verified by the simulations. The simulation results and the positions of evacuees are shown in Figure 13. When there was no airflow in the tunnel, the gas caught up with the evacuee at about 7m (126m in real tunnel) on the upper side as shown in (a). This result indicates that the evacuee may not reach the nearest emergency exit safely. On the other hand the evacuee on down side was able to reach the exit safely. Under the condition with the longitudinal airflow of 0.12 m/s (0.5m/s in a real tunnel) shown in (b) the gas diffused nearly symmetrically also at the height and the green line doesn’t come into the gray area on the both side of the fire point. From this result the evacuees were able to reach exits safely on the both side of the fire point. In the longitudinal airflow 0.24m/s (1.0m/s in a real tunnel) as shown in (c), the gas flows more in the direction of down side and the evacuee on the down side was in the gas at less than 16.8m (300 m/s in real tunnel; standard distance of emergency exits) from the fire point. The evacuee on upper side was able to reach the exit without the exposure of the gas. From these results it is numerically verified that there is an ideal longitudinal airflow for the safe evacuation in the situation of fire on a slope, and it is 0.5 m/s on the slope of 3% at 5MW fire in a real tunnel.
Figure 13 Comparisons of the gas behavior and the position of evacuees at 1.5m
CONCLUSION

In this paper it was assumed that the 5MW fire occurs on a 3% gradient slope in a road tunnel under the traffic congestion, and the smoke behavior as well as the safety analysis for the evacuation was examined by experiments and simulations using FDS. When there was no longitudinal airflow, more smoke spreaded toward upper side of the ignition point, therefore the evacuee there might not be able to escape 300m, the standard distance of emergency exits, before the smoke caught up with him. When 0.5m/s of the longitudinal airflow existed in the tunnel, the airflow made the smoke-spreading symmetric and the safe circumstance was kept on the both side of the ignition point. It became obvious from the result that the adequate longitudinal airflow worked effectively at early stage of fire so as to keep a safe circumstance. Further investigation will be necessary since the suitable longitudinal airflow may vary depending on the gradient and the fire scale.

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Sprinklers and Major Fire Spread in a Tunnel: A Theoretical Model

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ABSTRACT

This research follows work on water mist systems which was presented at the ISTSS conference in Montreal in 2016 and reported in references [1,2]. A model of the effect of sprinklers on major fire spread in a tunnel is considered via the construction of a theoretical model. It employs the concepts of non-linear dynamical systems theory and identifies the onset of instability with major fire spread in a tunnel. The purpose is to identify the thermo-physical and geometrical conditions which lead to instability and sudden fire spread. It uses as a starting point one of the non-linear models for major fire spread which have been developed by the author over many years and assumes that a sprinkler system operates.

The existence of a longitudinal forced ventilation is assumed and the model predicts the critical heat release rate needed for a fire to spread from an initial fire to an item with a given assumed shape; in the presence of a sprinkler system. The increase in the critical heat release rate which may be produced by the presence of the sprinkler is estimated. The target object may be taken to approximate a vehicle and there is assumed to be no flame impingement on the target object. The illustrative case approximating fire spread from an initial fire to a heavy goods vehicle (HGV) is presented; it is not restricted to this case, however. The model is being identified with the name FIRE-SPRINT C2, which is an acronym of Fire Spread in Tunnels, Model C, Version 2. It has been developed from an earlier model, FIRE-SPRINT C1 and considers a case where, in the absence of a fire fighting system, there is the potential for a major fire.

The results are compared with those found in [1,2] for the effect of water mist systems and a condition for the most suitable drop diameter is suggested for consideration and investigation.

KEYWORDS: tunnel, fire, sprinkler, mist, water, model, non-linear

INTRODUCTION

Fire protection measures aimed at preventing or mitigating the effects of major fire spread in a tunnel are a matter of primary concern internationally. One of the protective measures which may be adopted centres on water-based systems; water mist or sprinklers. In this research a non-linear model of major fire spread in a tunnel has been constructed and the effect of sprinklers estimated. It is intended to complement work on the effect of water mist which was presented at a conference in Montreal in 2016, ie ISTSS2016 [1] and also in a journal paper, [2].

Major fire spread in tunnels has already been modelled in a series of papers by this author; see chapters 10 and 16 of reference [3] for a summary. A tunnel similar in size to the Channel Tunnel has been assumed, with a longitudinal ventilation, and fire spread from an initial fire to a target object has been considered. The principles of non-linear dynamical systems theory have been used to identify a point of thermal instability and this has been identified with the point of spread to the target. Non-linear dynamical systems theory has been applied to many systems which exhibit ‘jump’ phenomena and, within the field of fire modelling, has been applied to the jump associated with flashover in a
compartment fire; see, for example, reference [4] as well as major fire spread in a tunnel. For more, see other papers referred to.

For tunnel fires, the critical heat release rate (HRR) for fire to spread from the initial fire to the target object has been calculated. In previous work three models, making different assumptions about the extent of flame and smoke, have been created which assume there is no flame impingement on the target object. The fire spread in these models would correspond to spontaneous ignition of the target. The three models have been identified with the acronyms FIRE-SPRINT A1, FIRE-SPRINT A2 and FIRE-SPRINT A3. The model which assumes the greatest extent of flame is FIRE-SPRINT A3 [5] and using this model the critical heat release rate for the case considered was found to be between 30 and 40 MW, with a ventilation velocity of 2m/s. The case considered was that of a tunnel similar to the Channel Tunnel and a separation of 6.45m.

Also, a model which assumes flame impingement on the target object does exist has been created [6] and this has been identified with the acronym FIRE-SPRINT B1. Flame impingement reduces the calculated critical rate of heat release considerably, by the order of 60-70%. A comparison between theory and experiment for these models has been carried out using results from the only large-scale experiment to date to measure major fire spread in a tunnel [7]; as known to the author. Far more large-scale experimental tests examining the conditions for major fire spread in tunnels need to be conducted, and these should be carried out by organizations which are independent of commercial interests.

For purposes of fire protection a fundamental question arises: if a sprinkler system were to be operating, what would be the calculated critical heat release rate (HRR) for fire spread? Specifically, for the case where there is no flame impingement on a target object, what would be the calculated critical HRR in the presence of a sprinkler system? The case considered is that of a fire which, without fire fighting of some kind, has the potential to become a major fire, with a HRR of the order of tens or even hundreds of megaWatts.

A MODEL OF MAJOR FIRE SPREAD WITH A SPRINKLER SYSTEM

The effect of a sprinkler system has been investigated using the the non-linear model FIRE-SPRINT C2, which is an acronym for Fire Spread in Tunnels, Model C, Version 2. That model has been derived from the model FIRE-SPRINT C1, which was described in references [1,2]. The model FIRE-SPRINT C1 itself had been derived from an earlier model, FIRE-SPRINT A3, see reference [5]. The model FIRE-SPRINT A3 is for a case without a fixed fire suppression system and predicts the critical rate of heat release for fire to spread from an initial fire to a neighbouring object, via spontaneous (ie ‘remote’) ignition. Flame impingement on the target is assumed not to take place. This object may be taken to represent a HGV. A longitudinal ventilation of 2m/s is assumed and the tunnel is about the size of the Channel Tunnel. The model has been described in detail in reference [5]; here a very brief description only is given.

BASIC STRUCTURES OF FIRE-SPRINT A3, FIRE-SPRINT C1 AND FIRE-SPRINT C2

The model FIRE-SPRINT A3 assumes that the tunnel has ‘sides’ and ‘ceiling’ which form a partial circle as indicated in Figures 1 and 2. The floor is shown by the upper surface of the lower shaded region. It is assumed that there is a burning object within the tunnel and that a longitudinal forced ventilation of air at ambient temperature pushes smoke to one side of the fire, partially or wholly surrounding a rectangular cuboidal target object. Flame is assumed to extend beyond the downstream edge of the fire and to go over the target object. The central flame section, between the initial fire and the target, is assumed to be deeper than the flame section which extends over the target object.
A control volume (CV), which hot gases enter and leave, is indicated by the dashed lines. Different emissivities have been assumed and calculated for different sections of the control volume. For further details see [5].

The model FIRE-SPRINT C1 was created from FIRE-SPRINT A3 and has been described in reference [1]. The model FIRE-SPRINT C2, which is intended to simulate the effect of sprinkler action, has been created from FIRE-SPRINT C1. Key assumptions which are common to both are
given below. These define the basic parameters $D_m1$, $N_{DNLS}$ and $N_{DSW}$. Changes have been made to the assumptions in FIRE-SPRINT C1 in order to better represent temperatures and thereby heat loss; the result is FIRE-SPRINT C2. Full details of the differences are given in reference [8].

The key common assumptions are:
1. A water-based fire suppression system is assumed to exist and to discharge water into the control volume (CV) and over the initial fire; at a discharge rate density denoted by the parameter $D_m1$ (mm/min).
2. Some of the water discharged is transported downstream by the forced ventilation, out of the CV. The fraction of water discharged into the CV which is transported downstream is identified with the parameter $N_{DSW}$ (DSW indicating ‘discharged, swept away’).
3. Some of the water discharged hits the lower surfaces and some does not. The fraction of water discharged into the CV which does not hit the lower surfaces is identified with the parameter $N_{DNLS}$ (DNLS indicating ‘discharged, not lower surfaces’).
4. Heat is extracted from the CV via the evaporation of water.
5. Heat is extracted from the target object because of water impingement.
6. The water discharged causes the flame temperature to be reduced.

Further details of the assumptions made are given in reference [8].

**ILLUSTRATIVE SIMULATIONS**

Simulations have been carried out for a case which approximates that of the rail tunnel under the English Channel. An initial fire has been assumed which might be taken to represent a burning heavy goods vehicle (HGV) or similar object. The target object has been taken to represent a second HGV behind the object on fire. The geometrical dimensions of the target object and the separation from the object of the initial fire have been chosen to approximate two HGVs; one HGV being in each of two adjacent carriers in a train [9]. The train is taken to be stationary and longitudinal forced ventilation is assumed to exist which tends to move the smoke produced by the initial fire towards the target object. The velocity, $v$, of forced ventilation has been taken to be 2m/s as a ‘base case’. This is approximately the value intended for the under-sea section of the Channel Tunnel in the case of a stationary burning HGV; in order to keep an amenity coach, in which the drivers would be travelling, free of smoke. For the sprinkler system, for this initial case, a discharge rate density of 10 mm/min has been assumed. This value has been taken as it seems to be a fairly typical value used for sprinkler systems. For example, in the Burnley tunnel in Australia the discharge rate density used seems to be between 8 and 9 mm/min, see reference [10]. Also, 10 mm/min is the value used in tests carried out by SP (now RISE) in Sweden, [11]. For the simulations carried out here, $N_{DNLS}$ has been assumed to have the value 0.13 and $N_{DSW}$ to have the value 0.059; see [8]. Full details of the other input values are as given in Appendix A. Solutions for the case of $v = 2m/s$ have been found and reported on in reference [8]. The profile of equilibrium states in the $T/M_{fun}$ plane and the eigenvalue trace have been found; see [8]. ($M_{fun}$ is the unenhanced fuel mass loss rate, see [5]).

The value of the heat release rate, $Q_f$, at which the onset of instability takes place is being called the critical heat release rate, $Q_{fc}$. In the simulations carried out, the base case assumed is that for which the length, $L_0$, of the CV is 14.2m. This value for $L_0$ has been estimated as that which might typically exist between the rear of one HGV and the rear of a second HGV behind it in the Channel Tunnel; assuming the length ($L_1$) of the main body of the second HGV to be 7.75m. It would be equivalent to a separation, $S$, between the downstream edge of the initial fire and the front of the target HGV of 6.45m; ie where $S = L_0 - L_1$. For the case where $v = 2m/s$ the critical value of the heat release rate, $Q_{fc}$, at which the loss of stability occurs is found to be about 51.5 MW; see [8]. This is the value at which spread to the target HGV would be expected, given the assumptions made. This may be
compared with a value for $Q_{fc}$ of 38.6 MW found using the model of reference [5], ie FIRE-SPRINT A3 without the sprinkler. That is, given the assumptions made for this initial case, the sprinkler system appears to have increased the critical rate of heat release by approximately 13 MW.

It is known, however, from simulations using FIRE-SPRINT A3 [5], that there is a sensitivity to the assumed length of the control volume, $L_0$. That is, if a shorter CV length is assumed, the calculated value for $Q_{fc}$ alters and, all else being the same, becomes smaller. In this case, if the assumed length of the CV is reduced, the sprinkler is calculated to increase the critical rate of heat release by about 6MW and not 13MW. This is because the value for $Q_{fc}$ becomes 38.0 using FIRE-SPRINT C2, compared with 32.2 using FIRE-SPRINT A3. (The results for the ‘reduced CV length’ are for $L_0=10.325m$ and $L_1=3.875m$; separation remains the same at 6.45m). See [8] for more on this.

Simulations have also been conducted with variation in forced ventilation velocity. In addition to $v = 2m/s$, considered above, forced ventilation has been considered at 3,4,5,6 m/s as well. The assumed discharge rate density is the same, ie 10mm/min. It is to be expected that the values of $N_{DNLS}$ and $N_{DSW}$ will vary with forced ventilation velocity. This means that it has been necessary to estimate the values of $N_{DNLS}$ and $N_{DSW}$ at these velocities. This is considered in Appendix B, where the following two equations have been derived:

$$N_{DNLS} = 1 - \exp(-0.07V)$$ \hspace{1cm} \{1\}

$$N_{DSW} = N_{DNLS} (1 - \exp(-0.3V))$$ \hspace{1cm} \{2\}

Where: $N_{DNLS}$, $N_{DSW}$ are as defined above; ie fractions between 0 and 1, inclusive.

$V$ = Velocity of the longitudinal forced ventilation velocity in m/s

The above equations are intended to provide approximate estimates of $N_{DNLS}$ and $N_{DSW}$ for the forced ventilation velocities considered here. Precise values would be expected to depend upon the specific features of any given system.

Using these equations, values assumed for the fractions are as given in Table 1. Employing the values of Table 1, results have been found for the critical HRR assuming different forced ventilation velocities and these are given in Table 2, comparing results using FIRE-SPRINT C2 with those using FIRE-SPRINT A3, ie without a sprinkler. As an example, the equilibrium profile and eigenvalue trace for the case where $v = 4m/s$ is given in Figure 3.

**Table 1**: Values assumed for the parameters $N_{DNLS}$ and $N_{DSW}$ for different forced ventilation velocities, using the equations derived in Appendix B.

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>$N_{DNLS}$</th>
<th>$N_{DSW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.13</td>
<td>0.059</td>
</tr>
<tr>
<td>3</td>
<td>0.19</td>
<td>0.11</td>
</tr>
<tr>
<td>4</td>
<td>0.24</td>
<td>0.17</td>
</tr>
<tr>
<td>5</td>
<td>0.3</td>
<td>0.23</td>
</tr>
<tr>
<td>6</td>
<td>0.34</td>
<td>0.28</td>
</tr>
</tbody>
</table>
The increase in critical HRR is given at each velocity. It is seen that for the cases of forced ventilation velocities of 5m/s and 6m/s that the system does not go unstable for FIRE-SPRINT C2, implying that the fire would not spread at any value of the HRR. However, it must be borne in mind that these simulations do not assume an increase in flame deflection with increase in velocity. If flame deflection does increase with velocity then instability and fire spread to the second vehicle would be possible.

Table 2 also shows that for velocities of 2 to 4m/s that the increase in critical HRR ranges from 12.0 to 15.0 with an average of 13.3 MW.
Table 2: Values calculated for the critical HRR for fire spread using FIRE-SPRINT C2 (ie with a sprinkler) and using FIRE-SPRINT A3 (ie without a sprinkler).

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Using FIRE-SPRINT A3 (MW)</th>
<th>Using FIRE-SPRINT C2 (MW)</th>
<th>Increase in critical HRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>38.6</td>
<td>51.5</td>
<td>12.9</td>
</tr>
<tr>
<td>3</td>
<td>71.8</td>
<td>83.8</td>
<td>12.0</td>
</tr>
<tr>
<td>4</td>
<td>104.5</td>
<td>119.5</td>
<td>15.0</td>
</tr>
<tr>
<td>5</td>
<td>139.0</td>
<td>Not go unstable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>176.0</td>
<td>Not go unstable</td>
<td></td>
</tr>
</tbody>
</table>

SENSITIVITY CONSIDERATIONS

As indicated in the text above, it is known that for the FIRE-SPRINT models the predicted critical HRR is sensitive to the assumed length of the control volume. Therefore, results have also been found assuming a ‘reduced CV length’ (see text above) and these are given in Table 3.

Table 3: Values calculated for the critical HRR for fire spread using FIRE-SPRINT C2 (ie with a sprinkler) and using FIRE-SPRINT A3 (ie without a sprinkler); assuming a ‘reduced CV length’ (see text for details).

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Using FIRE-SPRINT A3 (MW)</th>
<th>Using FIRE-SPRINT C2 (MW)</th>
<th>Increase in critical HRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>32.2</td>
<td>38.0</td>
<td>5.8</td>
</tr>
<tr>
<td>3</td>
<td>54.5</td>
<td>66.3</td>
<td>11.8</td>
</tr>
<tr>
<td>4</td>
<td>87.3</td>
<td>96.6</td>
<td>9.3</td>
</tr>
<tr>
<td>5</td>
<td>119.1</td>
<td>128.9</td>
<td>9.8</td>
</tr>
<tr>
<td>6</td>
<td>152.1</td>
<td>162.5</td>
<td>10.4</td>
</tr>
</tbody>
</table>

It may be seen from Table 3 that at values for velocity of 5m/s and 6m/s that the system does go unstable and fire spread is predicted. The increase in critical HRR ranges from 5.8 to 11.8MW with an average of 7.9MW.

CAVEAT: FLAME DEFLECTION AND THE CRITICAL HRR FOR FIRE SPREAD

In these simulations the degree of flame deflection has been assumed not to change as the velocity of forced ventilation is increased. In the real world it would be expected that the amount of flame deflection would increase with increase in ventilation velocity. The experimental work of references [11] & [12] indicates that a significant flame deflection would be expected and the probabilistic modelling, using Bayesian methods, of reference [13] indicates that the probability of flame
impingement on a target object would be expected to increase with increasing forced ventilation velocity.

Results using the model FIRE-SPRINT B1, see [6], which assumes flame impingement, show that the calculated values for $Q_{FC}$ in that case are much less than for spontaneous ignition. Also, flame deflection without actual impingement would be expected to reduce the $Q_{FC}$; all else the same. It is likely, therefore, that the values of $Q_{FC}$ reported in this paper will be higher than would actually be expected, as velocity is increased beyond 2m/s. The values should, therefore, be regarded as upper bounds on the actual values of $Q_{FC}$.

As these considerations would apply to the cases both with and without a sprinkler operating, ie to both FIRE-SPRINT A3 and FIRE-SPRINT C2, then the increases in $Q_{FC}$ found with a sprinkler (if increases in flame deflection with velocity were to be accounted for) may, perhaps, be regarded as very approximately the same as found here. That is it may be argued that the values found for the increases in $Q_{FC}$ may be regarded as, very broadly, indicative of what might be expected if the degree of flame deflection had been assumed to increase with velocity in the simulations. However, this argument is extempore and work on this would be needed to find the effect of increasing flame deflection with velocity.

**COMPARISON BETWEEN EFFECTS OF A SPRINKLER AND WATER MIST**

It may be seen that, in the range 2-6 m/s, the expected increase in critical HRR afforded by using a sprinkler at a typical discharge rate density for a sprinkler (10mm/min) is predicted to be about 6-15 MW. From reference [1] it may be seen that the expected increase in $Q_{FC}$ given by using a water mist system at a typical discharge rate density for such a system (4mm/min) has been predicted to be about 4-12 MW. {Also, in a separate study using FIRE-SPRINT C2 (see [8]) it was found that the increase in $Q_{FC}$, at $D_{m1}=10\text{mm/min}$, could range from 4-27 MW, using a sprinkler system. This may be compared with the range of 1-16 MW, found in [2], for a water mist system at $D_{m1}=4\text{mm/min}$.}

Although the models used are different (FIRE-SPRINT C2 for the sprinkler study and FIRE-SPRINT C1 for the water mist study) the differences in assumptions are such that the results for the cases considered here may be compared; see reference [8] for more details. As a very broad indication, therefore, it may be inferred from the work carried out here that a sprinkler system is likely to be more effective than a water mist system at increasing the critical HRR for fire spread, all else being the same and at a typical discharge rate density for each system.

**THE MOST SUITABLE DROP DIAMETER: A CONSIDERATION**

In related research, see reference [8], the results suggest a condition for the most suitable drop diameter range in order to increase the critical HRR as much as possible through the use of a water-based fixed fire fighting system. *It is essential that it be borne in mind* that this condition has emerged for the particular case considered only, ie a tunnel similar in size to the Channel Tunnel with a forced ventilation velocity of 2m/s and fire with a target object and spacing as described above in this current conference paper. The work of [8] suggests that in order to maximize the increase in $Q_{FC}$ then the parameter $N_{DNL_{LS}}$ should be as large as possible but also $N_{DSW}$ should be as low as possible. That is, it seems to be desirable for the drops to be large enough so as to not be swept away by ventilation and out of the CV; however, not so large as to hit the lower surface. Further, for the case considered, that criterion indicates that droplets should be no smaller than about 300$\mu$m (ie microns) in diameter; however, not much larger either. As a very approximate rule-of-thumb for the case considered, that might suggest droplets in the range 300-400$\mu$m. It is to be
stressed that this has been found for the particular case considered; to what extent it might apply to other cases would be a matter for consideration. The general condition, ie that stated above in relation to $N_{DNLS}$ and $N_{DSW}$, may or may not be of general application. It is stated here in a very provisional sense and put forward for consideration and investigation. There should certainly be large-scale experimental tests conducted in order to investigate this condition.

**LARGE-SCALE EXPERIMENTS ARE REQUIRED**

Experimental test results to enable comparison with the results given here are not available, to the knowledge of this author. Results from large-scale experiments for both sprinklers and water mist are certainly required, for tests which are such as to allow a fire to continue to grow and spread to a target object with the sprinkler or mist system still operating. The fire must be allowed to grow such that, after the sprinkler or mist has been activated, it would continue to a HRR sufficient to permit spread to a second object. Tests carried out so far have, to the knowledge of this author, not allowed this to happen; that is, the water-based system has been turned on too early to be able to investigate this. It may well happen that in an operational tunnel a fire would grow to a relatively large size before the sprinkler or mist system had been brought into action in such a way as to be genuinely effective against the fire. In such a case the fire may spread after the activation of the sprinkler or mist system.

A broad indication of the critical HRR for fire to spread to a second object in a tunnel, without a sprinkler or water mist system, has already been arrived at [7]. It should be possible, therefore, to construct tests which would be expected to produce fire spread to a second object, with a sprinkler or mist system operating.

Tests are also needed in order to estimate the number of water drops and volume which are ‘swept away’ and out of the CV; the parameter, $N_{DSW}$, could then be estimated. Also the number of drops and volume which do not reach lower surfaces need to be found, to enable estimates of $N_{DNLS}$ to be made. Only one estimate of the amount of water not to have hit the lower surface in an experimental test [14] has been reported in the literature; to the knowledge of this author. Finally, there need to be experiments to test the condition for most suitable drop diameter which has been suggested. Experimental tests should be carried out by organizations which are ‘independent’ and have no commercial interests, and by researchers who have no commercial or other interest in seeing a test result of a particular kind.

**CONCLUSION**

A model for the critical heat release rate required for fire to spread from one object to another, given a sprinkler system is operating has been described. It is for a tunnel similar in size to the Channel Tunnel between France and England and with a distance between the downstream edge of the fire and a target object of 6.45m. There is assumed to be no flame impingement on the target. It uses non-linear dynamical systems theory. Simulations have been carried out at values of forced ventilation velocity in the range 2-6m/s and with a sprinkler discharge rate density of 10mm/min (ie 10 litres/min/m$^2$). It has been assumed that the fire has the potential for the HRR to continue to rise significantly beyond the activation of a sprinkler system. The model created is being identified with the name FIRE-SPRINT C2 and is a development of an earlier model, FIRE-SPRINT C1, which was applied to water mist [1].

It has been found that the expected *increase* in $Q_{fc}$ due to the presence of a sprinkler system is very approximately in the range 6-15 MW. That is, the operation of the sprinkler system has increased the expected value of the critical HRR by about 6-15 MW, by comparison with a tunnel with no sprinkler operating. This may be compared with an approximate range of 4-12 MW using a water mist system, as found in the work of reference [1]. It should be noted that the discharge rate density for the range found in [1] was at a value more typical of a water mist system, ie 4 mm/min. It is important to
remember that these results are for the input parameters as given. There would be uncertainty in these parameters, especially in the values for NDNLS and NDSW.

In a separate study using FIRE-SPRINT C2, see [8], which considered different values for these parameters it was inferred that, in a real-world case, the increase in Qfc because of the operation of a sprinkler system could be as low as about 4MW or as high as about 27 MW; ie a range of approximately 4-27 MW. This compares with the corresponding range found in [1] for a water mist system of about 1-16 MW. In reality it would certainly be wise to assume a value closer to the lower end of a range rather than the upper end. It is always necessary to try to allow for the unanticipated and a cautious approach should certainly be followed. While considerable accuracy is not being claimed for these numerical results, it is expected that they would be very broadly indicative of the increase in the critical HRR for fire spread using a sprinkler system. Also, comparing with the calculated effects of water mist, it appears that a sprinkler system would, on the whole, be expected to be more effective than a water mist system in reducing the probability of fire spread to a second object. It must be remembered that this study has assumed a fire which is such that, in the absence of a fixed fire suppression system, it would be expected to spread to a second object, which may correspond to a HGV.

Experimentalists are strongly urged to test these results in full-scale tests; see the section above on experimental tests. Also, there is a great need for experimentalists to carry out tests in order to provide estimates for the parameters NDNLS and NDSW. All such tests should be carried out by organizations which do not have an interest, commercial or otherwise, in seeing a particular kind of result.

It is to be hoped that the theoretical results found in this work will provide a very broad indication of the critical HRR necessary for fire to spread to a second object in a tunnel fire in the presence of a sprinkler system. The results found for sprinklers may be compared with the results found for water mist in earlier work, [1]. Whichever system may be used, it is vital that it be employed as part of an integrated system of control and not regarded as some kind of ‘isolated add-on’, see eg [16].

APPENDIX A : INPUT DATA

FIRE-SPRINT C2 is derived from FIRE-SPRINT C1, which itself is derived from FIRE-SPRINT A3 and the values used for parameters which are common to all three models are as given in reference [5]; other than for flame temperature, T\text{f}, for which see below. Assumed values of parameters which were introduced as part of creating FIRE-SPRINT C1 are as given in reference [2] and assumed values of parameters which have been introduced (or altered from FIRE-SPRINT C1) as part of creating FIRE-SPRINT C2 are as given in [8] unless given below or otherwise stated in the text.

T\text{f} = 1100 (\text{oK}); assumed to be lower than the flame temperature without a sprinkler system (ie lower than 1300 oK as used in reference [5]).

NDNLS = 0.13; NDSW = 0.059; Dm1 = 10.0 mm/min

APPENDIX B: EQUATIONS FOR N_{DNLS} AND N_{DSW}

Estimates need to be arrived at for the values of N_{DNLS} and N_{DSW} for different forced ventilation velocities. While these values would be expected to depend upon different factors, it is assumed here that there would be a strong dependency on the velocity of forced ventilation, V. First an equation for N_{DNLS} will be derived and then an equation for N_{DSW}, at a given N_{DNLS}. To derive an approximate equation for the dependency on V of N_{DNLS}, ie the fraction of water discharged into the CV which does not hit lower surfaces, the following assumptions have been made:

\{1\} N_{DNLS} is a number between 0 and 1.0, inclusive.
For $V = 2\text{m/s}$ then $N_{DNLS} = 0.13$. This has been estimated in [8] using available information as given there.

As $V$ tends to infinity then $N_{DNLS}$ tends to 1.0

A suitable form for an equation is: $N_{DNLS} = 1 - \exp(-b \ V)$; $b$ = a constant

The assumptions above may be combined to give:

\[ N_{DNLS} = 1 - \exp(-0.07 \ V) \quad \{B1\} \]

This equation has the property that at $V = 0$ then $N_{DNLS} = 0$. This would not be expected to be very realistic for a sprinkler system, although it would be expected to be more realistic than for a water mist system. However, the equation should not be regarded as valid for velocities significantly less than 2m/s. As the intention is to apply it for velocities above 2m/s then this is regarded as acceptable.

To derive an approximate equation for $N_{DSW}$, i.e., the fraction of water discharged into the CV which is transported downstream, the following assumptions have been made:

At $V = 2\text{m/s}$ then $N_{DNLS} = 0.13$ and $N_{DSW} = 0.059$. This has been estimated in reference [8] using available information as given there. In that paper, to estimate an initial value for $N_{DSW}$ the results of experimental tests were used. As $V$ tends to infinity then $N_{DSW}$ tends to $N_{DNLS}$.

A suitable form for an equation is: $N_{DSW} = N_{DNLS} (1 - \exp(-a \ V))$; $a$ = a constant

The assumptions above may be combined to give:

\[ N_{DSW} = N_{DNLS} (1 - \exp(-0.3 \ V)) \quad \{B2\} \]

As with equation \{B1\} above, this equation should not be regarded as valid for ventilation velocities significantly below 2m/s. It is assumed that they provide plausible values, however, for 2m/s and above.

REFERENCES


Functions of Water Spray Systems in Japanese Expressway Tunnels

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ABSTRACT

Water spray systems (WSS) in Japanese road tunnels were uniquely developed and are now called fixed firefighting systems (FFFS) around the world. This paper describes the background of the development of FFFS as well as the current specifications. It also summarizes the issues faced in Japan and future actions to be taken based on the situation in Europe where research, development and introduction of FFFS have progressed since 1999 when a tragic tunnel fire occurred.

KEYWORDS: fixed firefighting system, water spray system, sprinkler, water mist system, deluge system, longitudinal ventilation

INTRODUCTION

The Meishin Expressway between Ritto and Amagasaki cities was opened in 1963 with the aim of boosting the industrial economy. Thereafter, the construction of arterial roads including the Tomei Expressway was promoted. However, since approximately 70% of Japan is mountainous, national expressways connecting cities require many tunnels. Accordingly, after the Holland Tunnel fire in the United States in 1949, discussions on countermeasures for vehicle fires in road tunnels were started in late 1950s. It was pointed out that, since it was planned to use longitudinal ventilation for these tunnels, it was necessary to prevent fires from spreading and to prevent damages under longitudinal airflow. Experimental studies were then started [1].

BACKGROUND OF THE WSS DEVELOPMENT

As part of the studies, a meeting was held with scholars and experts in 1959, who discussed the safety in the event of a fire in a tunnel using the longitudinal ventilation strategy (which was planned to be used when constructing medium-scale tunnels). The meeting also focused on preventing the spread of fire due to longitudinal airflow; safe evacuation of maintenance staff, passengers and vehicles ahead of and behind a burning vehicle; firefighting assistance; and heat protection for the ventilation system and equipment within a tunnel. New tunnel fire protection facilities using water curtains created by sprinklers or drenchers were proposed [2]. Furthermore, a semi-transverse ventilation system (fresh air distribution type) with a ceiling panel was adopted in the Meishin Expressway since there were no jet fans in Japan at the time of planning. For reference, Japan installed its first jet fans (inner diameter 630 mm, manufactured by Voith in Germany) in the Okuda tunnel on the Kitakyushu Expressway in 1966 [3].

The following subjects must be considered when developing new tunnel fire protection facilities:
- Burning characteristics of vehicle fires
- Method for protecting facilities within tunnels
- Spreading of fire heat to leeward and temperature distribution under longitudinal airflow of approximately 4–8 m/s
- Air velocity and spray pattern of droplets when sprinklers are installed in the tunnel ceiling
- Evaporation rate of droplets in high-temperature airflow, and cooling effect by heat exchange
- Chemical characteristics of gas generated during combustion, and smoke condition
- Cost-effectiveness of each type of extinguisher or firefighting equipment

In tests on these subjects, an ordinary truck was selected as a typical fire source in road tunnels, and the target fire load was proposed to be approximately 9 m² (Class B fire) since the capacity of the truck was 100 to 150 liters of gasoline. For the spray head, the deluge type head was proposed instead of a fusible link or glass bulb used in general sprinklers. The deluge type head applies water simultaneously to the spraying areas (each spraying area is activated immediately after the corresponding fire detection system detects a fire). Regarding fire detection systems, there was concern that the heat detection method could not detect the fire location accurately since the wind direction could be reversed under longitudinal airflow, so the flame sensing method which detects flames directly was also considered [4].

TEST PLANNING AND EVALUATION

Model Tunnel Tests

In 1960 when the tests on WSS were started, there were few relevant precedents or literature in the world. Therefore, when developing the specifications for WSS, tunnel fire tests and evaluations were conducted using a fire pan in a model tunnel (scaling ratio 1:5) to observe the changes in temperature after discharging water, the changes in airflow velocity within the tunnel, and the fire detection capability of the detection system. In these tests, methanol and gasoline were used as fuels. Figures 1 and 2 as well as Table 1 show the model tunnel used and the general outline of the tests [5].

![Figure 1. Longitudinal view of 1/5 model tunnel](image)

![Figure 2. Layout of water spray heads](image)

**Table 1. Specifications of model tunnel and major instruments**

<table>
<thead>
<tr>
<th>Item</th>
<th>Specifications</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Scale: 1:5</td>
<td>Model tunnel: Reinforced concrete</td>
</tr>
<tr>
<td></td>
<td>Diameter: 1.96 m, Internal height: 1.24 m</td>
<td>Wind tunnel: Steel plate</td>
</tr>
<tr>
<td>Axial fan</td>
<td>Engine-driven axial fan: Diameter 0.8 m</td>
<td>2500 rpm =&gt; Ur 8.0 m/s</td>
</tr>
<tr>
<td>Spray nozzle</td>
<td>4 rows, a pattern, b pattern</td>
<td>Three types of spray head</td>
</tr>
<tr>
<td></td>
<td>4 rows × 13 sections = 52 heads</td>
<td>Droplet size: about 0.3–1.5 mm</td>
</tr>
<tr>
<td></td>
<td>Flow rate: 18 liters/min/head</td>
<td>Water is sprayed by pattern a or b</td>
</tr>
<tr>
<td>Fire source</td>
<td>Steel fire pan: 0.25×0.25 m, 0.5×0.5 m, 1.0×1.0 m</td>
<td>Fuel: Gasoline, alcohol</td>
</tr>
<tr>
<td></td>
<td>H = 0.06 m</td>
<td></td>
</tr>
<tr>
<td>Longitudinal wind speed</td>
<td>3.0 m/s, 5.0 m/s, 8.0 m/s</td>
<td></td>
</tr>
<tr>
<td>Wind measurement point</td>
<td>From tunnel entrance: 2.0 m, 10.2 m, 19.0 m</td>
<td>Fan rotation speed and air velocity</td>
</tr>
<tr>
<td>Thermocouple trees</td>
<td>Height from floor: +0.1 m, 0.2 m, 0.4 m, 0.7 m, 1.0 m</td>
<td>From fire pan: 2.0 m, 5.0 m, 9.0 m, 14.0 m</td>
</tr>
<tr>
<td>Fuel level reduction rate</td>
<td>Measured with external manometer</td>
<td></td>
</tr>
<tr>
<td>Sucking combustion gas</td>
<td>Gas type: Carbon monoxide, Nitrogen dioxide</td>
<td>From fire pan: 5.5 m, Height: 0.6 m</td>
</tr>
</tbody>
</table>
These model tests revealed the following:

- The temperature decreases with increasing number of spray heads.
- Spraying water directly at the fire source is expected to reduce temperature more effectively. (It is necessary to accurately detect the fire location.)
- For fire detection, the air velocity within the tunnel should not change.
- A manual water spraying system should be provided.
- The direction of wind within the tunnel needs to be the same as the driving direction.
- When the air velocity exceeds approximately 8 m/s, heat effects and toxic gas are mitigated, which is beneficial for the initial firefighting.
- However, relying exclusively on fire protection facilities is not recommended.

These results showed that there is a correlation between the gradient of heat air flow trajectory generated by the fire source and longitudinal air velocity. An empirical formula for calculating temperature distribution was also derived. The temperature distribution corresponding to a pan fire of 9 m² of gasoline in a full-scale tunnel is estimated as shown in Figure 3.

Full-scale Tunnel Tests [5]
Full-scale tunnel tests were conducted based on the above results of the model tunnel tests. However, in the tests, alcohol was used instead of the initially-planned pan fire of gasoline since this tunnel was about to open as the first expressway in Japan. Alcohol has a low rate of heat release and emits little smoke and soot. In these tests, since alcohol was used instead of gasoline, the temperature rise in the tunnel and the temperature drop due to water spray were evaluated in terms of gasoline combustion.

Test Yard
- Location: Tennozan Tunnel on Meishin Expressway
- Ignition point: approximately 150 m from the portal on the east side
- Fire source: a pan of approximately 9.0 m² of alcohol
- Spray heads: water flow rate of 115 liters/min, discharging length of 36 m, heads installed on both sides at intervals of 4 m (total of 18 heads)
- Locations of temperature measurement: 0.5, 1.8, 3.1 and 4.4 m above the road surface
- Locations of air temperature measurement trees: 2, 4, 6, 8, 10 and 12 m downstream from the pan
- Locations of air velocity measurement: 0.5, 1.8, 3.1 and 4.4 m above the road surface
- Approximately 15 m upstream from the fire pan

Figure 4 shows the cross-section of the Tennozan tunnel.

Results
In model tunnel tests using a pan of 1 m² of gasoline, tests were conducted using 4, 8 and 16 nozzles of 18 liters/min. The results showed that 16 spray heads was too many. Although 4 spray heads had a slightly lower cooling effect than 8 spray heads, there was little difference. The reason is thought to be that 4 spray heads cover a broader area with water and the heat-exchange efficiency is higher than
with 8 spray heads. Additionally, it was observed that spraying water directly at the fire source reduced the temperature more quickly.

In the full-scale tunnel tests, water was sprayed from 2 spray heads (115 liters/min) at the fire source of about 9 m² of alcohol in order to observe the reduction in temperature. This fire size is assumed to be about 1.34 m² when converted to gasoline. Since the result was similar to that of the model tunnel test, the water flow rate required to suppress a fire was calculated by converting the water flow rate used in the full-scale tunnel test to the gasoline fire of 1 m²:

- Water flow rate required to suppress a fire = 115 [liters/min] × 2 [spray heads] / 1.34 [m²] ≅ 170 [liters/min/m²]

When the target fire size is a gasoline fire of 9 m², the total amount of water flow is as follows:
- Total amount of water flow = 170 [liters/min/m²] × 9 [m²] × 1.3 (excess ratio) ≅ 2,000 [liters/min]

When this water flow rate is applied to a specific area (approximately 45 m in length and 7.2 m in width within the tunnel), the water spraying density is calculated as follows:
- Water spraying density = 2,000 [liters/min] / (45 [m] × 7.2 [m]) ≅ 6 [mm/min]

In this case, since the water pressure is between 0.29 and 0.39 MPa, 6 liters/min is considered to be enough for 1 m² of road surface although the water flow rate depends on the expected fire size.

In order to spray water effectively, it is desirable to spray water over a range from directly above the fire source to several meters windward simultaneously. However, to do this, the fire detector must be able to detect the fire location accurately and the water spraying sections must be selected automatically. If the air velocity is not constant, it is sufficient to spray water over 20–30 m on both sides of the fire source (including the fire source), leaving a wide margin.

In order to quickly spray water after fire detection, automatic water spray valves are always filled with water and pressurized, and the pump must be able to be activated at any time. Therefore, enough water for WSS needs to be stored to operate for at least 30 minutes (40 minutes at present).

In this way, the specifications of the road tunnel WSS for suppressing the fire source by covering the surrounding area with a large amount of spray water were determined by the model tunnel experiment and the real tunnel experiment and were then confirmed through actual verification experiments [6]. (Note that the data were obtained from tests conducted over 50 years ago.)
sidewall on both sides at intervals of 12 m [7].
To improve ease of maintenance, in the Enasan Tunnel opened in 1975 (transverse ventilation system with ceiling panels), spray heads were attached only to one sidewall (the second generation) [8]. The Kanetsu Tunnel, which opened in 1985, is a long tunnel with bidirectional traffic and has no ceiling panels for the longitudinal ventilation system. Therefore, spray heads were attached to one side. In the tunnel, tests using a fire pan of gasoline (Class B fire) and bus fire tests (Class A fire) were conducted before the tunnel was opened (the third generation) [9]. Subsequently, the New Tomei Expressway opened to traffic in 2012 in order to mitigate the chronic congestion caused by heavy traffic on the original Tomei Expressway. This tunnel has a large cross-section for the three lanes with a road shoulder. In the tunnel, spray heads with a long-distance sprinkle type nozzle were adopted since they were attached only to one side (the fourth generation) [10]. The cross-sectional area of the tunnel is twice as large as a conventional mountain tunnel. In 2002, fire tests were performed for a fire pan of 9 m$^2$ of gasoline, a large bus fire, and fire spreading between passenger cars to verify the effectiveness and smoke extraction characteristics of WSS [11].

**Transition of WSS**
Table 2 shows the historical transition from the initial spray pattern at the time when the first WSS was installed in a real tunnel to the current spray pattern.

<table>
<thead>
<tr>
<th>Spray pattern</th>
<th>Layout</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Generation</td>
<td></td>
<td>Normal two-lane tunnel with ceiling panels</td>
</tr>
<tr>
<td>Since 1968</td>
<td></td>
<td>Transverse ventilation</td>
</tr>
<tr>
<td>Spray from both sides</td>
<td></td>
<td>Semi-transverse ventilation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spray length: 36 m × 2 sections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Head installation interval: 4 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water density: 6 mm/min</td>
</tr>
<tr>
<td>2nd Generation</td>
<td></td>
<td>Normal two-lane tunnel with ceiling panels</td>
</tr>
<tr>
<td>Since 1975</td>
<td></td>
<td>Transverse ventilation</td>
</tr>
<tr>
<td>Spray from one side</td>
<td></td>
<td>Semi-transverse ventilation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spray length: 50 m × 2 sections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Head installation interval: 5 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water density: 6 mm/min</td>
</tr>
<tr>
<td>3rd Generation</td>
<td></td>
<td>Normal two-lane tunnel</td>
</tr>
<tr>
<td>Since 1985</td>
<td></td>
<td>Longitudinal ventilation</td>
</tr>
<tr>
<td>Spray from one side</td>
<td></td>
<td>Spray length: 50 m × 2 sections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Head installation interval: 5 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water density: 6 mm/min</td>
</tr>
<tr>
<td>4th Generation</td>
<td></td>
<td>Large section area tunnel</td>
</tr>
<tr>
<td>Since 2012</td>
<td></td>
<td>Three lanes with shoulder</td>
</tr>
<tr>
<td>Spray from one side</td>
<td></td>
<td>Longitudinal ventilation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spray length: 50 m × 2 sections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Head installation interval: 5 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water density: 6 mm/min</td>
</tr>
</tbody>
</table>

**Current WSS**
As shown in Table 2, the third generation of WSS is currently used in general tunnels with two lanes, and the fourth generation is used in the New Tomei Expressway and future urban expressways. Figure 5 shows the layout of the third generation of WSS.
For the WSS installed in expressway tunnels, water is always refilled from water pipes located in the
passageway for tunnel inspectors, to automatic valve devices located every 50 m. In the event of a fire, water is sprayed from header pipes located at the upper part of the sidewall. The water flow rate is 6 mm/min, the water pressure of the spray head is 0.34 MPa, the water flow rate per combination spray head is 250 liters/min, and the installation interval is 5 m. The water flow rate per spraying area is 2,500 liters/min since 10 spray heads are attached to one spraying area.

For reference, Table 3 shows the prices for the main components of the WSS. Note that the prices may vary depending on the contract conditions or quantity ordered.

### Table 3. Estimated prices of WSS related equipment in Japan (€1 ≈ ¥130)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Estimated unit price (€/unit)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic valve</td>
<td>12,200</td>
<td>50 m spacing</td>
</tr>
<tr>
<td>Spray head</td>
<td>250</td>
<td>5 m spacing</td>
</tr>
<tr>
<td>Water supply piping</td>
<td>11,000</td>
<td>50 m spacing</td>
</tr>
<tr>
<td>Flame detector</td>
<td>2,200</td>
<td>25 m spacing</td>
</tr>
</tbody>
</table>

![Figure 5. Layout of current expressway tunnel WSS (3rd generation)](image)

**Installation Standard for Emergency Facilities in Road Tunnels in Japan**

All road tunnels in Japan are categorized into five grades (AA, A, B, C and D) by tunnel length and AADT as shown in Figure 6. Appropriate fire emergency facilities according to tunnel grade have been installed as shown in Table 4. In principle, WSS is installed in AA grade tunnels.

### Table 4. Emergency facilities for each category of Japanese road tunnels

<table>
<thead>
<tr>
<th>Emergency facilities</th>
<th>Tunnel grade</th>
<th>AA</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication and alarm equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency telephones</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Emergency pushbuttons</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Fire detectors</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variable message signboards</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Fire extinguishing equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire extinguishers</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Fire hydrants</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency exit signs</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventilation for smoke control or escape doors</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evacuation signs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire taps</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wireless communication facility</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio rebroadcasting system or public address system</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water spray system</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCTV</td>
<td>●</td>
<td>●</td>
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</tbody>
</table>

● Mandatory for all tunnels, ○ Requirements to be determined
Figure 6. Determination of Japanese tunnel category

Statistical Data of Tunnel Fire Accidents

The worst tunnel fire accident in the history of Japan’s expressway occurred in the Nihonzaka Tunnel on the Tomei Expressway in 1979 as shown in Table 6. The fire was caused by a rear-end collision at the tail of traffic congestion near the tunnel exit. Seven people died and 173 vehicles were burned out, and it took two months to re-open the tunnel. After this accident, the Installation Standard for Emergency Facilities in Road Tunnels was revised in 1981, corresponding to the construction of long tunnels, and the standard was revised in 2001 in response to changing needs. Fortunately, there have been no large-scale fire incidents in Japan since the Nihonzaka Tunnel fire.

As of April 2016, the total length of all national expressways was 9,265 km and the total length of 1,021 tunnels exceeded 1,036 km (this value is not the total length of all tubes; in Japan, both inbound and outbound lanes are counted as one tunnel) [12].

Table 7 shows the number of fire accidents in expressway tunnels for the 23 years between 1989 and 2012 although the data is somewhat old. During this period, 4 to 21 fire accidents occurred every year, and 283 in total, giving 12.3 accidents a year on average. Thus, there is roughly one tunnel fire accident every month on all the expressways in Japan [13].

Table 6. Fires in Japanese expressway tunnels

<table>
<thead>
<tr>
<th>Tunnel grade</th>
<th>Number of tubes</th>
<th>Total length [km]</th>
<th>Number of fire accidents 1989–2012</th>
<th>Usage of WSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>84</td>
<td>323</td>
<td>132</td>
<td>75</td>
</tr>
<tr>
<td>A</td>
<td>480</td>
<td>700</td>
<td>102</td>
<td></td>
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<tr>
<td>B</td>
<td>728</td>
<td>495</td>
<td>34</td>
<td></td>
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<tr>
<td>C</td>
<td>232</td>
<td>81</td>
<td>15</td>
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<tr>
<td>D</td>
<td>183</td>
<td>36</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1,707</td>
<td>1,635</td>
<td>283</td>
<td>75</td>
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</table>

Table 5 shows the number of fire accidents for each tunnel grade. AA grade tunnels account for the largest number of fire accidents even though the number of tunnels is fewest. There has been no fire accident in D grade tunnels. Of the total number of tunnel fire accidents, 132 were in AA grade tunnels, and WSS was used 75 times (55 times for vehicle malfunction fires, 20 times for accident fires). WSS was used in about 60% of AA grade fires: water spraying started on average 5.4 minutes.
after the fire occurred, the average spray time was 24.7 minutes, and the average time taken for the fire brigade to arrive was 24.8 minutes.

For reference, the operation of WSS in expressway tunnels was shifted to the count-down method in 2003 [14].

TREND OF WSS AND FFFS

History of Major Experiments, Fire Accidents and Standards

Table 6. Chronology of WSS in Japan and relevant events overseas

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
<th>Accident</th>
<th>Guideline Regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1949</td>
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<tr>
<td>1954</td>
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<tr>
<td>1959-1963</td>
<td>Development of WSS Experiment Model &amp; Full-scale Tunnel</td>
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<tr>
<td>1964</td>
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<td>2017</td>
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</tbody>
</table>
Table 6 summarizes the tests for WSS conducted in Japan, the accidents that influenced the Japanese specifications for WSS, and the technical standard established based on these data in chronological order. The first tunnel in the world equipped with FFFS was the "Battery Street Tunnel in Seattle" in 1954. In Japan, experimental research on WSS began in 1959 as shown in Table 6. Subsequently, a large tunnel fire accident occurred in the Suzuka Tunnel (245.6 m) on National Route 1 in Japan in 1967, in which 13 trucks were burnt out. Based on the lessons learned from this accident, the Technical Standard for Road Tunnels was established, providing the basic standard for fire disaster prevention facilities in road tunnels. The first WSS to be installed in an actual tunnel in Japan was in 1968; since that time, WSS have evolved in line with improvements in maintenance efficiency and technological progress.

Paradigm shift of FFFS

In 1965 in Europe, a tunnel fire test was carried out using a large fire pan of flammable liquid (95 m³, 1,000 liters of gasoline) in the Ofenegg Tunnel in Switzerland. However, the fire pan burned for a long time until the sprinklers were activated. As a result, a large amount of steam was generated and visibility was reduced. It was also observed that the smoke layer was destratified after spraying water. In addition, after the fire was extinguished, the flammable gas that had been generated reignited and exploded. The testing facility was destroyed and 3 people were injured. The results of the Ofenegg test were reported to several authorities including PIARC, and it is considered that incorrect opinions on FFFS were spread worldwide via these authorities [15]. PIARC raised several concerns about FFFS instead of recommending it at congresses held in Sydney in 1983, Brussels in 1987 and Montreal in 1992. However, after the Mont Blanc Tunnel fire accident in 1999, FFFS was recognized as an effective means of protecting the tunnel structure, even though concerns remained about the safety of life. Subsequently, the European Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network was published in 2004 and several studies and verification tests were performed in a cross-sectional manner by research institutions and manufacturers in European countries to improve tunnel safety. The development of two types of FFFS has progressed: FFFS using water mist and FFFS using larger droplets which are expected to have a certain effect even under a longitudinal airflow. In the context of these circumstances, PIARC published “Road Tunnels: Assessment of Fixed Firefighting Systems” in 2008 [16], and “Fixed Firefighting Systems in Road Tunnels: Current Practices and Recommendations” for road tunnel managers and designers in 2016 [17]. These documents describe PIARC’s previous approaches to FFFS, factors for deciding whether FFFS should be installed or not, considerations during the design phase, risk assessment, system definition and procurement, the need for continuous research and studies, and issues on CFD modeling, as well as current operational methods, maintenance, international standards and the status of adoption in each country.

Penetration of FFFS and Remaining Issues

Table 7 shows the tunnels where FFFS has been installed or is currently being installed worldwide, excluding Japan [17], [18], [19], to the extent known. The water mist system (WMS) is mainly used in Europe, while the deluge system is mainly used in the United States, Australia and Asia. In some cases, a compressed air foam (CAF) system is used. Tunnel fire suppression systems used to be called sprinklers in PIARC and NFPA publications, but the term “fixed firefighting system (FFFS)” is now used all over the world. Regarding international commissioning methods and full-scale tests, currently, it is proposed that tunnel length, measurement items and instrumentation layout should be standardized to facilitate the comparison of test results. In addition, risk evaluations are performed with and without FFFS and it is believed that the safety performance of tunnels is gradually being clarified [20]. Meanwhile, it is normal practice in Japan to plan according to the installation standard for tunnel emergency facilities. For this reason, it is generally difficult to apply new technologies to such facilities. However, in the case of tunnels with special conditions, countermeasures will be examined by a committee of technical experts. Although it is not clear whether this is the cause or not, tunnel WSS related papers submitted by Japan at international conferences have not been confirmed since 2004 [21]. However, issues regarding the operation and maintenance of FFFS remain. Accordingly, it is time to start exchanging information in order to improve tunnel safety by reviewing Japan’s
PIARC proposes the following activities and studies in order to get a better understanding of and improve the performance of FFFS [17]:

- Human behavior and responses in a fire environment
- Alternative suppression and activation techniques
- Collection of test data in order to determine ceiling temperatures in fire tests and modelling studies
- The development of standard test procedures and protocols specific to road tunnels
- The development of a standard methodology for capturing data on fire events and the use of FFFS so that improvements can be integrated into the system design
- The development of protocols for commissioning FFFS
- The development of on-board suppression systems for vehicles

The following technical issues regarding the effectiveness of both WMS using smaller droplets and the deluge system using larger droplets have been raised, although the information is somewhat old [22]:

- Can WMS effectively suppress fires involving various types of vehicles and cargo loads?
- Can WMS effectively suppress fires under higher airflow velocities?
- What are the optimum ventilation conditions for effective suppression?
- Does gradient/buoyancy influence WMS effectiveness?
- Under what circumstances will fire spread between vehicles during WMS application?
- Under what conditions (if any) are WMS demonstrably better at suppressing fires in tunnels than conventional sprinkler/deluge systems? (and vice-versa)

Table 7. Tunnels where FFFS is installed recently

<table>
<thead>
<tr>
<th>Country</th>
<th>Name of tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>Mona Lisa Tunnel, Felbertauern Tunnel, Arlberg Tunnel (under reconstruction)</td>
</tr>
<tr>
<td>France</td>
<td>A86 Tunnel</td>
</tr>
<tr>
<td>Italy</td>
<td>Brennero Tunnel, Virgolo Tunnel</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>Roermond Tunnel, Swalmen Tunnel</td>
</tr>
<tr>
<td>Norway</td>
<td>Vålereng Tunnel, Fløyfjell Tunnel</td>
</tr>
<tr>
<td>Spain</td>
<td>M30 Calle Tunnels, Vielha Tunnel, De Vielha-Juan Carlos Tunnel</td>
</tr>
<tr>
<td>Sweden</td>
<td>Tegelbacken Tunnel, Klara Tunnel</td>
</tr>
<tr>
<td>Denmark</td>
<td>Oresund Tunnel</td>
</tr>
<tr>
<td>Finland</td>
<td>Helsinki City Service Tunnel</td>
</tr>
<tr>
<td>Germany</td>
<td>Pörzberg Tunnel, Jagdberg Tunnel</td>
</tr>
<tr>
<td>UK</td>
<td>New Tyne Tunnel, Dartford Tunnel</td>
</tr>
<tr>
<td>USA</td>
<td>CANA Northbound Tunnel, Southbound Tunnel, Battery Street Tunnel, Mercer Island Tunnel, Mt. Baker Ridge Tunnel, I-5 Tunnel</td>
</tr>
<tr>
<td>Canada</td>
<td>George Massey Tunnel (Vancouver, British Columbia)</td>
</tr>
<tr>
<td>Australia</td>
<td>Adelaide Hills Tunnel, North/South Busway Tunnel, M7 Clem Jones Tunnel, Airport link, Kemp Place Tunnel, Inner City Bypass A &amp; B, Inner Northern Busway, City Link Tunnel, Mitcham/Frankston Tunnel, N/A: North/South Tunnel, Graham Farmer Tunnel, Sydney Harbour Tunnel, M5 East Tunnel, Lane Cove Tunnel, Eastern Distributor, M4 Tunnel, Cross City Tunnel</td>
</tr>
<tr>
<td>China</td>
<td>Baiyun Road, Xiang Huang Road</td>
</tr>
<tr>
<td>Korea</td>
<td>Inje Tunnel, Juck Ryung Tunnel</td>
</tr>
<tr>
<td>Singapore</td>
<td>Woodsville Tunnel, Marina Coastal Expressway</td>
</tr>
<tr>
<td>Taiwan</td>
<td>Under construction: Dongao Tunnel, Guanyin Tunnel, Gufeng Tunnel, Chung-jen Tunnel</td>
</tr>
</tbody>
</table>

CONCLUSIONS

This paper summarized the background of the development of WSS, the current situation and issues in Japan, and the international situation. Due to limitations of space, the comparison between Japanese FFFS and international FFFS was brief. In Japan, WSS is not designed in principle to be used at the peak of a fire, but as a means to cover the area around the fire source with a water curtain during the fire development phase in order to suppress or attenuate expansion of the fire until the fire brigade
starts firefighting. In any fire, the fire size is 0 MW in the initial phase and reaches the peak after a certain period of time. Therefore, how quick WSS can detect the location of a fire to suppress it, and how quickly preparations for evacuation and firefighting can be made, are the keys. Future topics to be addressed include the following:

- Verification of each type of fire scenario and its effectiveness (Class A and B fires)
- Using CFD, studies on evaluation methods for WSS
- (Limit) performance verification of the current specifications for WSS
- Further improvement in the fast fire detection method and system reliability
- Re-verification and technical improvement of the water spraying density
- Risk assessments and method of selecting alternative means, etc.

Japan has constantly conducted studies on safety measures against fires in road tunnels. However, it is also a fact that we have not reported any information about WSS since 2004. Since the bias against WSS, which spread worldwide for a long time, has now disappeared, this paper gathered together information about the early period of WSS. We would like to express our highest respect for the wisdom and decisions of our predecessors in an era when there was not enough technical information. We strongly believe that further discussions are needed in order to improve the safety of road tunnels.

REFERENCES

Committee C.3.3 Road Tunnel Operations, ISBN 2.84060-208-3.
Large scale fire tests with different types of fixed fire fighting systems in the Runehamar tunnel

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ABSTRACT

The paper presents the main results of the six large-scale tests with different types of fixed firefighting systems (FFFS) that were carried out in the Runehamar tunnel in June 2016. It describes the background to the tests and the performance of the different systems, and draws conclusions regarding the efficiency of the systems. The fire load consisted of 420 standardised wooden pallets and a target of 21 wooden pallets. Five of the tests were carried out with a 30 m long deluge zone delivering varying water densities using three different types of side-wall nozzles and an interval distance of 5 m. One test with 93°C glass-bulb nozzles (sprinkler head) in the same zone was also conducted. In the five deluge tests, the detection system was simulated using thermocouples in the tunnel ceiling. The alarm was registered when the ceiling gas temperature reached 141°C, and the system was activated manually after a delay of 4 minutes. The protection goal of the system was to prevent fire spread to a target positioned 5 m from the rear of the main fuel area, and to ensure that the fire did not exceed 30 MW in size. The system setups tested were found to meet these goals.

KEYWORDS: Wood pallets, Fixed Firefighting System (FFFS), heat release rate, water density, time delay.

INTRODUCTION

In 2013, SP Fire Research performed six large-scale tests in the Runehamar tunnel on behalf of the Swedish Transport Administration (STA) [1]. These large-scale tests are referred to hereafter as ‘the 2013 tests’. The purpose was to test a new concept, using large-droplet, side-wall nozzles for the Stockholm bypass tunnel. The test series used a water density of 10 mm/min, with 1.1 bar nozzle pressure. This new nozzle type was originally given the working title ‘T-REX’, but is now manufactured under the name ‘TN-25’ (Tunnel Nozzle with orifice K-25) by TYCO (Tyco Fire Protection Products). The T-Rex nozzle concept was originally developed by Brandskyddslaget AB, but was subsequently altered and produced by TYCO.

Prior to the 2013 tests, the STA decided to test a new safety concept using sprinkler technology, with large-droplet, side-wall nozzles mounted at the centre line of the tunnel ceiling. It was felt to be very important that adequate fire protection will be in place, as the Stockholm bypass will be a critical part of the transportation infrastructure of the region. The forecasted traffic density indicated that there was a risk of congestion in the tunnels, and it was therefore decided to use a fixed firefighting system. Tests using the TN-25 nozzle and 10 mm/min water density showed that the system performed very well, and in accordance with the requirements of the STA. The results of the 2013 tests are presented in References [1-3]. The design of the 2013 tests was based on a model-scale study carried out by SP Fire Research prior to the large-scale tests [4].

2 This is in US units (gpm/psi^{1/2}), corresponding to 360 l/min/bar^{1/2} in SI units.
3 Conny Becker at Brandskyddslaget AB was the person who originally proposed it.
New tunnel projects have come into focus in Sweden since 2013, and the installation of fixed firefighting systems (FFFS) is being considered for many. One is an existing tunnel (the Göta Tunnel) in which a predicted change in the traffic situation may consider a solution using a FFFS, but with a lower water density than is necessary in the Stockholm bypass tunnel. This has resulted in renewed discussion regarding the performance of large-droplet, side-wall systems with lower water densities and nozzle pressures, focused primarily on limited access to water supply and complications in reconstructing drainage systems.

The timeline for the Stockholm bypass project was well suited to the 2013 tests. The discussed TN-25 solution made it possible to design the system with regard to its requirements, in terms of both the water supply capacity and drainage system. There were, however, questions raised regarding systems located in exit ramps using a lower nozzle pressure. These ramps were narrower than the main tunnel tubes, and so require reduced throwing lengths and thus less nozzle pressure. The testing of the TN-25 with a lower nozzle pressure was therefore added to the 2016 test programme. The operational nozzle pressure used during the 2013 tests was 1.1 bar, with a throwing length of 7.5 m; in the tests presented here, the nozzle pressure used was much lower, at 0.55 and 0.69 bar, respectively. The throwing length was about 6 m for this pressure range.

In 2012, just as the discussion of side-wall nozzles had begun, a new tunnel was in the final stages of being designed (the Northern Link tunnel in Stockholm). Here, nozzles that were already on the market were chosen in order for the design of the water spray system to be finalised in time. The nozzle chosen was the Extended Coverage Ordinary Hazard (ECOH) SW-24 with a K factor of 160 l/min/bar$^{1/2}$ (K-11.2). The theoretical droplet diameter for this nozzle is roughly 60% of that of the TN-25 nozzles at 1.1 bar, with a throwing length of 7.5 m. This nozzle had not been tested for tunnels prior to its selection, and was therefore added to the 2016 test programme.

The 2013 tests with the TN-25 nozzle demonstrated that large-droplet, side-wall nozzles are effective in controlling fire size and fire spread for the tested scenario, which used wooden pallets [1]. TYCO proposed to the STA the development of a similar type of large-droplet, side-wall nozzle, but with a lower K factor that would yield similar throwing lengths. This would mean a lower water flow rate and slightly higher nozzle pressure, and thus lower water density in mm/min. A prototype, designated ‘TN-17’, with a K factor of 240 l/min/bar$^{1/2}$ (K-17), was therefore provided for the 2016 tests.

There is a strongly held opinion among tunnel engineers and sprinkler experts that thermal devices such as glass bulbs (automatic sprinkler heads) are not useful in tunnels with a longitudinal ventilation flow, and so deluge zones combined with detection systems have traditionally been used. The rationale is that convective flow from the fire can activate the wrong sprinkler heads downstream, jeopardising the entire system as too many sprinkler heads are activated (leading to a collapse of the FFFS). However, the STA is considering the installation of sprinkler heads for a specific tunnel project with a low longitudinal velocity. One reason for this is that SP Fire Research conducted an extensive small-scale research programme in order to explore the applicability of automatic sprinkler heads in longitudinal flow in tunnels [5, 6], which showed that sprinkler heads would work well in this application with a low longitudinal velocity, as well as in tunnels which ordinarily have a high ventilation rate that is reduced on activation, and those with transversal or natural ventilation. Li and Ingason [5, 6] clearly demarcate the limits for failure of a system based on longitudinal velocity, water flow rate, and activation temperature. ‘Low velocity’ is not defined by the authors but, based on the failure graphs presented, it is in the order of less than 2-3 m/s; ‘high’ velocities are at the level of 5-6 m/s. In order to further explore the model-scale results of the low-velocity scenario, it was decided to add a test that used sprinkler heads (equipped with glass bulb). The SW-24 sprinkler head, which is manufactured with 93°C fast-response bulbs, was selected, as the TN nozzles are not available with an automatic thermal device.

The general layout of the side-wall nozzle system discussed here is as follows; a pipe is positioned in the middle of the tunnel ceiling, with a pair of nozzles every 5 m, which horizontally spray water in two directions. This means that the nozzles are positioned back-to-back on the central ceiling pipe. The throwing lengths are in the order of 6-8 m, depending on the type of nozzle and pressure at the nozzle. The uniqueness of the system lies in its simplicity, and the fact that large droplets are thrown in the direction of both tunnel walls. This is not a common solution for tunnels, but a similar side-wall concept has been used in Australia and the US, albeit with smaller droplets [1]. The main goal of the system is to limit fire size and prevent fire spread during the period of evacuation in a congested traffic scenario inside the tunnel system.

The purpose of the 2016 tests was as follows:

1) To have a set of results to compare against those of the 2013 tests, which used the TN-25 nozzle, but using a lower nozzle pressure.
2) To test a new prototype nozzle, TN-17, in order to explore the possibility of using a lower flow rate but maintaining the same throwing length.
3) To test the Northern Link tunnel deluge system using the SW-24 nozzle.
4) To test a sprinkler head of type SW-24 (automatic).

Insofar as possible, the tests were to be performed under the same conditions as those of the 2013 tests. The same test setup and velocities were used in the Runehamar tunnel, which is situated roughly 5 km from Andalsnes, Norway. It is a two-way asphalted road tunnel that was taken out of service in the late 1980s, and is approximately 1,600 m long, 6 m high, and 9 m wide, with a cross-section of approximately 47 m². The tunnel has an average uphill slope of 0.5% up to roughly 500 m from the east portal (where the fans are located), followed by a 200 m-long plateau and then a 900 m-long downhill section with an average slope of 1% towards the west portal. The fire was located 600 m from the east portal, i.e. on the plateau section of the tunnel. The tunnel is protected with shotcrete at the test location.

In the following, detailed information about the test setup and programme is given and then the test results are presented.

DESCRIPTION OF EXPERIMENTAL SETUP

Description of water spray system
The same water spray system setup was used as in the 2013 tests [1]. The pipe was placed at the ceiling on one side of the tunnel, with nozzles discharging water towards the opposite wall and the fuel (see Figure 1). The water density in the deluge zone of the water spray system was the same as if the pipe had been located at the centre of a full-sized tunnel, where the system would be placed centrally and use a T-coupling to throw water symmetrically in both directions. The deluge zone was 30 m long, and the total water flow rate varied depending on the nozzle type used. In a full-sized tunnel, the deluge zone would be at least 50 m in length. A 600 m-long ground pipe (on the surface of the road) with a diameter of 140 mm (inside diameter of 127 mm) delivered the water from the water tank, located outside the tunnel portal. The ground pipe was connected to the ceiling pipe as shown in Figure 1. The water tank had a volume of 230 m³, and was refilled between tests with groundwater from the nearby mountain. The total tank water was sufficient to maintain a 120 minute continuous delivery of water for each test, using a 55 kW electrical pump with a maximum flow capacity of 2300 lpm at 7 bar.
Figure 1  The test setup and water spray system after activation.

The nozzles used are shown in Figure 2. They were fitted to the 140 mm diameter pipe with a T-coupling. The nozzles were located close to the tunnel wall, 4.65 m above the road surface. The height up to the ceiling was approximately 0.7 m. The distance between the nozzles and the side-wall was approximately 0.4 m. The pipe system and the nozzle locations are shown in Figure 1 and Figure 4. The nozzles were mounted every 5 m over a distance of 25 m. The total length of the ceiling pipe was 30 m (deluge zone).

Figure 2  The three nozzle types used in the tests. The K-factor varied for each: For TN-25 it was 360 l/min/bar$^{1/2}$; for TN-17 it was 240 l/min/bar$^{1/2}$; for SW-24 it was 160 l/min/bar$^{1/2}$.
The TN-25 is a horizontal spray nozzle with a K-factor of 362.9 l/min/bar^{1/2} (25.2 gpm/psi^{1/2}), and is a specialised open-deluge nozzle for use in tunnel fire protection systems. Its minimum and maximum working pressures are 0.7 and 2.1 bar, respectively, according to the data sheet5. The TN-17 is a prototype, and not currently available on the market. Its K-factor is 240 l/min/bar^{1/2} (17 gpm/psi^{1/2}). The third nozzle was a SW-24, with a K-factor of 161.3 l/min/bar^{1/2} (11.2 gpm/psi^{1/2}) and maximum working pressure of 12.1 bar. The SW-24 is an ECOH (Extended Coverage Ordinary Hazard) horizontal sidewall nozzle that uses a standard-response glass bulb, originally designed for use in ordinary hazard occupancies. The SW-24 sprinkler head used had a 3 mm-thick 93°C (green) glass bulb. In one deluge test with the SW-24 nozzles, the glass bulbs were removed prior to testing.

Fire source

The fire source consisted of 420 wooden pallets placed in the centre of the tunnel, 600 m from the west portal. This type of test fuel mock-up is often used to simulate the payload of a Heavy Goods Vehicle (HGV) trailer. A target, consisting of a pile of 21 wooden pallets, was positioned 5 m from the rear of the fuel mock-up in order to evaluate the risk of fire spread.

The wooden pallets were placed on lightweight concrete slabs (Siporex), with 12 mm-thick plywood boards mounted on top of the slabs. Ten rows, each consisting of 2 piles of 21 pallets, were placed on the slabs, as was the target, which constituted one additional row. In Figure 3, the main fuel load is shown from the side. In order to maintain the correct distance between the sprinkler nozzles and the top of the fuel load, the concrete platform was 0.2 m high. Based on experiences gleaned during the 2013 tests, this was not expected to influence the final results. Each pallet measured 0.8 x 1.2 m, i.e. the width of the fuel load was 2.4 m, weighed roughly 24 kg, and was approximately 0.143 m high. The total length of the fuel load was just over 8 m, and its total height was 3.03 m. The exposed fuel surface of one pallet was 3.3 m², and the heat release rate per square metre of exposed fuel surface was estimated at 0.06 MW [7]. Thus one row of wooden pallets was expected to produce 8.3 MW.

In total, the fuel load weighed just over 10 tonnes (441 x 24 kg). This meant that the potential energy content was approximately 180 GJ. The target consisted of 21 pallets, giving an additional energy of approximately 9 GJ, bringing the total to 189 GJ. The moisture content in the wooden pallets varied between 15 and 20%. In the 2013 tests, one test was carried out without water. The fire developed fully, and the target was consumed. Some fuel was left over, but most of the pallets were entirely consumed. The measured total energy consumed was 181 GJ, which is quite close to the theoretical value estimated [1].

Both the front and back of the fire source was covered with steel plates, as was the area above the pallets. This arrangement made it difficult for water to directly penetrate the pallets, increasing the heat release rate and the energy required to consume the fuel.

rigorousness of the test by reducing the ability of the system to fight the fire from above. A tarpaulin was mounted on the sides not covered by steel sheets during one of the 2013 tests, but this was not used in this study, both for practical reasons and because the test-setup had already been tested.

**The mock-up setup**

The setup of the mock-up in relation to the nozzles followed that used for the 2013 tests [1]. The vertical distance between the nozzles and the tops of the wooden pallets was 0.8 m. The horizontal distance from the opposite wall to the wooden pallets was 2.5 m (see Figure 4), and the horizontal distance between the nozzles and the vertical side of the wooden pallets was 2 m. The distance between each nozzle and the nearest wall was approximately 0.4 m, with a further space of 1.7 m from the wall to the ground pipe. The tunnel height was 6 m, and the total width of the road surface was 8.6 m.

![Figure 4](image_url)  
*Figure 4  Cross-section of the test setup used for the large-scale tests [1].*

**Instrumentation**

Gas temperature, gas concentration, visibility, radiation, water flow rate, and water pressure were measured every second. The heat release rate in MW was determined by measuring the gas and air flows approximately 1000 m from the fire, where a measurement station was located at the point marked as ‘Pile A’, at \(x = \text{c.} \ 1000 \text{ m},\) in Figure 5. In total, 22 thermocouples, 6 bi-directional pressure probes, 3 gas analysers (\(O_2, \ CO_2\), and \(CO\)), 5 plate thermometers (PT), 2 photocells, 1 water pressure monitor, and 1 water flow gauge were used in these tests. The location of each instrument is shown in Figure 5.

All of the ceiling thermocouples (Type K, 0.5 mm) were placed 0.4 m below the ceiling, except at Pile A. PTs were mounted at the ceiling at \(x = -18, \ 0, \ 9, \ 150 \text{ m}\) in order to estimate the incident heat flux towards this position. There was also a PT 1.5 m above the road surface, at \(x = -18 \text{ m}\). All of the PTs were placed so that their plates always faced the fire source.

One of the two photocell visibility instruments was placed at the measurement station \((x = \text{c.} \ 1000 \text{ m})\), with the other at \(x = 150 \text{ m}\). Smoke density was presented as a reduction (%) of air transparency over a given length (1.1 m), and was measured 1.5 m above the road surface. Air transparency was used to calculate visibility in m.
The thermocouples (Type K, 0.5 mm) were located close (50 mm away) to the nozzle positions N2, N4, and N6. The nozzles were positioned at the ceiling (Figure 4), 3.2 m from the centre line of the fuel load, and at a distance corresponding to \( x = -12.5 \) (N1), -7.5 (N2), -2.5 (N3), 2.5 (N4), 7.5 (N5), and 12.5 m (N6). The bi-directional probe and the thermocouple upstream at \( x = -50 \) m were placed at the centre line of the tunnel cross-section (see Figure 5).

Figure 5 The layout of the instruments used in the test series.

The transportation time was factored into the calculation of the heat release rate, which was based on an oxygen calorimetry (O2, CO2, and CO), and the same technique as used in References [1-3] was employed. More information about the performance of the tests, calculation of the heat release rate, visibility, and heat flux based on the measurements used is given in [8].

**TEST PROCEDURE**

For the tests that used the deluge system, a similar test procedure was used as in the 2013 tests [1], and the 2016 test programme is shown in Table 1. Five tests were performed with a deluge system (Tests 1-5), and one with sprinkler heads that used glass bulbs (Test 6).

To mimic a real detection scenario for the deluge system, the detection temperature was set at 141°C, and the first ceiling thermocouple to register this temperature was used as starting time (alarm) for the delay period. In all five tests the thermocouple at \( x = 4.5 \) m (7.3 m from the centre of the first row of piles, where the fire was ignited) reached the ‘detection’ temperature first. A four-minute ‘delay’ between detection (alarm) and activation was implemented for Tests 1-5 in order to simulate the manual operation time that a traffic control centre takes to initialise activation. In the 2013 tests this delay was varied – 2, 4, and 8 minutes – while the STA decided to maintain a constant four-minute delay for the tests presented in this report. Based on experiences during the 2013 test series, this corresponds to a heat release rate of roughly 10-15 MW at the point in time at which the water spray system is activated.

The longitudinal velocity during all of the deluge tests was set at 3 m/s, corresponding to a critical velocity for this type of tunnel and no backlayering of smoke. The velocity in Test 6, which used sprinkler heads, was set at 2 m/s, as it is known that, in the real tunnel where these sprinkler heads are to be installed, the longitudinal velocity is lower than 2 m/s. An additional reason for this relates to safety, in that the decision was made in order to prevent long backlayering. The fire protection lining mounted at the tunnel ceiling was of a limited length on the upstream side of the fire. It was found in previous model-scale studies that the automatic system should be able to work with this longitudinal velocity [6]. The decision to use a detection temperature of 141°C was based on the results obtained during the model scale tests [4], and further confirmed by the 2013 test results. Table 1 presents the test sequence, test dates, and physical parameters that were varied.
Table 1  Test programme of the 2016 large-scale tests in the Runehamar tunnel.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Test date</th>
<th>Nozzle type</th>
<th>K-factor</th>
<th>Flow rate per nozzle</th>
<th>Total flow rate</th>
<th>Nozzle Pressure</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>June 2016</td>
<td>TN-25</td>
<td>360</td>
<td>1/(min·bar(^{1/2}))</td>
<td>300</td>
<td>1800</td>
<td>0.69</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>TN-17</td>
<td>240</td>
<td>1/min</td>
<td>268</td>
<td>1608</td>
<td>1.25</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>TN-17</td>
<td>240</td>
<td>1/min</td>
<td>233</td>
<td>1400</td>
<td>0.95</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>TN-25</td>
<td>360</td>
<td>1/(min·bar(^{1/2}))</td>
<td>268</td>
<td>1608</td>
<td>0.55</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>SW-24</td>
<td>160</td>
<td>1/min</td>
<td>233</td>
<td>1400</td>
<td>2.13</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>SW-24 bulb</td>
<td>160</td>
<td>1/min</td>
<td>298</td>
<td>750-1000</td>
<td>4.5-6</td>
</tr>
</tbody>
</table>

The activation times varied slightly for the deluge tests (1-5), with an average of 8:03 and a maximum difference of 29 seconds. The heat release rate at activation varied between 8 and 12 MW. In most cases, two rows of piles were involved in the fire at the point in time at which the system activated.

The throwing length, trajectory, and spray pattern varied. Droplet size was dependent on nozzle pressure and K-factor. The largest droplets were emitted by the TN-25, and the smallest by the SW-24. The pressure of the TN-25 in Test 4 was only 0.55 bar, which is lower than the minimum working pressure recommended by the manufacturer, giving an observed throwing length of approximately 6 m. The throwing length for the SW-24 with a 2.1 bar nozzle pressure was roughly 7.5 m. The TN-17 had a lower K-factor and a higher pressure than the TN-25; thus, as can be expected, the TN-17’s droplet size and throwing length (approximately 6.7 m) fell between those of the TN-25 and SW-24. The throwing lengths are dependent on the pressure and direction of the nozzles. The throwing lengths given here should therefore only be regarded as tentative.

RESULTS

In the following, some selected test results is given. More test data can be found in the report [8].

Heat release rate

Figure 6 presents the calculated heat release rates, based on mass flow rates of O\(_2\), CO\(_2\), and CO, of all of the tests. The method of calculating heat release rate is presented in [8]. In the tests which used TN nozzles (larger droplets) the maximum heat release rate did not exceed 15 MW throughout the testing period. The lowest operational nozzle pressure with a large K-factor gave the best results (Test 4; TN-25, 0.55 bar). During the SW-24 tests the maximum heat release rate did not exceed 30 MW, except for one peak value of 31 MW after 48 minutes (Test 6; sprinkler head).

Figure 7 shows the fire conditions at 9 minutes after ignition and shortly after activation for all of the tests. The heat release rate was in the range of 8-12 MW for all of the tests. This can be compared to the measured heat release rates presented in Figure 6.
Figure 6  The measured heat release rates for Tests 1-6.

Figure 7  Fire development 9 minutes into the tests. All of the systems had been activated at this point, and the heat release rates were in the range of 8-12 MW.

**Deluge system**

One of the important criteria set by the STA was that, following the activation of the deluge system, the total heat release rate should not exceed 30 MW. As can be seen in Figure 6, this was met by all of the deluge systems (Tests 1-5).

The TN-17 nozzle (Tests 2 and 3) produced smaller droplets than the TN-25 (Tests 1 and 4), as is
shown in Figure 6, which demonstrates that the TN-25 yielded better results with regard to the risk of fire spread within the fuel area. The TN-17 was less able to control the fire spread throughout the test period. After an initial constant period of around 15 minutes the heat release rate continuously decreased, but after approximately 45 minutes the fire began to increase in size again, and continued to do so until the end of the test (see Figure 6).

One possible reason for this may have been the influence of the wind as the fire travelled through the fuel load, which became more pronounced as the fuel burned further downstream from the windbreak. This, together with how the water was delivered to the sides of the fuel load, was crucial. Generally, the pallets that directly faced the water spray (water side) survived longer than those on the other side (low water side), as the water directly hit the pallets on the water side but not those on the low water side. As the first row of pallets started to fall over or burn out entirely, the wind increasingly affected the fire growth rate, to the point where the system was no longer able to stop the fire spread effectively. This was the case for both the TN-17 and SW-24 nozzles. If the system is to stop the fire spread, this should be done before the fire has spread beyond 2-3 pallet rows.

In summary, how effectively the water was delivered to the piles on the low water side and to what extent the fire was suppressed before spreading to the second and third rows directly influenced whether the system was able to prevent further spreading.

The most effective way of comparing the efficiency of different nozzles is to integrate the total energy released during the test. The results are shown in further detail later.

**Automatic sprinkler system**

The test that used sprinkler heads (with glass bulbs) was different from those which used the deluge system (six open nozzles). Instead of starting the pump and directing it towards open nozzles (the ground pipe was full of water and the ceiling pipe was empty), the ceiling pipes were filled with water and pressurised at 5 bar. When a glass bulb was activated, water sprayed from that nozzle and the pump was activated. This created a short pressure drop, but this was recovered as soon as the pump built up the pressure to maximum again.

The longitudinal velocity was reduced from 3 to 2 m/s in order to maintain a certain level of backlayering, as the sprinkler system is sensitive to longitudinal velocity. The longitudinal velocity was not reduced further so as to prevent long backlayering lengths. The total backlayering after around 30 minutes was approximately 40 m, as confirmed by the thermocouples in the ceiling.

In Figure 8, a direct comparison between the deluge system and the SW-24 sprinkler system is shown. It highlights the fact that the deluge system was better able to maintain control initially, as it delivered water to the entire fuel load, unlike the automatic sprinkler system. This is also reflected in the heat release rate curve, as the nozzles further downstream were opened first. Both of the systems began to control the heat release rate at about the same time; approximately 20 minutes into the test.

The activation sequence of the sprinkler heads was of particular interest. All six sprinkler heads were equipped with bulbs (designated ‘N1’ to ‘N6’), with additional bulbs mounted at various points downstream of the fire in order to indicate if, and where, the temperature rose above 93°C (the temperature at which the bulbs break). The locations of these bulbs were $x = 17.5$ m, 27.5 m and 47.5 m, respectively. It should be noted that no water was connected to these bulbs, and so they did not contribute to the cooling after $x = 17.5$ m.
Gas temperature

In the following, a presentation of the measured gas temperatures at the centre line of the tunnel ceiling at distances $x = -4.5, -1.5, 0, 1.5, 4.5, 9.0, 15, 25, \text{ and } 150 \text{ m}$ are given for all six of the tests. Figure 9 give the ceiling gas temperatures, measured 0.4 m below the ceiling, for each $x=0 \text{ m}$ position. The gas temperature prior to activation was almost 400°C in all of the tests. When the system was activated during Tests 1-5, it cooled these gases effectively. In Test 6 the temperature was initially lowered, but increased again as the backlayering continued to increase in effect. The backlayering length was estimated to be approximately 55 m at its peak.

The highest temperatures were recorded at $x = 0 \text{ m}$, which was 3.8 m from the initial fire source. As the fire grew its position changed, and the temperature was reduced after a given time due to longitudinal flow. In some cases the ceiling temperature increased as the fire travelled through the fuel area. Note that the maximum ceiling gas temperature did not exceed 800°C in any of the positions. The highest temperatures were measured at $x = 0$ and $x = 1.5 \text{ m}$, in descending order of magnitude. Further information on temperatures are found in the test report [8].

On the upstream side, measurements were also made at $x = -10, -18, -30, \text{ and } -50 \text{ m}$ so as to estimate the backlayering length for Test 6. The highest temperatures were measured roughly 26 minutes into the test at these points, when the heat release rate was approximately 25 MW. The following maximum temperatures were obtained: $x = -10 \text{ m}, 180^\circ \text{C}; x = -18 \text{ m}, 210^\circ \text{C}; x = -30 \text{ m}, \text{ around } 100^\circ \text{C}$; $x = -50 \text{ m}$, no significant increase in temperature. 40 m is likely a good estimate for the average backlayering length. The maximum backlayering distance equivalent to the location $x = -55 \text{ m}$ at a longitudinal velocity of 2 m/s for non-sprinklered test. Due to the convective cooling of the fire plume of a 25 MW fire, one would expect the backlayering length to be somewhat lower, and so the calculated and measured values for backlayering length correlate relatively well.

The maximum gas temperature measured during the free-burning test conducted in 2013 was 1366°C.
This clearly demonstrates the impact that these water spray systems have in terms of protecting the tunnel construction.

![Figure 9](image-url)  
*The measured gas temperatures at the level of the ceiling at x = 0 m for Tests 1-6.*

### Total energy content

Table 2 presents a summary of the test results. The parameters given are the heat release rate at activation, $Q_{act}$, the highest ceiling temperature at activation, $T_{act}$, the maximum heat release rate after the system has been activated, $Q_{max, \text{after act}}$, and the incident maximum heat flux to the ceiling at $x = 0$ m, $\dot{q}''_{\text{max, after act}}$. This value is presented as the value at activation/maximum value after activation. Total energy, $E_{tot}$, is also given in GJ, and is an integrated value from the heat release rate curves for the entire test period. The total energy content of the fire load can be estimated by multiplying its mass with the theoretical heat of combustion for wood. There were 441 wooden pallets including those of the target, with each weighing around 24 kg. The theoretical heat of combustion for wood can be obtained from Tewarson [9]; 17.9 MJ/kg. This means that the total potential heat energy for this fuel load was 189 GJ.

### Table 2  Summary of the key heat energy parameters of the tests.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>$t_{act}$ (m:s)</th>
<th>$Q_{act}$ (MW)</th>
<th>$T_{act}$ (°C)</th>
<th>$Q_{max, \text{after act}}$ (MW)</th>
<th>$\dot{q}''_{\text{max, after act}}$ (kW/m$^2$)</th>
<th>$E_{tot}$ (GJ)</th>
<th>Equivalent number of pallets consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7:53</td>
<td>12.0</td>
<td>423</td>
<td>14.9</td>
<td>19/11</td>
<td>33</td>
<td>76</td>
</tr>
<tr>
<td>2</td>
<td>7:52</td>
<td>8.0</td>
<td>393</td>
<td>13.9</td>
<td>10/19</td>
<td>49</td>
<td>113</td>
</tr>
<tr>
<td>3</td>
<td>7:44</td>
<td>9.5</td>
<td>524</td>
<td>16.5</td>
<td>18/12</td>
<td>45</td>
<td>104</td>
</tr>
<tr>
<td>4</td>
<td>8:22</td>
<td>12.2</td>
<td>409</td>
<td>14.0</td>
<td>12/15</td>
<td>23</td>
<td>53</td>
</tr>
<tr>
<td>5</td>
<td>8:10</td>
<td>11.4</td>
<td>531</td>
<td>29.7</td>
<td>21/36</td>
<td>78</td>
<td>181</td>
</tr>
<tr>
<td>6</td>
<td>N4; 5:22</td>
<td>5.1</td>
<td>525</td>
<td>31.1</td>
<td>12/14</td>
<td>75</td>
<td>174</td>
</tr>
<tr>
<td></td>
<td>N5; 5:45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3; 6:47</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N6; 30:56</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the last column, a value is given for the equivalent number of pallets that have been consumed. This value was obtained by taking $E_{\text{tot}}$ for each test and dividing it by the heat of combustion and weight of all of the pallets. This figure does not necessarily correlate exactly with ocular inspections performed following the tests, but gives a good indication of how many pallets were consumed.

The heat release rate at activation ranged from 5 to 12 MW for all tests. The deluge tests varied between 8 and 12.2 MW. The ceiling temperature was in the range of 393-531°C. The maximum heat release rate after activation for the deluge tests ranged from 13.9 to 29.7 MW. For Test 6, the maximum heat release rate after activation was 31.1 MW. The maximum incident heat release rate as directed towards the ceiling after activation was found not to exceed 36 kW/m². This value is low as compared to the values measured in the tests in 2013 (approximately 400 kW/m²), when no water spray system was used.

**Visibility**

Visibility was measured at two positions downstream of the fire, and 1.5 m above the road surface. The positions were $x = 150$ and 1000 m. Figure 10 and Figure 11 give examples of the visibility measurements, which show that visibility was worse further away as there was no stratification at that location. At $x = 150$ m there was a stratification, which is confirmed by temperature measurements at the same location.

The best visibility at $x = 150$ m was obtained in Test 4, which used the low-pressure TN-25 nozzle. Further away, at $x = 1000$ m, the visibility was roughly the same for all tests, although Test 4 seemingly yielded the best visibility and Test 5 the worst, with nearly zero.

![Figure 10](image-url)  
*Figure 10 The measured visibility during Test 4 (TN-25).*
Gas analysis

The carbon monoxide volume concentrations at the mid-tunnel height and 1000 m downstream of the fire are given in Figure 12, which clearly show that the CO concentrations of Tests 1 and 4 (TN-25) correlate well. The results of the tests that used TN-17 lie at a higher level, with those of SW-24 higher still. This is in accordance with the order of the heat release rates in the tests. Note that a lower ventilation velocity was used for Test 6, and thus higher CO concentrations were obtained than during Test 5.

In Table 3, a summary of the maximum and minimum values for gas measurements at the mid-tunnel height and 1000 m downstream of the fire are given. A trend similar to that of CO can be observed for CO₂.
Furthermore, comparison of the test data with that of the 2013 free-burning test indicates that, when the water was applied, the production of incomplete combustion products, such as CO, increased. Further research is needed to investigate the implications of this, however.

**Table 3** Maximum or minimum values for gas measurements at mid tunnel height and 1000 m downstream of the fire.

<table>
<thead>
<tr>
<th>Test number</th>
<th>(O_2) x=1000 m (%)</th>
<th>(CO_2) x=1000 m (%)</th>
<th>CO x=1000 m (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.3</td>
<td>0.49</td>
<td>0.07</td>
</tr>
<tr>
<td>2</td>
<td>20.2</td>
<td>0.59</td>
<td>0.10</td>
</tr>
<tr>
<td>3</td>
<td>20.1</td>
<td>0.77</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>20.4</td>
<td>0.48</td>
<td>0.07</td>
</tr>
<tr>
<td>5</td>
<td>19.4</td>
<td>1.34</td>
<td>0.14</td>
</tr>
<tr>
<td>6</td>
<td>19.3</td>
<td>1.43</td>
<td>0.24</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

Larger droplets better penetrated the fuel load and facilitated the cooling of fuel surfaces directly, preventing further flame spread within the fuel load. The wooden pallets that were closer to the water spray system were more effectively extinguished, although this is also dependent on the trajectory of the droplets, which in turn is directly related to nozzle geometry, pressure, and K-factor. A higher nozzle pressure for the same K-factor raises the trajectory of the droplets and increases the throwing length. Taken together, these parameters determine the efficiency with which flame spread was controlled within the fuel load.

The TN-25 nozzle, using a lower pressure and water flow rate, did not perform worse than in the 2013 tests. On the contrary, the results have improved, particularly for the lowest pressure setting. It should, however, be noted that this operating pressure is less than the minimum requirement given by the manufacturer. The prototype TN-17 performed similarly to the TN-25 during the first 30 minutes of the test but after 45 minutes the fire redeveloped. The maximum heat release rate after the redevelopment was not higher than that of the first phase. The SW-24 nozzle performed most poorly, although it protected the construction well and kept the maximum heat release rate below that set by the STA as a goal.

The heat release rate upon activation ranged from approximately 5 to 12 MW. During the TN nozzle tests the heat release rate remained under control for a period of 15 minutes following activation, after which the fire size decreased over a period of 10-30 minutes. The TN-25 system prevented further flame spread within the fuel load, while the fire during the TN-17 test redeveloped after 45 minutes.

Testing with a sprinkler head showed the potential of this type of system with regard to tunnels with a lower ventilation rate, or where the ventilation strategy involves reducing the velocity after a fire alarm. Further testing is needed in order to explore the limitations of these systems. Particularly, using a sprinkler that emits larger droplets and an automatic device seems to be a feasible method.

The FFFS was able to maintain a heat release rate of lower than 30 MW in all five tests using a deluge system. Following the activation of the system, the maximum temperature at the ceiling never exceeded 800°C.

A pile of pallets, representing a target, was located 5 m from the end of the main fuel stack. It was used to assess the risk of fire spread to adjacent vehicles. In all of the tests in which the FFFS was
operational, the target was unaffected by the main fire.

The primary benefit of the FFFS is that it can be used to increase safety in tunnels, as such systems are able to fight fires that are relatively large and thereby potentially prevent major disasters. In a scenario in which congestion is an issue, and more specifically when a queue forms, the system increases safety by minimising the risk of propagation of a fire as it could occur.

REFERENCES


Expediting implementation of FFFS in road tunnels

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ABSTRACT

Road tunnel fixed fire fighting systems (FFFS) have made substantial progress in their incorporation. Initially utilized primarily in Asia, they have now become common in Europe and North America. They have been shown to prevent the spread of fire to nonincident vehicles and minimizing the damage to road tunnels. This has a significant benefit particularly to critical transportation corridors. Water application rate continues to be the most important design parameter and yet no guidance is provided, leaving designers to figure it out each time. The determination of this parameter is very important as water usage must be optimized, particularly for restricted water supplies. The ability of these systems to mitigate flammable liquid tanker (FLT) fires is not as well understood. The general practice has been to restrict their use or stipulate foam suppression. Both of these practices are influenced due to industry increased demand for usage. While there is evidence that the same system can provide reasonable mitigation, there is hesitation about allowing it. In short, FFFS implementation could be greatly enhanced by two considerations.

• Providing prescriptive water application rates that reduce the uncertainty in their criteria and objectives.
• Implementing a test program for FLT performance that would help reduce the uncertainty of system performance on these types of fires and allow greater confidence that these fires can be successfully mitigated without foam systems.

KEYWORD: FFFS, road tunnel, water application rate, tanker

HISTORICAL EXAMPLES OF FFFS IN ROAD TUNNELS

Road tunnel fixed fire fighting systems (FFFS) have made substantial progress in their incorporation. Initially utilized primarily in Asia, they have now become common in Europe and North America. A pair of tunnel fires highlighted their benefit, the Santa Clarita fire in Newhall, California and the Burnley Tunnel in Australia.

Nihonzaka Tunnel Fire
One of the largest tunnel fire incidents occurred in the Nihonzaka Tunnel (1) in Japan on July 11, 1979. The Nihonzaka Tunnel consists of two 2 km-long tubes with unidirectional traffic. There were no restrictions on hazardous materials travelling through the tunnel, although this changed as a result of the fire. The fire was started by a rear-end collision involving four trucks and two cars. The accident caused tanks on the vehicles to leak, and this fuel subsequently ignited. Seven people died in the fire and two were injured. Of the 230 vehicles in the tunnel, 173 were destroyed by the fire. The tunnel lining and the additional 45 mm (1¾ inch) thick reinforcement of the tunnel walls were damaged for a length of about 1100 meters (3600 feet). The greatest damage occurred in an area of about 500 meters (1640 feet) on either side of the seat of the fire. The road surface melted in places up to a depth of 200 to 300 mm (8 to 12 inches) average, with the maximum depth being 700 mm (28 inches).
It took two days to bring the fire under control and a week to finally extinguish it. The deluge sprinklers located in the tunnel were set off automatically by fire alarm systems. After about 10 minutes the fire appeared to have been extinguished. However, about 15 minutes later the fire flared up again. The water supply reservoir was emptied. Thereafter the fire grew to its maximum length.

**Figure 1. Nihonzaka Tunnel fire accident.**

**Newhall, Mont Blanc and Burnley Tunnel Fires.**
In the recent Newhall Tunnel fire in Los Angeles (2), for example, as many as 30 HGV’s were involved. While the fire origin was relatively small, it spread to the other vehicles, creating a much higher FHRR (Fire Heat Release Rate). The Mont Blanc Tunnel (3) also involved multiple vehicles. The primary mechanism of this is the heat flux generated by the originating fire. An FFFS system reduces this heat flux preventing the fire from spreading to other vehicles. This was confirmed in the Burnley Tunnel fire in Australia (4) where three vehicles were involved and the fire did not spread past the original three vehicles.

**Inferno on the Interstate: What Went Wrong?**

Heavyweight traffic, a slick roadway and a narrow tunnel with a blind curve add up to the big-rig version of the perfect storm.

These examples show that the FFFS provides a significant mitigation in tunnel damage from fire. This is especially important for critical infrastructure routes. Many Agencies require them and one of the leading industry Standards, NFPA 502 considers them conditionally mandatory. In contrast with the building environment, where suppression (sprinkler systems) are often mandated and prescriptive requirements are provided for implementation that allow for compliance enforcement, road tunnels often require a significant performance assessment. In order to make the installation decision easier, can these requirements be simplified?

**Figure 2. Newhall Pass Tunnel fire (Santa Clarita).**
The second major issue to be addressed is their implementation with flammable liquid tanker (FLT) cargoes and with the addition of conventional heavy goods vehicles (HGV). In many cases, FLTs are prohibited or restricted from tunnel usage. This may cause other issues with alternate routes. There is also some discussion as to whether different systems, such as foam or higher water application rates are necessary. Can an FFFS be provided that handles both HGV and FLT incidents, simplifying operational response?

**DETERMINATION OF A PRESCRIPTIVE REQUIREMENT**

Can a prescriptive requirement be established that meets the objective and allows these beneficial systems to be easily implemented? In order to answer that question it is necessary to understand how water interacts with fire. In general, the discussion of performance vs. prescriptive requirements involves the trade-off of relatively straight-forward (and sometimes very arbitrary) rules to be followed vs. analysis of the controlling factors of the situation and developing mitigations necessary to meet the intended requirements. In many cases, especially if the requirements are extremely arbitrary and have little basis other than fiat, performance-based design can offer significant advantages. On the other hand, prescriptive requirements can make implementation relatively easy.

**Background**

Prescriptive requirements do exist in many areas, but their variation and arbitrariness is clearly evident. Japan and Australia each have their own water application rates of 6 mm/min (0.15 gpm/sf) (5) and 10 mm/min (0.25 gpm/sf) (6) respectively. In European system tests (Benelux), a water application rate of 14 mm/min (0.35 gpm/sf) (7) has been tested. These values have been added to Figure 4 which shows a range of water application rates that are prescribed and accepted by local codes or standards within specific fire department jurisdictions. There is a significant variation and more importantly, little has been done to compare these under similar conditions.
Current practice in the United States generally follows NFPA 502 where system installation and its performance requirements are not mandated, as stated in Article 9.3.5.

Figure 4. NFPA 13, NFPA 15, and other international water application rates.

9.3.5 Layout Parameters. To achieve the design objectives in accordance with 9.2.1, discharge device coverage, spacing, positioning, spray characteristics, working pressure, and flow rates shall be determined by use of applicable codes, standards, or accepted practices, or where necessary, by an engineering analysis considering relevant available data resulting from full-scale tunnel fixed water-based fire-fighting tests of the type of fixed water-based fire-fighting system being used.

The problem with this article is that no applicable codes, standards or accepted practices have been defined for the water application rate. Therefore either an engineering analysis or full-scale testing is required to develop the key design parameters. In contrast NFPA 13, the standard for sprinkler systems and NFPA 15, the standard for water spray systems both prescribe water application rates for buildings. While it may be tempting to impose a “safe” rate that is probably excessive, this must be balanced against the duration of the fixed or restricted water supply. Restricted supplies can occur in remote areas where municipal supplies are limited. In such cases tankage may be required. For example, the Nihonzaka Tunnel in Japan had a FFFS system. Deluge sprinklers located in the tunnel were set off automatically by fire alarm systems. After about 10 minutes the fire appeared to have been extinguished. However, about 15 minutes later the fire flared up again. The water supply reservoir was emptied. Thereafter the fire grew to a length of more than 1100 meters (3600 feet). Therefore an optimum prescriptive water application rate should have been balanced with the available water supply.

Fire/Water Physics

Fire point theory as first described by Rasbash (8) relates to the effectiveness of the suppression agent (water), and to the fundamental fire properties. This model is based on the interaction between the heat required to vaporize a solid or liquid fuel and the effect that water has on the prevention of this vaporization. This interaction is illustrated in Figure 5. It is important to note that a solid or liquid fuel itself will not burn. A fuel will burn only after it is converted to a gaseous state by vaporization, which requires energy. A heat source (q") is required to vaporize the fuel. This heat source may either be radiated from the flame itself or radiated from an external source, such as an object burning nearby. The rate of conversion from solid or liquid to gas is the mass loss rate of the fuel (m") and the magnitude of the heat required to vaporize the fuel is ∆H_g. The heat that is generated by the burning of the fuel source (∆H_f) times the total amount of fuel gives the fire’s total energy potential.

The primary way in which applied water suppresses a fire is by cooling, which occurs when a portion of the fire’s energy is used to evaporate the water instead of vaporizing the fuel.
Cooling a fire by applying water causes the mass loss rate of the fuel to be reduced below a critical value, preventing vaporization of the fuel. This cooling occurs at the solid/gas interface. The measure of water’s potential to suppress a fire is its heat of gasification ($\Delta H_w$). The minimum rate of water application to extinguish a fire per unit area is known as the critical water application rate or critical application density ($m''_{w,ex}$).

![Figure 5. Dynamics of fire and extinguishment.](image)

Generally speaking, the amount of water required to extinguish a fire ($m''_{w,ex}$) depends on the net heat flux on the fuel surface, which is the combination of:

- The amount of radiation emitted by nearby burning objects, plus
- The amount of radiation emitted by the flame itself.

Solving for the water application rate, $m''_w$, gives Equation 1.

$$m''_w = \frac{q''_e}{\varepsilon_w \Delta H_w + \delta_w} + \frac{\Phi \Delta H_f m''_{cr} - q''_r - m''_{cr} \Delta H_g}{\varepsilon_w \Delta H_w + \delta_w}$$

(1)

noting that at flame extinction $m'' = m''_{cr}$, the critical fuel mass loss rate, $q''_e$ is the heat flux at flame extinction, and $\Phi$ is the maximum fraction of combustion energy flame reactions may lose to the surface by convection without flame extinction, described as the kinetic parameter.

The heat fluxes are external ($q''_e$), reradiated from the fuel surface ($q''_r$), and that removed from the surface or flame (by an extinguishing agent) as the flame extinction condition is reached. When water is the extinguishing agent, then the heat flux removed from the surface of a burning material by water evaporation, $\varepsilon_w$ is the product of water application efficiency and $\Delta H_w$ the heat of gasification of water (2.58 kJ/g). In addition, $\delta_w$ is the energy associated with the blockage of the flame heat flux and fuel vaporization at the surface per unit mass of fuel vaporized.

The first term on the right is the external heat flux component and the second term is the critical water application rate for flame extinction, which is related to the fundamental fire properties of the material. In contrast to the second term, the first can be considered to account for general fire effects such as shape and arrangement of materials. It is not dependent on the particular materials used.

Water as a suppression agent acts by preventing fuel vaporization, thus preventing these fuel vapors from mixing with oxygen and combusting. How effective is a water spray at doing this? For non-flaming fuel sources, i.e. target fuel piles that could be ignited by an incident, the energy equation can be modified from Equation 1 by considering only the external heat flux. This becomes Equation 2.

$$m''_w = \frac{q''_e}{\varepsilon_w \Delta H_w + \delta_w}$$

(2)
Setting $\delta_w$ equal to 0, $\varepsilon_w$ equal to 1 and solving for $q"_w$ as a function of $m"_w$ gives the calculated water-vaporized heat flux results shown in Figure 6. These can be compared to common heat flux levels as shown from Quintere (9) as shown in Table 1 to estimate the amount of water necessary to mitigate heat flux and its resulting fuel vaporization. It should be remembered that the purpose of this work is to develop a spray system that meets a particular objective. Fire point theory shows that heat flux is the key parameter for predicting water effectiveness and that understanding this allows for better predicting water spray performance.

Figure 6. Vaporized water heat flux.

Table 1. Common heat flux levels.

<table>
<thead>
<tr>
<th>Source</th>
<th>kW/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance of sun on the earth’s surface</td>
<td>≤1</td>
</tr>
<tr>
<td>Minimum for pain to skin (relatively short exposure)</td>
<td>~1</td>
</tr>
<tr>
<td>Minimum for burn injury (relatively short exposure)</td>
<td>~4</td>
</tr>
<tr>
<td>Usually necessary to ignite thin items</td>
<td>≥10</td>
</tr>
<tr>
<td>Usually necessary to ignite common furnishings</td>
<td>≥20</td>
</tr>
<tr>
<td>Surface heating by a small laminar flame</td>
<td>50-70</td>
</tr>
<tr>
<td>Surface heating by a turbulent wall flame</td>
<td>20-40</td>
</tr>
<tr>
<td>ISO 9705 room-corner test burner to wall 100 kw</td>
<td>40-60</td>
</tr>
<tr>
<td>ISO 9705 room-corner test burner to wall 300 kw</td>
<td>60-80</td>
</tr>
<tr>
<td>Within a fully-involved room fire (800-1000 C)</td>
<td>75-150</td>
</tr>
<tr>
<td>Within a large pool fire (800-1200 C)</td>
<td>75-267</td>
</tr>
</tbody>
</table>

**PRESCRIPTIVE REQUIREMENTS**

Having a prescriptive requirement in the governing Standard, such as NFPA 502, simplifies the process. From a risk perspective standpoint, it sets a ceiling on design requirements. More sophisticated methods can be used for improving on the design, but reasonable prescriptive requirements can make implementation less cumbersome. As always, what make sense for the situation is the primary objective.

**Occupancy Hazard Classification**

The Ordinary Hazard Classifications of NFPA 13 would appear to define the physical characteristics of HGV cargo loading. Use of these could automatically trigger prescriptive water application rates for FFFS.

5.3.2.1 *Ordinary hazard (Group 2) occupancies shall be defined as occupancies or portions of other occupancies where the quantity and combustibility of contents are moderate to high, stockpiles of contents with moderate rates of heat release do not exceed 12 ft (3.66 m), and stockpiles of contents with high rates of heat release do not exceed 8 ft (2.4 m).*
Table 2. Mitigated heat fluxes for water application rates and design areas.

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Mitigated Heat flux (kw/m²) (mm/min/gpm/ft²)</th>
<th>Mitigated Heat flux (kw/m²) (mm/min/gpm/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary 2</td>
<td>6.1/0.15 259</td>
<td>8.1/0.15 345</td>
</tr>
<tr>
<td>Ordinary 1</td>
<td>4.1/0.10 173</td>
<td>6.1/0.15 259</td>
</tr>
</tbody>
</table>

The mitigated heat fluxes from Table 2 are greater than the values for solid and liquid fuel fires as shown in Table 1.

Since the large fire incident is often dictated by HGVs, it is important to understand the physical limitations of trailers and fuel loads. The load height is set by legal restrictions. The dimension shown in Figure 7 is the minimum in the United States. In many states it is 150 mm (6 in.) higher. In one state, Alaska, it is 300 mm (1 ft.) higher. It should be emphasized these are legal maxima and in most cases, cargo, especially open cargo is stacked slightly less. This cargo arrangement would certainly comply with the limitations of Ordinary 2 Occupancy Hazard Classification and is just over the height limitation for Ordinary 1 Occupancy Hazard Classification. While Ordinary 1 would probably handle the situation, Ordinary 2 provides some additional safety factor for uncertainty. If it was strongly agreed that a lower water application rate would be beneficial, particularly for locations with supply limitations, then the more detailed performance analysis could be performed.

Discussion

FFFS have been shown to significantly reduce the damage caused by major fires in road tunnels. The code requirements often stipulate modelling or testing in all cases and do not include the most critical element, the water application rate. As a result, significant effort is spent developing a conceptual program, its justification methodology, and the implementation of developed results. This is in contrast to the general industry practice of defining a hazard classification and then applying a prescriptive water application rate to that arrangement. A default prescriptive requirement eliminates this uncertainty and standardizes the water application rate for relatively easy implementation. A prescriptive stipulation of Ordinary 1 Hazard Classification would mitigate the heat fluxes generated, controlling the fire, while Ordinary 2 would provide greater heat flux mitigation and allow a safety factor for usage.

FLAMMABLE LIQUID TANKERS

This is the next logical step in these systems. For various reasons this aspect has more uncertainty.

Define Requirements for Flammable Liquid Tankers

FLTIs are often restricted from tunnels. FFFS for tunnels that include FLTs are usually either foam systems or water systems of the prescribed rates from NFPA 13 and NFPA 15. Testing programs have shown that standard water sprays can reduce the FHRR. Adding foam systems to FFFS increases both system complexity and operational complexity. Other testing programs have shown similar fire control mitigation with plain water sprays and foam water sprays. This objective can be described as comparing effectiveness of water sprays with and without foam.
Foam
Foam is often thought to be the optimum suppression agent for flammable liquid fires. However, it does add complexity in functionality and implementation. The key question is does it provide any significant benefit for road tunnel spill scenarios as opposed to the pool scenarios for which foam is generally used. Testing has shown there may not be much difference.

Water
NFPA Standards (13 and 15) already stipulate a Commodity Hazard Classification (Extra Hazard 2, 12 mm/min, 0.30 gpm/sf) prescriptive water application rate, so this implies foam is not necessary for flammable liquid fires. Again testing has shown significant mitigation with lower water application rates for the thin-film fires expected in road-tunnel applications.

Flammable Liquid Fire Suppression
While much is known about how water reacts with solid fuel fires, the process of flammable liquid suppression with water is less well known. The mechanisms of how additives, such as foam, suppress these fires are better understood. In the case of foam, under the right conditions, it floats on the liquid surface and prevents the mixing of fuel vapors and oxygen necessary for combustion. It should be noted that these tests are usually based on flat contained liquid pools, not necessarily the situation on a highway tunnel. Recent testing has shown that water mists of very fine droplets can also control these fires without foam. Table 3 shows some tests performed by Lemaire (10) to compare the performance of various suppression agents. Note there was very little difference between the 1%AFFF (VerTest2) and plain water (PerTest1).

Table 3. Suppression of solid and liquid fuel fires.

<table>
<thead>
<tr>
<th>Test</th>
<th>SCENARIO</th>
<th>Initial ventila-</th>
<th>Start of suppression after ignition</th>
<th>Burning period</th>
<th>Nominal HRR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fire load</td>
<td>tion speed</td>
<td>s</td>
<td>s</td>
<td>MW</td>
</tr>
<tr>
<td>VerTest1</td>
<td>Solid: 180 pallets (80% wood, 20% plastic.)</td>
<td>1% AFFF</td>
<td>3.7</td>
<td>335</td>
<td>1140</td>
</tr>
<tr>
<td>VerTest2</td>
<td>Pool: 100 m² diesel oil</td>
<td>1% AFFF</td>
<td>4.0</td>
<td>96</td>
<td>150</td>
</tr>
<tr>
<td>PerTest1</td>
<td>Pool: 100 m² diesel oil</td>
<td>no additives</td>
<td>4.0</td>
<td>125</td>
<td>180</td>
</tr>
<tr>
<td>PerTest2</td>
<td>Pool: 100 m² diesel oil</td>
<td>1% Bioversal</td>
<td>~ 4</td>
<td>160</td>
<td>420</td>
</tr>
<tr>
<td>PerTest3</td>
<td>Solid: 720 pallets (80% wood, 20% plastic.)</td>
<td>no additives</td>
<td>~ 4</td>
<td>439</td>
<td>2100</td>
</tr>
</tbody>
</table>

Tests of Water Spray in Flammable Liquid Fires
Numerous tests and studies have been done that show water spray does suppress flammable liquid fires. Rasbash (11) investigated the effect of cooling by water sprays for flammable liquid fires with fire points higher than the water temperature. Experiments with burning kerosene showed that water spray effectively cooled the fire to extinction, and even for tests without extinction, the temperature-time record showed that the water spray maintained a steady temperature after 12 minutes. This seemed to indicate that the heat entering the fire and the heat leaving the fire reached equilibrium. Other experiments by Rasbash (12) investigated the effect of various water spray pressures and flow


rates on flammable liquid fires. He found that higher flow rates were needed for extinction of larger liquid fires, but that there was no advantage in increasing pressure for these type of fires. The application of spray however does have to meet certain conditions, particularly with regard to droplet size. Rasbash and Rogowski (13) conducted a series of tests in 300 mm diameter open vessels with flammable and combustible liquids of 50-60 mm thickness.

Figure 8 shows the plots of the gas/oil mixture and kerosene indicating significant control and extinguishment within one minute of spray application. Of significance in road tunnel applications is the approximately 50% drop in temperature below the surface of the burning liquid within 15 seconds after activation.

Figure 8. Temperature/time records below surface of burning liquid extinguished by water sprays.

Oil thickness varied from 50-60 mm thickness. The correlation of the critical parameters is established in the extinction time formula, Equation 4. The terms are defined as shown.

\[ T = 34,000 \times \left( \frac{D}{M} \right) \left( \frac{Y}{\Delta T^{1.75}} \right) \]  

<table>
<thead>
<tr>
<th>T</th>
<th>Extinction time.</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Median drop size</td>
</tr>
<tr>
<td>M</td>
<td>Flow rate</td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>Temperature difference between ambient and liquid fire point.</td>
</tr>
<tr>
<td>Y</td>
<td>Preburn time</td>
</tr>
</tbody>
</table>
One of the difficulties with this method is that it requires the difference between ambient temperature and the fire point. For Class I flammable liquids such as gasoline, the fire point is below ambient temperature.

Rasbash, Rogowski and Stark (14) conducted tests of additional liquids including alcohols and gasoline. Since gasoline is the most common liquid transported, attention will be focused on that. The tests were similar with 50-60 mm (2.0-2.4 inch) thick pools involved. Equation 5 and Equation 6 for gasoline and kerosene respectively were developed from regression analysis of the various tests. The additional term A is the entrained air velocity cm/sec.

Purtori (15) used particle tracking and laser-induced fluorescence to measure droplet sizes in standard sprinklers. Data showed a median droplet diameter range of 0.261 mm (0.010 inch) to 0.212 mm (0.008 inch). For purposes of this example, 0.261 mm (0.010 inch) will be used. Entrained air current is not a common value. Rasbash, Rogowski and Stark measured this for several sprinklers and the lowest value was approximately 160 cm/second (5.2 fps).

Gasoline
\[
t = 6.1 \times 10^{12} \times \left( \frac{D^{4.5}}{M^{2.1} A^{0.5}} \right)
\]  \hspace{1cm} (5)

Kerosene
\[
t = 2.6 \times 10^{5} \times \left( \frac{D^{6.9}}{M^{0.5} A^{3.2}} \right)
\]  \hspace{1cm} (6)

The context of this previous work has been to extinguish flammable liquid fires quickly, typically in less than one minute. However, road tunnels are different.

Figure 10 shows a significant drop in the time to extinguish a gasoline fire with a water application rate of 4 mm/min. At 6 mm/min., a reasonable design value, it is in the seven to eight minute range, consistent with expectations for solid fuel fires. Figure 10 also shows the points identified for two water application rates, one typical of that used for HGV fires and the other stipulated by NFPA 15 for flammable liquid fires. It should be noted that the prescriptive requirement of NFPA 15 is about double the HGV rate.

![Figure 10](image.png)

**Note:** Refer to Figure 4 for conversion of mm/min to gpm/square foot.

**Figure 10.** Time in seconds to extinguish a gasoline fire for various water application rates.
POOL-SPREAD CHARACTERISTICS
Like all fires, the heat release rate is dependent on the rate of fuel vaporization to mix with available air. Liquid fuels in contrast to solid fuels do not have an inherent surface area available for vaporization but conform to the surrounding boundaries. For roads, this means the liquid will follow the slope and will be limited by elements such as curbs, drainage channels, etc. that define the liquid surface boundary area. For this reason, an understanding of how a liquid fuel spreads on a surface is extremely important.

Pool spread and depth
The above referenced tests were done on liquid pools of 50-60 mm (2.0-2.4 inch) thickness. Most of the research has been performed on these relatively thick pool fires. A tanker incident in a road tunnel is more likely to cause the liquid to flow from the tank onto the roadway surface, more accurately described as a spill of much thinner thickness. Mealy (16) has shown that flammable liquid spills reaching their spread limits have a nominal thickness of about 0.7 mm (0.03 inch).

Figure 11. Film thickness for one to five percent slopes.

Film thickness over time

Note: 0.003m is approximately 0.12 inches.
Figure 11. Film thickness for one to five percent slopes.

The typical design tanker fire is considered to consist of a tank rupture either from a penetration or nozzle removal. This causes the liquid to flow through the nozzle and onto the roadway. An analysis of gasoline spilling onto a slope was performed to determine liquid thicknesses. The initial flow from the tank was considered as a flow through an opening and was determined for a series of circular openings. A 1-meter static head was assumed as the starting condition. These conditions were used to establish the flow and fluid velocity. The Navier-Stokes equations were used to determine the flow velocity based on gasoline fuel. Five increasing slopes were calculated, starting with one percent. This is a common roadway slope that allows surface water to drain. The maximum was five percent, one that can define a superelevation as well as a steep general road slope. Figure 11 shows these film thicknesses over time. Note that they drop fairly quickly from the spill to
less than 2 mm (0.08 inch) after 75 seconds. Given the previous water application rates in Figure 10, the proportion of water to gasoline rises rapidly. A spill will flow out from the source. Assume for this exercise that the spill flows in two directions and forms a quarter circle of radius 1 meter, with area as shown in Figure 12.

![Figure 12. Spill area for one to five percent slopes.](image)

By understanding the dynamics of liquid fires, mitigation effects can better be understood. Because liquids are unconfined, they can easily spread increasing the surface area and vaporization, leading to potentially very high heat release rates. Therefore, a mitigation can be to limit the pool spread by providing frequent drainage that limits the pool area.

**TEST COMPARISON**

![Figure 13. Temperature measurements using fine water spray with and without foam.](image)

One key piece of information that had been missing until recently was a comparison of plain water...
and the foam additive. Recent testing by Lakkonen (15) has provided that information. Figure 13 shows that once the spray is applied, the temperature starts dropping almost immediately and is in the tenable range in less than a minute, no matter what medium is used.

**Eisenhower Johnson Tunnel Testing.**

Rondinelli (18) presented results from concept testing for a water-only FFFS for the Eisenhower-Johnson Tunnels in Colorado. As part of this project, a proof-test was conducted of the ability for water-only to mitigate flammable liquid fires. Figure 14 shows the compliance with a goal to constrain the FHRR to less than 35 MW. The growth rate of the heptane pool was approximately 55 MW/minute. However, in all cases, the FHRR was substantially reduced after application of the FFFS. This shows that early activation is the most important factor.

**Figure 14. Reduction in FHRR for various tests.**

Figure 15 shows one Colorado fire test in more detail. As soon as the water spray is applied, the FHRR significantly decreases. It is not known why the data stops at 350 seconds. It could have stopped recording, been manually extinguished, or burned all the fuel.

**Figure 15. Detail of scenario F2.**
Figure 16 shows the suppressed condition as the fire is much less intensive than it would be otherwise as evidenced by flame height.

Figure 16. Pan test with the water spray activated.

Figure 17 provides a more direct comparison with unsuppressed fires on the left and the reduced flames on the right with the water spray. While these tests were not a direct comparison of foam, they are another indication that water spray alone is a significant mitigation for flammable liquid fires. What is also significant is that they reinforce two important points.

- The fire growth rate is much faster than the 20 MW/minute criterion for this Project.
- The rapid detection and application is more important than the suppressant.

Figure 17. Fires before and after FFFS application.
SP Test of Flammable Road Tunnel Spill
Ingason (19) tested a spill configuration for gasoline and E85 conditions for the following scenarios:

- Free burn test determined the amount of time it took for a 6-square meter spill to be consumed.
- 10 mm/min-foam provided for a continuous fuel flow for two minutes and the application of a 10-mm/min foam and water mixture.
- 10-mm/min water provided for a continuous fuel flow for two minutes and the application of a 10-mm/min water spray.

Figure 18 shows the use of foam resulting in a significant reduction in peak fire heat release rate. However, the duration was only a small amount longer for the water application case. A similar test was done with 5 mm/min water application rate that showed little difference between the two.

Discussion
Unlike solid fuel fires, there is much more uncertainty with regard to flammable liquid fires. The application of water sprays does mitigate the effects of these fires. The question has always been how much. The other factor that should be addressed is operational complexity. These fires are extremely rare, even among fire incidents and the hard question needs to be addressed if the benefit is worth the operational complexity of foam systems in addition to that of plain water?

CONCLUSION
There are significant benefits in providing FFFS for road tunnels. They have been shown to prevent the spread of fire to non-incident vehicles and minimizing the damage to road tunnels. This has a significant benefit particularly to critical transportation corridors. Water application rate continues to be the most important design parameter and yet no guidance is provided, leaving designers to figure it out each time. The determination of this parameter is very important as water usage must be optimized, particularly for restricted water supplies. The ability of these systems to mitigate FLT fires is not as well understood. The general practice has been to restrict their use or stipulate foam suppression. Both of these practices are facing pressure due to industry increased demand for usage. In short, FFFS implementation could be greatly enhanced by two considerations:

- Providing prescriptive water application rates reducing uncertainty in criteria and objectives.
• Implementing a test program for FLT performance that would help reduce the uncertainty of system performance on these types of fires and allow greater confidence that these fires can be successfully mitigated without foam systems.

REFERENCES

An integrated approach for fire evacuation safety assessment in underground physics research facilities

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2 CERN, European Organization for Nuclear Research

ABSTRACT

This paper introduces an integrated approach for evacuation assessment of nuclear physics research facilities exposed to fire risk. The approach combines the use of a simplified egress modelling method and advanced agent-based simulations of evacuation. An integrated multi-model approach is proposed here given the varying level of complexity concerning evacuation safety in different sections of underground physics facilities (ranging from simple straight/circular tunnels to complex experimental caverns and access shafts). This paper introduces a simplified probabilistic egress model based on existing hand calculations for 1D smoke spread modelling and it suggests a procedure for its combined use with advanced agent-based evacuation simulations. This includes the use of the outputs of the simplified egress model in underground smoke-filled portions of underground nuclear research facilities (e.g. tunnel arcs) as an input for complex agent-based evacuation simulations in the underground access shafts. An exemplary application of the integrated approach is presented for the simulation of a set of hypothetical fire risk scenarios in the Future Circular Collider (FCC) at CERN. This approach is deemed to facilitate fire evacuation safety assessment in underground physics research facilities by optimizing the simulation of relevant fire risk scenarios. A discussion on the advantages and implications of the use of an integrated approach in comparison with other safety assessment methods is presented.

KEYWORD: evacuation modelling, physics research, fire safety, egress, FCC, evacuation simulation

1. INTRODUCTION

Underground physics research facilities present unique characteristics from a fire evacuation safety perspective given the combined presence of very complex areas and simple long (either circular or straight) tunnels. This varying level of complexity poses significant challenges in the choice of the appropriate method for fire evacuation safety assessment. Given their uniqueness and complexity, a performance-based design is often employed for such type of facilities in the context of fire safety [1]. The choice of evacuation models and methods for the conduction of a performance-based design approach becomes critical since it needs to consider several factors among which 1) the possibly large size of the facility, 2) the possible behavioural interactions among evacuees, 3) the egress components available and 4) the varying degree of complexity of the geometric layout of the facility.

Evacuation modelling is a useful tool for the fire safety assessment of complex facilities and it has been successfully applied in a variety of contexts and infrastructures, such as tunnels [2], high-rise buildings [3], [4], metro stations [5], etc. To date, different types of evacuation models are available for fire safety design, ranging from simple hydraulic-inspired hand calculations [6] to agent-based models [7].

A recent review conducted within the feasibility study of the Future Circular Collider at the European Organization for Nuclear Research (CERN) [1] evaluated the current capabilities and applicability of evacuation models for underground physics research facilities. The conclusion of this review was that given the varying level of evacuation complexity in these facilities, different modelling approaches
should be used in relation to the portion of the facility under consideration, i.e. a simplified modelling approach is more suitable for the evacuation assessment of tunnel arcs, while agent-based simulations are deemed to be more appropriate when there is a need to simulate evacuation behavioural interactions in complex parts of the facilities (e.g., experimental caverns, access shafts, etc.). This poses the questions of whether there is a comprehensive tool or method that could be used for an entire complex facility, i.e. a tool which is suitable for both simple and complex geometric configurations and behavioural scenarios as well. In fact, the use of an advanced agent-based modelling approach for an entire facility may lead to the waste of computational resources given the simplicity of the geometric layout in certain portions of the underground space (i.e. simple straight/circular tunnels).

Mesoscopic modelling approaches (intended here as intermediate modelling approaches between macroscopic and microscopic simulations) in pedestrian evacuation modelling are still at an early stage of development. In addition, a limited set of studies [8] has been conducted to develop evacuation models which allow hybrid spatial discretization (i.e. models which allow to switch in different parts of the geometry from coarser networks to continuous spaces) and those models are still at an early stage of research.

To address this issue, a collaboration project has been initiated by CERN and the Department of Fire Safety Engineering at Lund University with the scope of developing a set of procedures and methods for aiding evacuation safety assessment in physics research facilities. In particular, this paper presents a novel integrated multi-model approach which has been developed with the scope of optimizing computational resources and at the same time giving the opportunity to simulate complex behavioural interactions in the portions of the facilities which require such level of sophistication. The approach includes the development of a simplified egress model for the simulation of people movement in simpler smoke-filled environments which can be approximated with a 1D geometry (e.g. straight/circular tunnels) based on a 1-dimensional model of smoke spread in tunnels [9] and a procedure for its coupling with agent-based evacuation simulations.

This paper first presents the novel simplified 1-dimensional egress model and then it proceeds with the integrated modelling approach procedure. In order to exemplify the proposed methodology, an application is presented for a set of hypothetical fire evacuation scenarios in the Future Circular Collider (FCC), which is undergoing a feasibility study and that could become the largest particle accelerator in the world. These scenarios have been simulated combining the novel simplified 1D egress model and an agent-based evacuation simulator, namely Pathfinder [10].

2. METHOD

The proposed integrated multi-model approach for the evacuation safety analysis of physics research facilities is presented here (see Figure 1). The first step of the integrated approach is the identification of the design fire scenarios which would affect evacuation (e.g., type and location of the fire source), design behavioural scenarios (e.g., number, location and type of occupants, evacuation behaviour, etc.) and boundary conditions (e.g. geometric configuration, environmental conditions, technical safety systems, etc.). After these basic assumptions have been identified, a 1D smoke propagation modelling approach is adopted for the calculation of the visibility conditions as well as toxic species resulting from the design fire. Those variables have been chosen since they represent two of the main outputs from fire scenarios which would affect evacuation. The output of this modelling step is used as an input to perform simplified egress modelling calculations of people movement in smoke-filled areas. This includes the representation of the impact of smoke on people movement [11]. A simplified modelling approach is intended here as a modelling approach in which people movement is simplified into movement in 1-dimensional space.

It should be noted that physics research facilities generally include tunnels which host particle accelerators. These portions of the facilities are generally simpler than the access shafts and those are the parts in which the 1D modelling approach is suitable for use. The fire safety design of
underground nuclear research facilities often relies on the compartmentation assumption, thus the access shafts are assumed smoke-free if the fire is located in the tunnels. While the 1D approach could be in principle used also for scenarios in which the fire is in other portions of the facilities, it would be preferable to use a more complex fire modelling approach for those cases (given their complexity). The suggested integrated approach is recommended for the cases of a fire in the simpler parts of the facilities (i.e. the tunnels) and compartmentation is present.

Given the presence of compartmentation or the availability of protected zones in nuclear research facilities (i.e. protected tunnels or areas), the output of the egress modelling corresponds to the occupants’ arrival times to smoke-free areas. At this point, an advanced egress modelling approach is used to simulate the behavioural interactions in this complex spaces (e.g. experimental caverns, access shafts, etc.) in which different egress components might be available (e.g. refuge areas, stairs, elevators, etc.). The coupling is performed using the capability of agent-based evacuation models which allow the generation of the so-called occupant sources, i.e. locations in which it is possible to have agents entering the evacuation scenario at a given point in time. This corresponds to the arrival time calculated with the simplified modelling approach.

![Schematic flow chart of the integrated multi-model approach.](image)

### 2.1. Definition of the scenarios

The first step of the integrated approach consists in the identification of the scenarios to be investigated. This includes both the identification of the design fire scenarios as well as the occupant behaviour design scenarios. The boundary conditions of the scenarios need to be identified as well. These includes the basic assumptions needed for the representation of the fire (for a review of boundary conditions in fire scenarios, see [12]) as well as the definition of the occupant behavioural scenarios [13]. It should be noted that the approach presented here is designed to account for the impact that fire might have on occupants during the evacuation process, thus the definition of the scenarios should be done to identify the possible areas in which occupants might be exposed to smoke.
2.2. Smoke propagation modelling

One dimensional smoke spread calculations are used to estimate the visibility conditions in the environment as well as the toxic species produced by the fire. The equations for 1D smoke propagation modelling are taken from the work of Ingason et al. [9] where they have been presented for the assessment of smoke spread in tunnels. The first step is the calculation of the average mole fraction of the species over the cross section in relation to the position where the occupants are located. These calculations assume a transport time which is the time it takes to transport the heat from the fire location to a certain distance. Once the species produced by the fire have been calculated, it is possible to calculate the visibility in the environment (expressed often in relation to optical density [14]). The visibility is calculated relating it to the Heat Release Rate (Q) at an actual position downstream the fire at a certain time, \( \tau \). Gas concentrations are also calculated with the equations proposed by Ingason et al. [9].

In addition, the impact of toxic gases on humans is calculated using Purser’s Fractional Effective Dose (FED) concept [15], which considers the ratio between the accumulated dose of inhaled toxic species and the accumulated dose which leads to people incapacitation. In the present implementation of the model, the impact of carbon monoxide CO, hydrogen cyanide HCN and the hyperventilation effect of carbon dioxide CO\(_2\) (vCO\(_2\)) are considered. The calculation of the FED allows calculating when people reach incapacitation (i.e. they are not deemed to be able to continue walking in smoke due to the presence of toxic gases) in relation to the distance walked in a smoke-filled environment.

2.3. Simplified egress modelling

A simplified egress model is developed to represent occupant movement in simple geometric configurations. This assumes that the people in a straight or circular tunnel can only move in one direction (along the tunnel), which can be approximated with a 1D modelling approach. The model uses a distribution of pre-evacuation times and walking speeds. The walking speed is initially assumed unimpeded since the occupant loads are generally low in the tunnel arcs of this kind of facilities, and therefore there are no flow constraints. The values of walking speed are drawn for each individual from the distribution using near-random sampling techniques (Latin hypercube sampling).

As a conservative assumption, it is considered that the occupants are always in a smoke-filled environment and that their walking speeds are never higher than the smoke propagation speed. Therefore, it is necessary to represent the impact of smoke on walking speed [11]. This includes the reduction of movement abilities given the presence of smoke (and the subsequent deterioration of the visibility conditions in the environment) [16]. In fact, several research studies have proved that the presence of smoke reduces people’s walking speeds [17]–[19].

The representation of the impact of smoke on walking speed is implemented within the simplified model adopting the linear correlation suggested by Fridolf et al. [20] and that has been based on a set of evacuation experiments conducted at different levels of visibility (i.e. different extinction coefficients) [16], [18], [19], [21]. In their suggested correlation, Fridolf et al. recommend to consider 3 m of visibility as the threshold to start decreasing movement speed due to smoke (see Eq. 1).

\[
\nu = 0.31 + 0.34V
\]  

The simplified egress model makes use of Latin Hypercube Sampling to generate multiple repeated simulations of the same scenario which considers different values drawn from the assumed distributions (e.g. pre-evacuation times, walking speeds). This method was found to be suitable for probabilistic evacuation modelling [22] and it allows to evaluate the impact of repeated simulations on results [23]. The results of the model include therefore a distribution of arrival times of the occupants of the tunnel arcs to the smoke-free areas (e.g. protected corridors, different compartments, etc.).
2.4. Advanced egress modelling

The arrival times output obtained with the simplified egress model are used as an input for advanced egress modelling. This modelling approach is recommended in any part of the nuclear research facility in which more complex interactions between occupants and between occupants and the environment may take place. For this reason, agent-based modelling is deemed to be an appropriate approach to simulate human behaviour. This includes for instance the behaviour in the experimental caverns and access shafts in which multiple types of egress components might be available (e.g., refuge areas, elevators, stairs, etc.).

The coupling between the two modelling approaches requires the use of occupant sources within the agent-based model (i.e. areas in which occupants appear in the simulation at given times). The occupant sources should be located in the position where the transition between the two modelling approaches take place (e.g. this can correspond to a door entrance where people reach a protected corridor, at the access of a particular egress component, etc.). Several agent-based evacuation models [10], [24] present this functionality, thus making it possible for the user to use them for the representation of the coupling between different modelling approaches.

3. MODEL CASE STUDY

The model case study is designed to reflect a plausible geometric configuration of a portion of the Future Circular Collider (FCC), whose study is currently hosted by CERN. The FCC design is at the feasibility stage in which different geometric configuration options for high-energy circular colliders are under consideration. The length of the whole accelerator is expected to be in the range of 80-100 km and it includes four locations for experiments. The FCC is an underground facility with varying depth. The maximum expected depth of the collider is 400 m below ground.

3.1. Geometric layout and egress components

The maximum depth of the facility (400 m) is assumed for the simulation study in order to consider the most conservative case. For this reason, the access shafts in correspondence to the experimental caverns are assumed to be of 400 m of depth. The area under consideration in this model case study includes a 10 km long tunnel arc as well as one of the experimental caverns, a service cavern and the access shaft for reaching the ground level. One of the geometrical configuration options being considered in the feasibility study is the split of the tunnel arc into fire compartments of approximately 160 m. The FCC facility is a very deep underground infrastructure, thus the evacuation to the ground is performed with elevators. An elevator lobby is present in the access shaft (see yellow zone in Figure 2) in order to gather the evacuees prior reaching the ground through the elevators (see red elements in Figure 2). A handling elevator shaft of 8 m x 4 m is located behind the elevators (see grey zone in Figure 2). This area is not available for people.

![Figure 2](imageURL) Schematic representation of the geometric layout of the portion of the FCC where the access shaft is located.
Figure 2 shows a schematic representation of the access shaft area, which includes 2 elevators and a stair, the evacuation lobby and the service cavern. The 10 km tunnel arc is not in Figure 2 (it starts on the right edge of the figure), but it is included in the case study. This tunnel arc has a diameter of 4.5 m and an area of the tunnel section equal to 15.9 m². The scenario under consideration assumes the presence of a collective transportation mean to facilitate movement along the tunnel arc.

### 3.1.1. Elevators

Two occupant evacuation elevators are adopted in this case study for the evacuation of people (i.e. to reach the ground). Both elevators are considered usable during the entire evacuation duration except for one trip after 20 min in which a trip for firefighters intervention is assumed. The assumption of 20 min is based on an estimation of the time needed by CERN brigades to access such type of facility. The main characteristics of the elevators are summarized in Table 1. The assumed cabin dimension is 2.7 m x 1.9 m, with a corresponding nominal load of 35 people (this is assumed slightly lower than the maximum occupant load of 38 people).

<table>
<thead>
<tr>
<th>N. of elevators</th>
<th>Max speed (m/s)</th>
<th>Acceleration (m/s²)</th>
<th>Nominal load</th>
<th>Open+close time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4</td>
<td>0.67</td>
<td>35</td>
<td>15</td>
</tr>
</tbody>
</table>

### 3.1.2. Transportation means

The protected corridors of the tunnel arcs are equipped with a collective transportation mean consisting of a small electrical tractor (this is solution adopted also in other nuclear research facilities). The speed of the transportation mean is 20 km/h and it is able to host 6 people (1 driver and 5 passengers). The transportation means allow overtaking and to do a U-turn (needed for bi-directional movement).

### 3.2. Model input calibration

The methods and assumptions employed to calibrate the inputs for the integrated approach such as the assumed design fire, people walking speeds, pre-evacuation delays, behavioural modelling, elevator modelling, etc. are briefly presented here. The main focus of this model case study is to show an exemplary application of the integrated approach, thus no detailed information are provided concerning all assumptions adopted for the definition of the scenarios and their boundary conditions, but the implementation of reasonable assumptions is provided in order to show the applicability of the developed methodology.

#### 3.2.1. Design fire

In this case study, polyethylene was selected as reference fuel in order to represent a design fire for cables. The design fire assumes the fire spreading to up to six cable trays and a peak HRR of approximately 9 MW (considering the fire spread from one tray to the one above). The fire is assumed to be located near an access shaft in such a way that it blocks the access to the access shaft and occupants are forced to walk along the whole 10 km length of the tunnel arc). Further information concerning the HRR is available in [25]. Some of the main assumptions adopted in the 1D smoke propagation modelling are presented in Table 2. It should be noted that the main purpose of this paper is to illustrate the methodology adopted for studying evacuation safety rather than performing an actual full performance-based design of an infrastructure. For this reason, limited information is given here on the justification of the assumptions adopted in the design fire scenario (e.g. assumed materials, yields, boundary conditions, etc.). The values have been chosen in order to represent realistic conditions and they are in line with current scenarios being evaluated at CERN for the FCC.
facility. Nevertheless, different assumptions might have been made while illustrating the integrated approach.

### Table 2 Main assumptions of the design fire scenario.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature</td>
<td>20 °C</td>
</tr>
<tr>
<td>Heat of combustion (effective) - Polyethylene</td>
<td>38400 kJ/kg</td>
</tr>
<tr>
<td>Ventilation speed</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Yields of CO</td>
<td>0.06 kg/kg</td>
</tr>
<tr>
<td>Yield of CO2</td>
<td>2.76 kg/kg</td>
</tr>
<tr>
<td>Yield of soot</td>
<td>0.06 kg/kg</td>
</tr>
<tr>
<td>Mass optical density</td>
<td>230 m²/kg</td>
</tr>
</tbody>
</table>

#### 3.2.2. Design behavioural scenarios

The evacuation scenarios under consideration assume the evacuation of a single entire tunnel arc between two access shafts (10 km of length) in which 50 people are expected to be located in the arc and 150 people in the service cavern. This estimation is based on the occupant load in similar physics facilities, i.e. the Large Hadron Collider (LHC) at CERN. The occupants are assumed to walk in the smoke-filled portion of the tunnel and then access the protected corridor when reaching the cross passage allowing the access to it.

Given the expected population in the facility (which does not include children or elderly people), a uniform walking speed distribution is assumed (0.8-1.0 m/s). The maximum value of 1.0 m/s has been selected in order to keep the conservative assumption that the walking speed of people is always lower than the ventilation speed in the tunnel (i.e. people walk through smoke). A truncated log-normal distribution (min=0 s, max= 180 s, μ=60 s, σ=60 s) of pre-evacuation time is assumed for people in the tunnel arc and in the service cavern. An exception is made for three people which are assumed to be located on movable platforms in the service cavern, thus having a higher pre-evacuation time (=180 s). Research studies [26] show that this type of distribution is the most appropriate for approximating pre-evacuation times.

#### 3.3. Modelling

After the calculation of the toxic species and visibility conditions in the smoke-filled parts of the tunnel, the simplified modelling approach is used to calculate the arrival times at the smoke-free parts of the tunnels. In the simplified egress modelling, Latin hypercube sampling (implemented using the software @Risk [27]) is used for drawing the sample values from the distribution (this is based on 1000 iterations, this value has been chosen to be sufficient large in order to not have a significant impact of the number of iterations on results), while the pseudo-random sampling in the advanced model is based on the method adopted by the model itself (based on seed generation). The convergence method from Ronchi et al. [23] is employed to evaluate the stability of results in relation to the simulated number of runs. Given the need to simulate elevators, the choice of the model to use has been limited to only the models which include elevator modelling. A recent review [1] has identified the characteristics that evacuation models need to include in order to be applicable for underground nuclear research facilities. Among the models suitable for this type of facilities, the egress model Pathfinder [10] has been selected for use. Pathfinder is a continuous model (i.e. the movement in space is represented using a coordinate system) and it makes use of Reynolds’ steering model [28] for the simulation of people movement (see Figure 3).
3.4. Model results

The results of the evacuation simulations are presented in Figure 4. The step-wise shape of the results is due to the presence of elevators, i.e. people arrive to the exit in groups given the nominal load of the elevators. The evacuation is completed in less than 40 min. Results are mostly driven by the elevator journeys and waiting times in the lobby, i.e. people waiting for elevators to return from their trips.

Occupant densities have also been investigated in the elevator lobby. In fact, agent-based evacuation models permit to estimate the Level of Service (LoS) [29], which is a measure of the space usage. The highest level of service (i.e. Level of Service F, which corresponds to 0.19 people or less per squared m) is reached only in the proximity of the elevators while people are waiting for elevators (see an example of the red colour in Figure 5). In contrast, a qualitative analysis of the level of service results show that the elevator lobby is largely able to accommodate the people waiting for elevators with a level of service which reaches a maximum peak of LoS E (it does not reach LoS F).
4. DISCUSSION

The results of the case study can be used to discuss the integrated approach proposed in this paper in relation to the characteristics of nuclear physics research facilities. Simplified models allow a rapid configuration of model input setup given the simplicity of the assumptions in use. They are also generally not computationally expensive, thus allowing the simulation of multiple scenarios in a relatively short time. This characteristic is particularly valuable in case the fire safety designers are interested in investigating multiple scenarios. Simplified models are also generally associated with a higher level of transparency, given the simplicity of the assumptions used for the calculation of evacuation times. Nevertheless, their level of accuracy in capturing complex geometric layout and human behaviour is generally lower.

Advanced models allow a more accurate representation of the space given their ability to represent it in 2 or 3 dimensions. In addition, the interactions between the agents and between the agents and the space can be simulated to a higher extent given the fact that they often sub-models for the simulations of different factors possibly affecting evacuations. The examples provided in the present case study include the representation of transportation means, queuing at elevators, etc. Further sub-models could potentially be taken into consideration in these scenarios (i.e. physical exertion of occupants, complex group dynamics, the impact of the actions of staff on human behaviour, etc.). Their main limitations rely on the time needed for their calibration as well as the computational time needed for running the simulations. In some instances, the representation of fire and smoke spread interactions rely on the interaction with even more computationally demanding fire simulators [24], [30], thus possibly being associated with large computational times.

The proposed integrated modelling approach aims at making use of the advantages of both types of models. In order to apply the integrated approach, it is important therefore to select the most appropriate simplified and advanced models for the calculation. The present paper includes the use of an ad hoc developed simplified model and an existing commercial model. Nevertheless, other models with similar characteristics may be used to apply the integrated approach. To facilitate this choice, Table 3 presents a summary of the characteristics that evacuation models should include in order to simulate the evacuation process in different parts of underground physics facilities and in relation to the type of scenario under consideration.

The benefits associated with an integrated approach making use of different levels of complexity appear therefore evident, since it allows to optimize computational resources as well as the time needed for model input calibration/configuration. These would facilitate the study of a larger number of relevant fire evacuation scenarios in a relatively shorter time.
Table 3  Checklist of characteristics in evacuation models in relation to the portion of the underground physics research facilities and the scenario under consideration

<table>
<thead>
<tr>
<th>Long tunnel arcs</th>
<th>Experimental caverns with access shafts</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Quick computational time (e.g., 1D models are preferable)</td>
<td>• At least 2D representation of the space</td>
</tr>
<tr>
<td>• Easy implementation of fire and smoke effects on evacuation</td>
<td>• Representation of flow constraints</td>
</tr>
<tr>
<td>• Representation of staff behaviours (if needed)</td>
<td>• Representation of 3D elements of the space (if needed)</td>
</tr>
<tr>
<td>• Representation of social interactions (if needed)</td>
<td>• Occupant Evacuation Elevator modelling (if needed)</td>
</tr>
<tr>
<td>• Issues associated with long distances (choice of movement speeds, transportation means, etc.)</td>
<td>• Representation of ascending stair evacuation (e.g. fatigue, etc.)</td>
</tr>
<tr>
<td></td>
<td>• Representation of choice between different vertical egress components</td>
</tr>
<tr>
<td></td>
<td>(stairs vs elevators)</td>
</tr>
</tbody>
</table>

This paper should be considered a starting point for further developments of evacuation simulation approaches which includes the integration between different levels of modeling sophistication. Current research efforts in this direction are mostly focusing on hybrid spatial discretization [8], i.e. the split of space with different levels of resolution (from a coarse network to a continuous space). In contrast, the full integration of different modelling approaches in case of scenarios still need further investigations.

The case study of the design of underground nuclear research facilities is a good example of the need for such type of integrated approach adopting different levels of modelling sophistication. Nevertheless, this approach is deemed to be useful also for other types of facilities with varying levels of complexity. For instance, multi-purpose buildings where different occupancy types may be present or any other building in which varying levels of geometric layout complexity are present.

5. LIMITATIONS

The present paper focuses primarily on the use of evacuation modelling for fire-related hazards. Additional types of hazards may be present in physics research facilities (i.e. radioactive, cryogenic fluids, etc.). Their possible effects on evacuation are not taken into consideration in this paper. Nevertheless, the modelling approach present can be applicable for such scenarios in case of no interaction between occupants and these hazards.

The limitations of the individual modelling approaches still hold when considering their integration, with a possible propagation of uncertainties during the coupling of simplified and advanced models. For example, the uncertainty associated with the evacuation times calculated with a simplified model will be carried over in the calculations made with advanced agent-based evacuation models. For this reason, it is important that the user takes appropriate measures to consider the impact of those uncertainties and address them while making fire safety design decisions based on the evacuation modelling results.

6. CONCLUSIONS

The present paper introduces an integrated modelling approach for the study of evacuation safety in underground nuclear research facilities. The approach adopts a combined use of modelling approaches with different levels of sophistication. The great advantage of the methodology proposed is that it allows to explicitly model complex behavioural interactions with agent-based evacuation models in the most complex parts of the facility, while allowing rapid simplified calculations of evacuation movement in simpler parts (i.e. straight/circular tunnel arcs).
ACKNOWLEDGMENTS

This paper is part of the collaboration framework between Lund University and the European Organization for Nuclear Research (CERN), concerning the feasibility study of the Future Circular Collider (FCC) (Addendum FCC-GOV-CC-0052 (KE3193/HSE)). The purpose of this collaboration is to enhance the exchange of information for fire protection at physics research facilities. Participants belong to particle physics research laboratories (i.e. CERN, ESS, Max IV, Fermilab and Desy) as well as academic institutions. The paper presented here is part of “Work Package 4: Evacuation” of the collaboration. The authors thank all partners of the collaboration framework for their support and feedback throughout the work.

REFERENCES


Evacuation Tests with Elevated Platforms in Railway Tunnels

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ABSTRACT

In recent years an increasing amount of elevated platforms in railway tunnels has been designed. Due to the reduced height difference compared to evacuating a train directly down to the track area, elevated platforms have been highlighted as a method to increase personal safety. However, the knowledge on the actual impact of elevated platforms is based on limited experience, why there is a need of complementary basic data for input and validation within this field. The purpose of the performed experiment presented in this paper, was to study human behaviour when evacuating along an elevated platform for different scenarios. The overall project objective was to develop basic data for guidelines regarding fire safety design concerning evacuation along elevated platforms. The experiment was carried out at the subway station at Skarpnäck, Stockholm, during autumn 2016. There were a mixed population of 111 participants and in total five test scenarios were conducted. In scenario 1, 3 and 5 all the participants walked from one end of the walkway to the other. In scenario 2 and 4 the participants were divided into two groups, where one group walked (as in scenario 1, 3 and 5) from one end of the walkway to the other, while the other group started inside the train parked next to the elevated platform and joined the flow on the walkway as the first group passed the train doors. In addition to these five tests scenarios, reference tests and a survey study was performed.

The results from the experiment show that the flow rate along the elevated platform decreased as the walkway was getting narrower. This was true for all the areas where the flow was measured. The flow rate on the walkway was higher where the train was parked next to the platform, compared to where the platform was open to the track area. Together with information collected in the survey study, this indicated that the height difference between the elevated platform and the track area affected the participants. The video analysis showed that the entire width of the walkway was used to a larger extent when a train was parked next to the walkway, compared to when one side was open to the track area. This also gives an indication of the significance of the height difference.

When the participants were asked how they perceived their ability to pass others walking slower, nearly half of those who took part of the survey study experienced problems with passing others walking slower then themselves.

One of the three wheelchair users who participated in the test felt discomfort caused by the height and width of the elevated platform. In the survey, the test person indicated that the width of the walkway was of great importance for the sense of safety. The fact that the person stopped and hesitated where the train ended and it got open to the track area, indicates that the height difference between the platform and the track area also can affect the movement along an elevated walkway for persons using wheelchairs.

KEYWORD: elevated platform, elevated walkway, evacuation test, flow rate, railway tunnel
INTRODUCTION

This study was a part of the project “Elevated platforms in railway tunnels”. The project was a cooperation between RISE Research Institutes of Sweden and Brandskyddslaget. The project was initiated and financed by The Swedish Transport Administration.

In recent years an increased amount of elevated platforms in railway tunnels has been designed. An elevated platform, or elevated walkway, is a platform or walkway positioned at the same level as the floor of the train, or somewhere in between the rail top and the floor level. Due to the reduced height difference compared to evacuating a train directly down to the track area, elevated platforms have been highlighted as a method to increase personal safety. If an evacuation situation occurs, the passengers can step out on the platform and thereby avoid the situation where they have to jump out of the train all the way down to the track area. However, the knowledge on the actual impact of elevated platforms is based on limited experience, why there is a need of complementary basic data for input and validation within this field.

The purpose of the performed tests was to study human behaviour when evacuating along an elevated platform for different scenarios and the overall project objective was to develop guidelines for fire safety design concerning evacuation along elevated platforms.
THE EXPERIMENT

The test site
The large scale experiment was carried out at Skarpnäck’s subway station, located north of Stockholm. The station is owned by Stockholm Public Transport.

Since the station platform at Skarpnäck is wider than what an elevated platform in a tunnel usually is, a temporary walkway was built using screen walls placed next to the northern part of the platform edge, see Figure 1. This solution was useful when performing the experiment, since the width of the walkway could be adjusted. The total length of the screen wall creating the walkway was 93.6 m. Along the first half of the walkway a train was located on the rail track next to the elevated platform. The platform is in level with the train floor, making the height difference between the walkway and the track 1.4 m.

![Figure 1](image1)  
*Figure 1  The test site – Elevated walkway*

Since the experiment was carried out at night, there was no traffic and the station was closed, making the entire station (ticket hall and platform) available for the experiment. During the experiment the power on the tracks on both sides of the platform were disconnected and earthed. The southern part of the platform was used for building a 30 m long corridor where the reference tests were made. The corridor was built with the same kind of screen walls used to build the walkway, see Figure 2. Using screen walls, the width of the corridor could be adjusted in the same way as the walkway. Figure 3 shows a sketch of the test site.

![Figure 2](image2)  
*Figure 2  The test site – Corridor*
The subway station at Skarpnäck is equipped with three rows of light placed in the ceiling. One row is placed in the centre of the platform and the other two is located over the north respective south platform edge. Before the experiment was carried out the luminous intensity was measured on the walkway and in the corridor. The intensity varied, but was in average approximately 300 lux along the walkway and approximately 30 lux in the corridor.

Participants
The participants were recruited from the public. To spread information about the experiment both local and national radio channels, local newspapers and social media were used. Information about the experiment was also published at studentkaninen.se and within organizations that previously showed interest in participating in this type of event, for example Statistföreningen (the society of background actors) and Missing People. Teachers and students at Mälardalen University (MDH) and Royal Institute of Technology (KTH) were also contacted.

A web page was created where information related to the experiment was published. It was through this forum that the participants signed up for the experiment. When signing up, more detailed information was sent out. After receiving the information, the participants had to confirm that they still wanted to take part of the experiment. When confirming, they were added to the list of participants. In total, 300 persons signed up for the experiment. From the 300 persons, 200 were assigned and 111 were present on the day of the experiment.

In Table 1 the number of participants per test scenario is presented.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Participants</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>111</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>111</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>110</td>
<td>One of the wheelchair users chose not to take part of this test run.</td>
</tr>
<tr>
<td>4</td>
<td>110</td>
<td>One of the wheelchair users chose not to take part of this test run.</td>
</tr>
<tr>
<td>5</td>
<td>106</td>
<td>Wheelchair users were asked not to attend due to safety reasons. Two persons had to leave before this test run.</td>
</tr>
</tbody>
</table>

In Table 2, 3 and 4 general information about the participants (age, gender and disabilities) is presented. The information was collected from a survey study that was carried out after the experiment. One person chose not to participate in the survey study, why the statistics are based on the answers from the other 110 participants.

Of the 110 participants in the survey study, two persons did not disclose their age and gender. These two have therefore been excluded from the statistics presented in Table 2 and Table 3, meaning that the information summarized in these tables are based on the answers from the remaining 108 participants.
Table 2  Participants – Age

<table>
<thead>
<tr>
<th>Age</th>
<th>Participants</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 – 20</td>
<td>9</td>
<td>8.3</td>
</tr>
<tr>
<td>21 – 30</td>
<td>34</td>
<td>31.5</td>
</tr>
<tr>
<td>31 – 40</td>
<td>19</td>
<td>17.6</td>
</tr>
<tr>
<td>41 – 50</td>
<td>27</td>
<td>25.0</td>
</tr>
<tr>
<td>51 – 60</td>
<td>7</td>
<td>6.5</td>
</tr>
<tr>
<td>61 – 70</td>
<td>9</td>
<td>8.3</td>
</tr>
<tr>
<td>71 – 77</td>
<td>3</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Table 3  Participants – Gender

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th>Percent</th>
<th>Women</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participants</td>
<td>59</td>
<td>54.6</td>
<td>Participants</td>
<td>49</td>
</tr>
</tbody>
</table>

Of the 110 participants in the survey study, one person answered that he/she had both visual and hearing impairment and another person that he/she had cognitive, vision and hearing impairment. Therefore, these two persons are represented two respectively three times in Table 4.

Table 4  Participants – Disabilities

<table>
<thead>
<tr>
<th>Wheelchair users</th>
<th>Vision Impairment</th>
<th>Hearing Impairment</th>
<th>Cognitive Impairment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participants</td>
<td>Percent</td>
<td>Participants</td>
<td>Percent</td>
</tr>
<tr>
<td>3</td>
<td>2.7</td>
<td>9</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Experiment procedure

On the day of the experiment, the participants were instructed to arrive at the Central Hall in Stockholm Central Station for registration. Here they were provided with number tags (wests to put over their clothing) and were as well informed about the procedure of the experiment. After the registration, the participants traveled together in a group from the Central Station to Skarpnäck’s subway station.

When the participants arrived at Skarpnäck, the experiment started with a reference test in the corridor built on the southern part of the platform. In this test the width of the corridor was 1.2 m. The participants walked from one end of the corridor to the other, first individually and then as a group. After this, the tests along the elevated walkway were initiated. It soon became apparent that when the participants became comfortable with the surroundings, the learning effect had an impact on their behavior as they were moving faster and with less hesitation. In order to get better reference values the first reference test was repeated. This time the test was performed as a group test with no individual tests and it was repeated three times. In between the tests the width of the corridor was adjusted. In the first test the width was the same as before (1.2 m), in the second test the walkway was narrowed down to 1.05 m and in the last test the width was adjusted to 0.9 m.

The tests along the elevated walkway was divided into five scenarios, see Table 5.
Table 5 Experiment procedure – Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>All participants were instructed to walk from position A to B, see Figure 3. No further instructions were given. The width of the walkway was 1.2 m.</td>
</tr>
<tr>
<td>2</td>
<td>Half of the participants were asked to start the evacuation from inside the train (group A) and the rest of the participants (group B) were instructed to move from position A to B, as in scenario 1. When group B walked pass the train doors, group A was instructed to step out on the walkway and walk towards position B together with the others and thereby create a merging flow. The width of the walkway was 1.2 m.</td>
</tr>
<tr>
<td>3</td>
<td>The layout in this scenario was the same as scenario 1, but here the width of the walkway was 1.05 m.</td>
</tr>
<tr>
<td>4</td>
<td>The layout in this scenario was the same as scenario 2, but here the width of the walkway was 1.05 m.</td>
</tr>
<tr>
<td>5</td>
<td>The layout in this scenario was the same as scenario 1, but here the width of the walkway was 0.9 m.</td>
</tr>
</tbody>
</table>

In order to make it easier to analyze the video material collected during the experiment, the participants were told to stand in a line in numerical order before crossing the starting line in each test scenario. This made it easier to determine whether the participants passed each other during the test or not. The same procedure was also used in the reference tests performed in the corridor. The participants were clearly instructed that the numerical order only was their starting position and they were told to keep their own pace during the test runs and overtake others if needed. The exception to this structure was the persons starting in the train in scenario 2 and 4, who were randomly placed.

In order to increase the group density and make sure that the participants were affected by each other during the tests, they were forced to stand close together in a tight crowd when starting each test. This applied both to the reference tests in the corridor and the tests along the walkway.

After the experiment, the participants were asked to take part in a survey study where they were supposed to answer questions about themselves and their experiences during the experiment. Afterwards, a short lecture about fire safety in general and fire safety in tunnels in particular was held, free for the participants to join. There they also were given the opportunity to ask questions about the experiment as well as the content of the lecture.

RESULT

Flow Rate
To measure the flow rate in the corridor and along the walkway, markers (lines across the corridor/walkway) were used. The number of people crossing a line was summed up with a five second interval. The values were then converted to persons per second, see Table 6. The flow rate was measured at four positions;

- In the reference corridor (1)
- At the first part of the walkway (were the train was parked next to the walkway) (2)
- At the last part of the walkway (where it was open to the track area) (3)
- In the doorway of the train (4)

The number within the brackets refers to the position numbers in Table 6.
Table 6  
Result – Flow rate

<table>
<thead>
<tr>
<th>Position</th>
<th>Flow rate</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean value [persons/second]</td>
<td>Spread [persons/second]</td>
<td></td>
</tr>
<tr>
<td>1. Corridor (reference value)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width 1.2 m</td>
<td>1.42</td>
<td>0.8 – 2.00</td>
<td></td>
</tr>
<tr>
<td>Width 1.05 m</td>
<td>1.24</td>
<td>0.8 – 1.60</td>
<td></td>
</tr>
<tr>
<td>Width 0.9 m</td>
<td>0.9</td>
<td>0.4 – 1.20</td>
<td></td>
</tr>
<tr>
<td>2. Walkway (train)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width 1.2 m</td>
<td>1.58</td>
<td>1.00 – 2.00</td>
<td></td>
</tr>
<tr>
<td>Width 1.05 m</td>
<td>1.36</td>
<td>1.00 – 2.00</td>
<td></td>
</tr>
<tr>
<td>Width 0.9 m</td>
<td>1.06</td>
<td>0.8 – 1.40</td>
<td></td>
</tr>
<tr>
<td>3. Walkway (track area)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width 1.2 m</td>
<td>1.22</td>
<td>0.40 – 2.00</td>
<td></td>
</tr>
<tr>
<td>Width 1.05 m</td>
<td>1.00</td>
<td>0.40 – 2.00</td>
<td></td>
</tr>
<tr>
<td>Width 0.9 m</td>
<td>0.84</td>
<td>0.40 – 1.00</td>
<td></td>
</tr>
<tr>
<td>4. Doorway (train)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width (walkway) 1.2 m</td>
<td>1.00</td>
<td>0.60 – 1.60</td>
<td></td>
</tr>
<tr>
<td>Width (walkway) 1.05 m</td>
<td>0.62</td>
<td>0.20 – 1.40</td>
<td></td>
</tr>
</tbody>
</table>

To get an indication of the distribution between the flow on the walkway and the flow out of the train, the merging ratio was observed at the point where group A stepped out of the train and joined group B on the walkway. It showed that, in general, the flow rate out of the train was larger than the flow rate along the walkway. This was true in both scenario 2 and 4. In the survey study, the participants were asked if they in the experiment been in group A or B. After specifying what group they belonged to, group B got the question if they felt as if the persons evacuating the train limited their possibilities to pass the train doors. In the same way, group A was asked if the persons on the walkway limited their possibilities to step out of the train. The answers in the questionnaires showed that group B experienced a greater interference from group A, than the other way around. In general, group B saw group A as causing the difficulties that occurred in the merging flow, when they stepped out of the train. Group A generally saw it as a common problem caused by the fact that two flows merged into one.

The use of the width of the walkway
During the tests, markers (lines along the platform edge) were fixed on the floor creating intervals of 10 cm, see Figure 4. These markers were used to estimate the utilization rate of the width of the walkway by using the collected video material and count the number of participants placing their outer foot (the foot closest to the track area) in each interval.

Figure 4  The use of the width of the walkway – Markers
If a person placed the outer foot within two intervals, he/she was counted to the inner interval, unless a bigger part of the foot clearly was in the range of the outer interval. If a person clearly was within one of the intervals presented in the tables below, but it was not possible to evaluate within which one, the person was excluded from the statistics.

When analyzing the collected video material the use of the width of the walkway was observed in two positions – one in the first part of the walkway (where the train was parked next to the walkway) and one in the second part of the walkway (where it was open to the track area). In Table 7 and 8 the numbers of participants within the intervals closest to the track area in scenario 1, 3 and 5 are presented. Table 7 shows the values collected from the first part of the walkway and Table 8 shows the values collected from the second part.

**Table 7** The use of the width of the walkway – Number of participants within the different intervals (train)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>–0.1</th>
<th>0.1 – 0.2</th>
<th>0.2 – 0.3</th>
<th>0.3 – 0.4</th>
<th>0.4 –</th>
</tr>
</thead>
<tbody>
<tr>
<td>P %</td>
<td>P %</td>
<td>P %</td>
<td>P %</td>
<td>P %</td>
<td>P %</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>3</td>
<td>14</td>
<td>9</td>
<td>68</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>4</td>
<td>17</td>
<td>5</td>
<td>66</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>3</td>
<td>11</td>
<td>21</td>
<td>54</td>
</tr>
</tbody>
</table>

In this table, 17 (scenario 1), 19 (scenario 3) and 17 (scenario 5) persons were excluded from the statistics because it was not possible to evaluate from the collected video material within which interval the persons put their outer foot.

**Table 8** The use of the width of the walkway – Number of participants within the different intervals (track)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>–0.1</th>
<th>0.1 – 0.2</th>
<th>0.2 – 0.3</th>
<th>0.3 – 0.4</th>
<th>0.4 –</th>
</tr>
</thead>
<tbody>
<tr>
<td>P %</td>
<td>P %</td>
<td>P %</td>
<td>P %</td>
<td>P %</td>
<td>P %</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>16</td>
<td>83</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>4</td>
<td>11</td>
<td>8</td>
<td>71</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>2</td>
<td>7</td>
<td>12</td>
<td>81</td>
</tr>
</tbody>
</table>

In this table, 5 (scenario 1), 17 (scenario 3) and 4 (scenario 5) persons were excluded from the statistics because it was not possible to evaluate from the collected video material within which interval the persons put their outer foot.

In Table 9, a comparison between the numbers presented in Table 7 and Table 8 is presented. The numbers are specified in percent. The outer range (–0.1) is not included in this table, as it was not relevant in any of the test scenarios.

**Table 9** The use of the width of the walkway – Number of participants within the different intervals (comparison)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>0.1 – 0.2</th>
<th>0.2 – 0.3</th>
<th>0.3 – 0.4</th>
<th>0.4 –</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Train %</td>
<td>Track %</td>
<td>P Train %</td>
<td>Track %</td>
<td>P Train %</td>
</tr>
<tr>
<td>1</td>
<td>3.19</td>
<td>0.94</td>
<td>14.89</td>
<td>5.66</td>
</tr>
<tr>
<td>3</td>
<td>4.35</td>
<td>4.26</td>
<td>18.48</td>
<td>11.70</td>
</tr>
<tr>
<td>5</td>
<td>3.37</td>
<td>1.96</td>
<td>12.36</td>
<td>6.86</td>
</tr>
</tbody>
</table>
The ability to pass others walking slower

In the survey study, the participants were asked how they experienced their ability to pass others walking slower during the experiment. In Table 10, the answers from the questionnaire have been compiled. One person out of the 110 that participated in the survey, responded with contradictory answers and his/hers answers was therefore excluded from the statistics presented in Table 10.

Table 10  The ability to pass others walking slower – Summary of answers from the survey study

<table>
<thead>
<tr>
<th></th>
<th>As you walked along the elevated walkway, did you pass others walking slower than yourself?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Without any problems</td>
<td></td>
</tr>
<tr>
<td>Participants</td>
<td>10</td>
</tr>
<tr>
<td>Percent</td>
<td>9.1</td>
</tr>
<tr>
<td>But with difficulties</td>
<td></td>
</tr>
<tr>
<td>I wanted to, but could not</td>
<td>36</td>
</tr>
<tr>
<td>I did not feel the need to</td>
<td></td>
</tr>
</tbody>
</table>

In the video material collected during the experiment it can be seen that the participants did not jostle to pass others. Generally, they only passed others when a gap occurred and it became natural to overtake. Sometimes the outer part of the walkway (closest to the track area) was used. If two persons walked side by side blocking someone behind them, the person being blocked generally chose to slow down and keep his/hers position.

Possibilities for wheelchair users to evacuate along elevated platforms

There were in total three wheelchair users participating in the experiment. Their age and gender are presented in Table 11.

Table 11  Possibilities for wheelchair users to evacuate along elevated platforms – General information about the participants

<table>
<thead>
<tr>
<th>Tag number (the assigned west number)</th>
<th>Age</th>
<th>Gender</th>
</tr>
</thead>
<tbody>
<tr>
<td>619</td>
<td>64</td>
<td>Man</td>
</tr>
<tr>
<td>628</td>
<td>48</td>
<td>Woman</td>
</tr>
<tr>
<td>675</td>
<td>30</td>
<td>Woman</td>
</tr>
</tbody>
</table>

In the survey study, the participants were asked questions about how the height and width of the walkway affected them during the experiment. A summary of the wheelchair users’ answers on these questions can be seen in Table 12.
Table 12  Possibilities for wheelchair users to evacuate along elevated platforms – Summary of answers from the survey study

<table>
<thead>
<tr>
<th>Statement</th>
<th>Person</th>
<th>I agree completely</th>
<th>I partly agree</th>
<th>I partly disagree</th>
<th>I totally disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>The height difference between the track area and the walkway made me feel uncomfortable.</td>
<td>619</td>
<td></td>
<td>x</td>
<td></td>
<td>628</td>
</tr>
<tr>
<td></td>
<td>628</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt uncomfortable because the walkway was too narrow.</td>
<td>619</td>
<td></td>
<td>x</td>
<td></td>
<td>628</td>
</tr>
<tr>
<td></td>
<td>628</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The height difference between the track area and the walkway did not really affect me.</td>
<td>619</td>
<td>x</td>
<td></td>
<td></td>
<td>628</td>
</tr>
<tr>
<td></td>
<td>628</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I think the walkway was wide enough.</td>
<td>619</td>
<td>x</td>
<td></td>
<td></td>
<td>628</td>
</tr>
<tr>
<td></td>
<td>628</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The height difference between the track area and the walkway made me move more carefully than usual.</td>
<td>619</td>
<td>x</td>
<td></td>
<td></td>
<td>628</td>
</tr>
<tr>
<td></td>
<td>628</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The width if the walkway made me move more carefully than usual.</td>
<td>619</td>
<td>x</td>
<td></td>
<td></td>
<td>628</td>
</tr>
<tr>
<td></td>
<td>628</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I was afraid to get injured during the experiment.</td>
<td>619</td>
<td>x</td>
<td></td>
<td></td>
<td>628</td>
</tr>
<tr>
<td></td>
<td>628</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I was not afraid that I would fall off the walkway down to the track area.</td>
<td>619</td>
<td>x</td>
<td></td>
<td></td>
<td>628</td>
</tr>
<tr>
<td></td>
<td>628</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The height difference between the walkway and the track area did not affect my moving speed.</td>
<td>619</td>
<td>x</td>
<td></td>
<td></td>
<td>628</td>
</tr>
<tr>
<td></td>
<td>628</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The width of the walkway did not affect my moving speed.</td>
<td>619</td>
<td>x</td>
<td></td>
<td></td>
<td>628</td>
</tr>
<tr>
<td></td>
<td>628</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Table 12 it can be seen that participant 628 felt discomfort during the experiment due to the height and width of the walkway. In her questionnaire it is clear that the width of the walkway is of great importance for her to feel safe. The person talked in favor of a broader walkway than the widest one used in this experiment.

The wheelchair users moved close to the screen wall, independent of the width of the walkway and the density of people. An example of this can be seen in Figure 5, where the left picture shows an example of a situation where the density was high and the right picture shows an example of a situation where the density was low.
Figure 5  Possibilities for wheelchair users to evacuate along elevated platforms

Generally, a gap in the flow was created in front of and behind the wheelchair users, as can be seen in Figure 5. The size of the gap varied with the density of people. The gap was bigger with a lower density.

In general, the non-wheelchair users showed respects for the participants using wheelchair by paying attention and give space.

Other observations
When there was enough space for the participants to walk independently of each other, they chose to walk close to the wall. Those who knew each other beforehand often walked side by side, and others preferred to walk in a line one and one. When the density increased, the participants structured differently depending on the width of the walkway, see Table 13. Figure 6, 7 and 8 illustrates the different structures.

Table 13  Other observations – Different structures depending on the width of the walkway

<table>
<thead>
<tr>
<th>Width of walkway</th>
<th>Structure</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 m</td>
<td>Two and two.</td>
<td>6</td>
</tr>
<tr>
<td>1.05 m</td>
<td>Two and two, with an offset.</td>
<td>7</td>
</tr>
<tr>
<td>0.9 m</td>
<td>One and one.</td>
<td>8</td>
</tr>
</tbody>
</table>
In the survey study it was found that persons who knew each other beforehand, and therefore tried to stay together during the experiment, got separated in scenario 2 and 4 when the flow out of the train merged together with the flow in the walkway. The participants, who mentioned this, added a comment saying that in the experiment they continued walking, but if it had been a real situation they would have stopped and made sure that family and friends did not get left behind.
DISCUSSION AND CONCLUSIONS

The results from the experiment show that the flow rate decreases with the width of the walkway. This was true for all places where the flow rate was measured.

The flow rate at the first part of the walkway (were the train was parked) was higher than the flow rate at the last part of the walkway (where it was open to the track area) and the flow rate in the reference corridor. Both the collected video material and the survey study shows that the height difference between the walkway and the track area affected the participants. Therefore it can be assumed that the difference in flow rate between the first and the last part of the walkway is caused by the effect of this height difference. Why the flow rate was lower in the reference corridor than on the first part of the walkway has not been further investigated. An explanation could be that the light conditions were different. The lights were located above the walkway, which resulted in a luminous intensity of 300 lux, compared to the 30 lux measured in the corridor.

After studying the video material from the experiment, it can be seen that the participants did not walk close to the platform edge (no one used the 10 cm closest to the track area). This was true for the full length of the walkway, independent of the width. It was also seen that the participants walked closer to the platform edge when there was a train parked next to the walkway than they did when it was open to the track area.

When the participants were asked how they experienced their ability to pass others walking slower than themselves, 41.8 % answered that they never felt a need to overtake someone in the experiment. In an evacuation caused by, for example, fire it may have been that more people would feel the need to pass others due to the fact that the situation itself could cause more stress, but also because people who know each other would be keener on staying together.

If the participants who responded that they felt the need to pass others walking slower than themselves during the experiment (32.7 %) are summed up with those who answered that they did pass others, but with difficulties (14.5 %), nearly half of the participants (47.2 %) experienced problems with overtaking other persons on the walkway.

One out of three wheelchair users participating in the experiment one person felt discomfort caused by the height difference between the walkway and the track area as well as the width of the walkway. This person chose not to participate in scenario 3 and 4, where the width of the walkway was narrowed down from 1.2 m to 1.05 m. In the survey study she clarified that the width of the walkway is of great importance for her to feel safe, but the fact that she in both scenario 1 and 2 stopped and hesitated where the train parked along the walkway ended and as well participated in all reference tests in the corridor, independent of the width, indicates that the height difference between the walkway and the track area had an impact as well.

In order to make the evacuation process along elevated walkways more effective, the possibilities for people to overtake others walking slower than themselves, should be further reviewed. Since nearly half of the participants could not, alternatively experienced difficulties, passing others one suggestion for future studies is to investigate how the design of an elevated walkway can be improved to make overtaking easier.

The height difference between the elevated walkway and the track area affected the participants in several aspects. The flow rate decreased with the width of the walkway and the full width of the walkway was not used to the same extent where it was open to the track area, compared to where a train was parked next to the walkway. This can be derived to the reluctance to walk close to the edge of the walkway where there was a height difference between walkway and track, as the same behaviour not could be seen on the opposite side between the walkway and the wall. The height difference also affected one of the wheelchair users to such an extent that she stopped and hesitated in the middle of the walkway where it got open to the track area. Another suggestion for further work is
therefore to investigate how the walkway could be designed, and what attachments it can be equipped with, to reduce the impact of the height difference.

ACKNOWLEDGEMENTS

The experiment was performed with support from MTR Nordic AB (MTR), Stockholm Public Transport (SL) and Stockholm Greater Fire Brigade (SSBF). The authors would like to thank these organisations, and the funders – the Swedish Transport Administration – that made the full-scale tests possible to perform.

Karl Fridolf, former colleague to the authors, was the initiator of the project, performed the literature study and also performed a pilot experiment that made a profound base for the full-scale tests. Karl Fridolf should therefore be especially thanked for his contribution. Many others have also helped out during the preparation or performance of the full-scale tests, of which special thanks should be directed to fire engineer Per Rohlén who, as always, provided the authors with valuable photos and thoughts.
A Methodology for Assessing Driver Behaviour and Improving Safety and Customer Experience in Long Urban Road Tunnels

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¹Roads and Maritime Services, Sydney, Australia
²Australian Road Research Board, Sydney, Australia

ABSTRACT

Projects currently in development and/or delivery in Sydney will provide a five-fold increase in the lane kilometres of road tunnel in operation and will increase the longest possible continuous subterranean journey from 4km to above 30km. The resultant road tunnel network will deliver many possible fully subterranean routes that are longer than 20km. This paper describes a program of work that is currently underway that aims to better understand driver behaviour in long tunnels, to assess whether new aesthetic design measures should be included in long road tunnels to reduce fatigue and wayfinding risk and also to provide a methodology through which such new designs can be assessed.

Aspects of this work already complete have confirmed the state of international understanding of these issues, and the authors have gained an understanding of driver perception of current New South Wales (NSW) tunnels through user focus groups and a survey. This information will inform a user-centric tunnel design guideline which will be used for the future development of targetted design solutions. The work has included development and application of a methodology, by which proposed design measures can be tested for effectiveness. The methodology is based on the use of a driving simulator and an instrumented vehicle.

KEYWORD: road tunnels, driver behaviour, driving simulator, safety, human factors, design, aesthetics

INTRODUCTION

The number of tunnels on the Sydney motorway network has been steadily growing since the 1960s. However, projects currently underway will deliver a huge step increase in operating tunnel assets. These increasingly long tunnels require new and innovative design solutions. To understand the need to newly consider the drivers’ perspective, it is necessary to understand the step change that is underway.

The majority of the existing NSW tunnels (Table 1) carry more than than 100,000 vehicles per day despite most being uni-directional tunnels with only 2 lanes in both tubes. The resultant total of approximately 90 lane kilometres is mostly operated and maintained by private tollways concessionnaires who have leased the assets from the state.
Table 1 – Motorway tunnel lane kilometres in operation in NSW in 2017

<table>
<thead>
<tr>
<th>Motorway Tunnels (2017)</th>
<th>Year of Opening</th>
<th>Journey Length (km)</th>
<th>Lane kilometres* (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain</td>
<td>1962</td>
<td>0.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Art Gallery Road</td>
<td>1962</td>
<td>0.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Mascot (Airport)</td>
<td>1968</td>
<td>0.55</td>
<td>4.4</td>
</tr>
<tr>
<td>Sydney Harbour</td>
<td>1992</td>
<td>2.3</td>
<td>9.2</td>
</tr>
<tr>
<td>Norfolk (M2)</td>
<td>1997</td>
<td>0.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Eastern Distributor</td>
<td>1999</td>
<td>1.7</td>
<td>11.5</td>
</tr>
<tr>
<td>Dacey Todman</td>
<td>1999</td>
<td>1.1</td>
<td>3</td>
</tr>
<tr>
<td>Cleveland Street</td>
<td>1999</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>M5 East</td>
<td>2001</td>
<td>4.0</td>
<td>17</td>
</tr>
<tr>
<td>Cooks River</td>
<td>2001</td>
<td>0.55</td>
<td>2.2</td>
</tr>
<tr>
<td>Cross City</td>
<td>2005</td>
<td>2.1</td>
<td>10.4</td>
</tr>
<tr>
<td>Lane Cove</td>
<td>2007</td>
<td>3.6</td>
<td>23.4</td>
</tr>
<tr>
<td>St Helena</td>
<td>2016</td>
<td>0.45</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-</strong></td>
<td><strong>-</strong></td>
<td><strong>89.5</strong></td>
</tr>
</tbody>
</table>

*For example, the Sydney Harbour Tunnel is a 2.3km long tunnel with two lanes in each of two tubes. It therefore has 2.3km x 2 lanes x 2 tubes = 9.2 lane kilometres

The existing assets have been developed with ‘air gaps’ between tunnels so that no existing journey exceeds the 4km end-to-end length of the M5 East Tunnel. Figure 1 illustrates the discrete nature of tunnels on the current network. It shows the existing M1 corridor through Sydney central business district consisting (north to south) of the Sydney Harbour (2.1km), Domain (0.4km), Art Gallery Road (0.4km), Eastern Distributor (1.7km), Cross City (2.1km), Cleveland Street (0.4km) and Dacey Todman (1.1km) tunnels. The tunnels are highlighted in red. The tunnels are mostly in a north-south alignment except the Cross City Tunnel which is east-west.

Figure 1  Example of the discrete tunnels that make up current network
In-tunnel Aesthetic

Current tunnels in Sydney have a disciplined simple internal aesthetic. Their design seems to have evolved to minimise the number of design elements, presumably with the intention that this will minimise driver distraction. The design of the tunnel environment seems controlled to the point that drivers are needed to exclusively focus on the driving task. The result is, for the current suite of relatively short tunnels in Sydney, that drivers have a very defined, yet ‘vanilla’, visual experience. Figure 2 shows a drivers view of the M5 East Tunnel (opened 2001). Readers will note the lack of carriageway shoulders, the ‘architectural’ panelling and the single line of continuous fluorescent lighting. There is an emergency walkway protected by safety barriers on the right hand side of the carriageway.

![Figure 2 Typical in-tunnel aesthetic of existing NSW Tunnels](image)

A risk of driving in significantly longer tunnels is that drivers, if experiencing this simple aesthetic over lengthy sections of their subterranean drive, might become become dis-engaged by the blandness of these surroundings possibly leading to distraction from the driving task. A sense of boredom or fatigue associated with the monotony of the experience may lead to poor driving behaviours. Also of note with regard to the existing tunnels is that decision making points within the tunnels are very few. Decision points are where the driver has a choice of either to continue in the main carriageway or divert onto a ramp. Of all the tunnels only one, the Eastern Distributor, has more than one decision point. In comparison to the Eastern Distribution which has two decision points in the southbound direction, future tunnels will have potential routes with many driver decisions points.
FUTURE ROAD TUNNELS

As of January 2018 there are three major projects in construction which, if taken together, would exceed the lane kilometerage of existing operational motorway tunnel assets. The NSW state government has committed to deliver two more similar-scale projects by 2023. In addition to this, planning approval for three further very large road tunnels infrastructure projects is being sought in 2018. If added to the current operating road tunnel assets, all these projects will result in a five-fold increase in the tunnel network (by lane kilometres).

Table 2 – Future motorway tunnel lane kilometres in NSW

<table>
<thead>
<tr>
<th>Motorway Tunnels</th>
<th>Possible Year of Opening</th>
<th>Approx Maximum Journey Length (km)</th>
<th>Approximate Lane kilometres (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4 East</td>
<td>2019</td>
<td>5.5</td>
<td>36.2</td>
</tr>
<tr>
<td>NorthConnex</td>
<td>2019</td>
<td>9.0</td>
<td>41.1</td>
</tr>
<tr>
<td>New M5</td>
<td>2020</td>
<td>9.0</td>
<td>51.8</td>
</tr>
<tr>
<td>M4M5</td>
<td>2023</td>
<td>7.5</td>
<td>59.4</td>
</tr>
<tr>
<td>Rozelle Interchange</td>
<td>2023</td>
<td>3.0</td>
<td>44.0</td>
</tr>
<tr>
<td>Western Harbour Tunnel</td>
<td>tbc</td>
<td>7.0</td>
<td>40.7</td>
</tr>
<tr>
<td>Beaches Link</td>
<td>tbc</td>
<td>7.5</td>
<td>61.1</td>
</tr>
<tr>
<td>F6 Extension (Stage A)</td>
<td>tbc</td>
<td>3.5</td>
<td>19.0</td>
</tr>
<tr>
<td>(Subtotal - Existing)</td>
<td></td>
<td></td>
<td>(89.5)</td>
</tr>
<tr>
<td><strong>Future Total</strong></td>
<td></td>
<td></td>
<td><strong>442.8</strong></td>
</tr>
</tbody>
</table>

* Planning approval and construction contracts for these projects are not yet confirmed. Therefore, the tunnel length and lane kilometerage is estimated.

Furthermore, all but one of the new tunnel assets would be joined together to form an extensive subterranean motorway network. Figure 3 shows the resultant fully-subterranean section of the motorway network.

Figure 3  Future road tunnel network in Sydney (dashed lines indicate new tunnel infrastructure)

Duration of Subterranean Journey

Due to the length of the underground network and the number of on and off-ramps there are a great many different underground routes. Most of these will be in excess of the longest current underground journey possible in NSW. There will be a number of potential journey routes that are in excess of 20km. Most of these routes will also be heavily trafficked. Table 3 takes a small sample of the many potential future journeys to illustrate the possible journey times.
Table 3  Sample future road tunnel journeys: Approximate duration of subterranean journey for a range of average speeds

<table>
<thead>
<tr>
<th>Entry Portal</th>
<th>Exit Portal</th>
<th>Approx. Journey Length</th>
<th>40(^a) km/h Average</th>
<th>60(^a) km/h Average</th>
<th>80(^a) km/h Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>New M4 (West)</td>
<td>St Peter’s Interchange (Airport)</td>
<td>12.5 km</td>
<td>18.8 mins</td>
<td>12.5 mins</td>
<td>9.4 mins</td>
</tr>
<tr>
<td>F6 Extension</td>
<td>North Sydney</td>
<td>17 km</td>
<td>25.5 mins</td>
<td>17 mins</td>
<td>12.8 mins</td>
</tr>
<tr>
<td>St Peter’s Interchange (Airport)</td>
<td>Beaches Link (Balgowlah)</td>
<td>21 km</td>
<td>31.5 mins</td>
<td>21 mins</td>
<td>15.8 mins</td>
</tr>
<tr>
<td>Beaches Link (Balgowlah)</td>
<td>New M5 (West)</td>
<td>32 km</td>
<td>48 mins</td>
<td>32 mins</td>
<td>24 mins</td>
</tr>
</tbody>
</table>

\(^a\)Posted speeds for main carriageway will be 80kph while posted speeds for ramps will be 60kph.

Decision points along the route will assist in ‘breaking up’ the journey into shorter sections. The longest section where the driver has no decision to make will be an approximate 7.5km section at the western end of the New M5. There are many other sections where the typical distance between decision points is approximately 4km.

**Wayfinding**

The new subterranean network will have the Rozelle Interchange at its centre. This interchange provides connectivity that is fundamental to the operation of the network. Drivers travelling north from the New M5 will choose between four possible directions at the Interchange, whereas drivers travelling east along the New M4 will have the choice of three directions.

Figure 4  Rozelle Interchange [1]

Wayfinding on the road network is typically provided by a mixture of driver knowledge / experience, traditional signage and technology solutions such as Global Positioning System (GPS). Signage and GPS may be more heavily relied upon when a driver is less familiar with a route, while a driver who has travelled a route on many occasions is less likely to require such prompts.
**Decision Points**

The extended length of the future underground network will also mean that there will be an increased number of directional decisions that drivers will need to make along their subterranean routes. Table 4 identifies the number of decision points that drivers will negotiate along each of the sample routes introduced in Table 3.

<table>
<thead>
<tr>
<th>Entry Portal</th>
<th>Exit Portal</th>
<th>Approx. Journey Length (km)</th>
<th>No. of Decision Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>New M4 (West)</td>
<td>St Peter’s Interchange (Airport)</td>
<td>12.5</td>
<td>4</td>
</tr>
<tr>
<td>F6 Extension</td>
<td>North Sydney</td>
<td>17</td>
<td>5</td>
</tr>
<tr>
<td>St Peter’s Interchange (Airport)</td>
<td>Beaches Link (Balgowlah)</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>Beaches Link (Balgowlah)</td>
<td>New M5 (West)</td>
<td>32</td>
<td>7</td>
</tr>
</tbody>
</table>

*Decision points are defined as where the driver needs to make a determination as to whether to remain on the main carriageway or use a ramp*  

**Tunnels and GPS**

Many drivers use Global Navigation Satellite System (or Global Positioning System (GPS)) to assist with route finding and optimising travel times. These systems require line of sight operation (to satellites) and multiple satellite signals are required for trilateration (positioning). While motorists might expect continuity of GPS service for using in-vehicle navigation systems, currently satellite signals are lost once a vehicle enters a tunnel as there is no ‘rebroadcast’ of GPS signals in tunnels.

Existing systems can respond to this lack of capability by estimating position via a ‘dead-reckoning’ process. The estimation is based on other sensors (speed, compass, accelerometer etc), and the accuracy of the estimated position varies based on:

- Quality of algorithm
- Availability of other sensors
- Driver behavior / traffic conditions
- Duration of trip (without GPS coverage).

The calculated dead-reckoning position error increases over time when GPS signal is not available. Travelling the distances envisaged in the future Sydney tunnel network will therefore be more likely to result in navigational errors, especially at complex underground interchanges such as Rozelle Interchange.

Smart phone devices may provide improved position information using a combination of:

- GPS
- Mobile phone carrier
- Wi-Fi networks
- Bluetooth.

There are a number of options being considered for how reliable GPS navigation might be achieved. Ideally, these options will be compatible with existing GPS receivers so that the greatest range of users will benefit. Options include:

- GPS Repeaters within the tunnel
- Pseudolites (a small transceiver used to create a local, ground-based GPS alternative) for GPS-based navigation within the tunnel.
There is therefore both the need to consider research to establish technology solutions but also to consider whether additional wayfinding assistance (signage) is needed to offset the loss of technology solutions.

POTENTIAL DRIVER BEHAVIOURS IN LONGER TUNNELS

Driving in longer future tunnels may result in a range of driver behaviours which are different to those exhibited on surface roads or in shorter tunnels. Aspects of road tunnels that might result in different driver behaviours include:

- Longer journeys
- More subterranean decision points on the journey
- Longer subterranean journey sections without decision points or other driver engagement.

Research shows that drivers behave differently in tunnels than surface roads [2, 3]. While in tunnels some drivers may feel the need to compensate for a higher (or lower) driving workload (cognitive load). Table 5 proposes some of the potential exaggerated behaviours that some drivers may experience when driving through longer tunnels. The table also aims to identify possible customer experiences of having to adjust behaviour for long periods. Output from user focus groups and a questionnaire survey both undertaken as part of this work will report feedback from drivers’ real experiences and confirm the driver behaviours actually experienced. Superimposed on the table are responses provided by Focus Group participants (see later section of this paper for further information). If tunnel users feel a heightened sense of anxiousness and need to concentrate more when the journey extends into short tunnels, then perhaps there will be a heightened effect in longer tunnels.

<table>
<thead>
<tr>
<th>Possible Adapted Behaviours Driving In Tunnels</th>
<th>Possible Customer Experiences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alert#</td>
<td>Anxious#</td>
</tr>
<tr>
<td>Relaxed#</td>
<td>Monotony</td>
</tr>
<tr>
<td>Boredom#</td>
<td>Fatigue / Tiring#</td>
</tr>
<tr>
<td>Distracted#</td>
<td>Stress#</td>
</tr>
<tr>
<td>Apprehensive / Cautious#</td>
<td>Claustrophobic#</td>
</tr>
<tr>
<td>Confused#</td>
<td>Disorientedated</td>
</tr>
<tr>
<td>Aversion# (light)</td>
<td>Frustration# (erratic traffic)</td>
</tr>
<tr>
<td>Stimulated</td>
<td>Convenience#</td>
</tr>
<tr>
<td>Concentration#</td>
<td>Gloomyness#</td>
</tr>
<tr>
<td>Speed</td>
<td>Safe (bad weather)#</td>
</tr>
<tr>
<td>Slow</td>
<td>Fear / Danger#</td>
</tr>
</tbody>
</table>

*Behaviours reported in Focus Groups in response to ‘how do you feel when driving in tunnels?’ based on experience of existing shorter tunnels.

Thus far, this paper has described the future subterranean road tunnel network planned for Sydney as well as identifying potential risks associated with driver behaviour in such long tunnels. The remainder of the paper sets out the methodology established to further understand the problem and to develop mitigating solutions.

A survey by Christensen et al, and referenced in [4], indicated that tunnel length affected the amount of fear they experienced. Survey respondees had more problems with driving in tunnels as the length of the tunnels increased. About 8% of the respondees indicated that they experienced strong anxiety, in some cases leading to phobic feelings.
PROJECT OBJECTIVES

While our experience tells us that humans will readily adapt to the new circumstance of driving in substantially longer tunnels, perhaps these longer journeys might increase driving risks for some of the driving public. The Austroads Tunnels Task Force and Roads and Maritime Services of NSW separately identified a need to further understand the likely response of drivers to driving through future longer tunnels. A program of work was devised with the assistance of road safety human factors experts from the Australian Road Research Board (ARRB).

The objectives of the program of work are:

1) To better understand safety risks related to driver behavior in longer road tunnels,
2) To guide the design of future long road tunnels with respect to these safety risks,
3) To understand road user’s perception of tunnels
4) To respond to stakeholder and community concerns about driving in long road tunnels in a robust scientific manner,
5) To mitigate safety risks and improve the customer experience by facilitating in-tunnel aesthetic designs that:
   a. Establish the road tunnel journey as an event
   b. Create subterranean landmarks
   c. Facilitate wayfinding
   d. Alleviate monotony in those longer sections of road tunnels that are without merge / diverge decision points
6) To establish a methodology through which such designs can be assessed for effectiveness and justified operationally.

Program of Work

The program of work is set out in Figure 5 below. Elements of the work have been informed by a number of different project participant organisations. The main deliverables are the User-Centric Design Guide and the Design Assessment Methodology, though the Literature Review and the User Needs Analysis are also project deliverables. Further discussion about the content and intent of the program is included below.
Literature Review

The first task in the program of work is to undertake a literature review. This has established the state-of-the-art by identifying and reviewing:

- Relevant human factors guidelines, checklists, standards or other documents
- Any literature on the impact of tunnel designs on driving performance and safety
- Any literature on studies that have been undertaken to rapidly prototype and evaluate road tunnel design concepts
- Any articles, reports and other documents that report research and initiatives undertaken to design and evaluate tunnel designs from a user-centred perspective.

The work also included consultations with international human factors experts that have had experience in user-centred tunnel design and evaluation. The expert consultation revealed the following key findings:

- There are no known checklists or guidelines to guide the user-centred design or evaluation of tunnels to optimise the user experience and safety
- European guidelines and studies mainly focus on safety and human behaviour in case of emergencies [5, 6]
- Simulator experiments have been used to inform the design of road tunnels including Stockholm Bypass [7, 8, 9]
- The experts provided further guidance that has assisted in designing the focus groups and survey.

The literature review and expert consultation tasks are complete.

User Needs Analysis

In order to optimise tunnel design from a user-centred perspective, it is necessary to understand the needs of users; that is, to determine what they do and do not like about driving in existing tunnels, and to determine what they need and would like to see in future tunnels. This information can be used to inform refurbishment of existing tunnels, and to inform and justify design requirements for new tunnels. It can also be used to inform tunnel-related community education programs. The feedback provided will be heavily influenced by driver experience of existing shorter tunnels.

This project uses two methods for eliciting and collecting this information: focus groups and survey.

Focus Groups

Focus groups are organised discussion groups, which are generally used to understand the collective attitudes, feelings and beliefs of a sample of the community regarding a specific topic. The primary advantage of employing focus groups in this project is to elicit a wide range of free-flowing and unconstrained issues and opinions about tunnel use which cannot be revealed through other methodologies. To obtain a diverse range of opinions and views regarding tunnels, focus groups were assembled primarily based on:

- The types of vehicles used by tunnel users (e.g. car/SUV, motorcycle, heavy vehicle)
- The regularity of use of tunnels.

It was determined that user groups should be assembled based on the frequency of the participants’ use of tunnels. Having more frequent users of tunnels in the same focus group as less frequent users may result in more frequent users being dominant as a result of their greater familiarisation with tunnels. As a literature review failed to identify precedent on how to differentiate by frequency of use, it was left to the project team to determine how this might best be done. As a result, it was determined by the project team including the project manager that frequent users were defined as those that
drive/ride through tunnels more than twice a week and an infrequent tunnel user was defined as one that drives/rides through tunnels approximately twice per month.

In designing the focus group study, the international experts recommended that the focus groups be kept as homogenous as possible based on drivers’ gender. They also suggested that the focus groups should include elderly drivers (aged 65 years and more) as they may perceive the tunnel experience differently from younger drivers. Therefore, seven focus groups were conceived:

- Car / SUV drivers – Frequent users – Male only
- Car / SUV drivers – Infrequent users – Male only
- Car / SUV drivers – Frequent users – Female only
- Car / SUV drivers – Infrequent users – Female only
- Elderly car / SUV drivers – Mix of frequent and infrequent users – Mix of male and female
- Motorcyclists – Mix of frequent and infrequent users – Mix of male and female
- Truck drivers – Mix of frequent and infrequent users – Mix of male and female

The information revealed through the focus groups has helped inform the design of a large-scale survey that will be sent out to a much larger segment of the NSW driving population. In order to elicit relevant discussion in the focus groups a set of twelve questions was developed. The questions included:

- Why do you use tunnels?
- How do you feel when driving in tunnels?
- What encourages / discourages you from using tunnels?
- Do you drive any differently in tunnels?
- What problems do you have when driving in tunnels?

Focus Group participants were also also presented with eight tunnel design features (existing or proposed), most of which are from Scandanavian countries (samples in Attachment B). The opinion of the participants regarding each design was sought and explored. Participants also provided information about what they liked and did not like about each design feature and whether they believed they would change their behaviour at that specific location in a tunnel where specific aesthetic designs were implemented.

**Survey**

The output of the focus groups was then used to inform the design of a self-reported survey which has been administered to a much larger, representative, sample of drivers in NSW. Such surveys normally consider choices that have already been made by people in relation to a topic, but can also be used to gauge likely community acceptance of proposed new tunnel design concepts. In relation to this project, the survey will reveal perceptions, opinions and experiences of a large cross-section of individuals with experience in using existing Sydney tunnels, thus building on the findings from the focus groups.

The survey will enable the collected respondent information to be broken down by different demographics, such as gender, age, socio-economic status, and place of residence. The survey will also enable information collected from frequent and infrequent tunnel users. Understanding the difference between these populations will provide important information about existing tunnel design features that might deter motorists from using existing tunnels. It might also provide information about how to encourage tunnel-phobic drivers to use tunnels. The survey will be designed to capture a broad range of information revolving around those issues discussed in the focus groups, and additional issues deriving from the literature review and expert consultations.

The procedure for designing and implementing the survey involves the following activities:

- Determination of survey items (i.e. which questions and hypothetical scenarios) that will be required. Survey items are based on the outcomes of the literature review, the expert consultations, and the focus groups.
• An online survey provider, will be subcontracted for completion of the survey by a sample of 500 respondents in NSW. Demographic parameters will be given to the subcontractor to ensure the sample of respondents are representative of the NSW driving public.
• Data from the contractor will be downloaded, cleaned and coded.
• Data will be analysed using inferential statistics and the outcomes, which will directly address the key research issues, will be documented.

**Driver Centric Design Guide for Road Tunnels**

Austroads’ Tunnels Task Force has developed and issued the Austroads Guide to Road Tunnels [10, 11]. The proposed output to this work is expected to be issued as an addendum to the Austroads Guide to Road Tunnels. It can therefore be used as a reference document when specifying the delivery requirements for road tunnels.

The Driver-Centric Design Guide will be informed not only by the new work undertaken in this program (i.e. the views and inputs of non-expert tunnel users) but also by the project stakeholder group which includes expertise in project development and delivery, human factors, road safety and road tunnel operations. The guide will emphasise those elements of existing tunnel design where most benefit can be gained by a renewed focus. The guide will not seek to override design or delivery standards where such standards already exist.

**Instrumented Vehicle Study (Simulator Calibration)**

It is important to understand how drivers actually behave in tunnels: whether they behave in the manner intended by the tunnel designers and, if not, why not. The intended behaviours include among other things adherence to the speed limit, wayfinding, vehicle following behaviours, response to tunnel signage and messaging and attention to activities critical for safe driving.

Prior to implementing aesthetic designs in a real tunnel, it is proposed to assess the impact of such designs on driver behaviour in a simulated environment. While there are many examples of simulators being used to inform road design [2, 3, 7, 8], it was felt necessary to choose a specific simulator and calibrate that simulator for the purpose of tunnel simulation.

The aims of the work are:
• To collect driving behaviour data in both a real and a simulated tunnel environment with an instrumented car to:
  • Better understand behaviour and performance of drivers in tunnels
  • Calibrate the use of the simulator as a means of representing real life driving behaviour and performance in road tunnels
• To validate the use of a simulator to study driving behaviour in tunnels.

Collecting data on driver behaviour in tunnels provides a database of information that can be used to:
• Review and assess existing tunnel designs
• Inform the development of design features for new tunnels that enhance safety and user experience
• Validate proposed tunnel design features (i.e. confirm through the simulator how people are expected to behave in real world conditions).

While instrumented vehicle studies have been deemed suitable for understanding driver behaviour, very few studies have utilised instrumented vehicles to investigate driving behaviour inside a tunnel [12].

Volunteer drivers will be recruited to drive an instrumented vehicle along a route which includes a specific tunnel in Sydney. A total of 18 drivers is proposed. The simulator contains a fully functioning Kia car complete with an automatic transmission, clutch, brake, accelerator and power-steering.
system. Therefore, a similar vehicle will be used as part of the instrumented vehicle test. A data acquisition system will be fitted to the vehicle and a portable eye tracking system will be used to determine what drivers fixate on when driving through the tunnel. For each driver, while driving through a tunnel, their driving behaviour (e.g. where they are looking), the behaviour of their vehicle (e.g. speed, lane position) and the behaviour of other road users with whom they interact (e.g. other drivers, motorcyclists, cyclists and pedestrians) will be recorded.

The data will be analysed afterwards to understand driver behaviour and performance in the tunnels.

**Simulator Assessment (Part A)**

In addition to the instrumented vehicle study, two simulator studies will be undertaken. Similar to the instrumented vehicle study, this first simulation study will provide information on how drivers behave and perform in tunnels to better understand issues around wayfinding, boredom and fatigue.

For this study, the advanced simulator owned by ARRB, in partnership with Curtin University in Western Australia (the ARRB/C-MUARC advanced driving simulator), will be used. The Sydney tunnel selected for the instrumented vehicle study will also be replicated in the driving simulator. This work will enable the calibration of the vehicle simulator for tunnel driving studies.

The same group of participants (i.e. the same participants that were involved in the instrumented vehicle study) will drive through the simulated tunnel environment. This is necessary to (a) increase statistical power when comparing performance between these drivers in the real and simulated tunnels (b) reduce the number of drivers required in the simulator study, and (c) yield data for Sydney drivers that compliments output from the user needs analysis and survey.

The simulator data (i.e. speed, lateral position, headway etc.) and eye tracking data will be analysed afterwards to understand driver behaviour and performance (including inattention and distraction) in the virtual tunnel. The driving performance from real tunnel to virtual tunnel will be assessed across groups.

**Simulation Assessment (Part B)**

The final piece of work is to evaluate the effectiveness of specific tunnel design features. This second simulator study will also use the ARRB/C-MUARC driving simulator. The same participants (as undertook the Part A assessment) will drive through a simulated tunnel environment with and without added features. Specific tunnel designs will be developed and superimposed on a hypothetical future tunnel. The proposed simulated tunnel alignment is included in Attachment A. It is approximately 20km long and includes a number of long intermediate sections (approximately 6km long) where there are no driver decision points. As drivers travel from south to north they will encounter aesthetic designs which aim to ‘break-up’ the journey and become subterranean landmarks along this route.

All participants will drive through the simulated tunnel. It will include the type of features for which we plan to assess driver reaction. These are:

- Long road tunnel sections without decisions points
- A series of decision points in close proximity.

There will be a ‘Basic Drive’ and the ‘Design Drive’. In the ‘Design Drive’, participants will drive through the tunnel treated with design features that are proposed to assist wayfinding, establish landmarks and ‘break-up’ long monotonous sections of straight carriageway. Some examples from international projects are included in Attachment B. At the end of the tunnel journey, the north end, drivers will be asked to navigate a series of decision points in close proximity. Aesthetic designs will be introduced to emphasise the decision point with the aim of aiding wayfinding. For the ‘Basic Drive’ all aesthetic design features will be removed.
Data obtained from the simulator study (i.e. speed, lateral position, headway etc.) and eye tracking device will be analysed afterwards to assess the impact of the implemented tunnel design feature(s) on driving behaviour and performance. This will involve statistical comparisons between driving behaviours and performances in the ‘Basic Drive’ and the ‘Design Drive’. Drivers will be asked their opinions on the effectiveness of the design measures (the user experience).

In addition, multiple drive throughs will be undertaken to gauge the response of frequent tunnel drivers. The data obtained from this study will inform how drivers interact with different design features inside a tunnel and their impact on driving behaviour and performance. It is also proposed to assess boredom and fatigue by simulating long tunnel journeys.

The drivers responses to these aesthetic designs will:
- Advise whether they meet their intended purpose
- Inform the design of any similar in-tunnel aesthetics on future projects.

CONCLUSION

This paper has described the development of an extensive road tunnel network in Sydney, Australia. Once complete, this road tunnel network will include many possible fully subterranean 20km journeys as well multiple driver decision points along those routes. For comparison, as of early 2018, the longest possible road tunnel journey in New South Wales is 4km. The paper has identified potential risks related to these long subterranean road tunnel journeys.

Having identified the potential issues, the paper has set out a methodology designed to:
- Understand the international state-of-the-art understanding of these issues
- Seek feedback on the driver experience of existing tunnels in NSW
- Inform development of user-centric design guidelines for road tunnels
- Provide a means through which designs can be assessed for effectiveness and operational justification.

The paper presents the need for and the logic used in developing this methodology. It does not present the output of the work. The output of the work will be presented in future scientific reports and papers.

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- Curtin University
- Roads and Maritime Services
- Transport for NSW
- Transurban

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- Dr Christopher Patten (Swedish National Road and Transport Research Institute)
- Dr Marieke Martens (TNO and University of Twente, The Netherlands)
- Marc Tesson (CETU, France)

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REFERENCES

ATTACHMENT A – Simulated Tunnel Alignment

Figure 6 Proposed Assessment Alignment

Proposed Alignment Design Features:

1) ‘Basic’ drive and ‘Design’ drive travel from point 1 to point 5
2) Number of decision points on ‘Basic’ and ‘Design’ drive is 4
3) Total length of Drive is approximately 20km
4) Maximum Length between decision points is approximately 7.5km
### ATTACHMENT B – Examples Of In-tunnel Aesthetic Designs

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Decision Point&lt;br&gt;<em>Norra Lanken (Northern Link), Sweden</em></td>
</tr>
<tr>
<td>8</td>
<td>Decision Point&lt;br&gt;<em>Norra Lanken (Northern Link), Sweden</em></td>
</tr>
<tr>
<td>9</td>
<td>Journey Event&lt;br&gt;<em>Eurasia Tunnel, Istanbul</em></td>
</tr>
<tr>
<td>10</td>
<td>Journey Event&lt;br&gt;<em>Lærdal Tunnel, Norway</em></td>
</tr>
<tr>
<td>11</td>
<td>Journey Event&lt;br&gt;<em>Eiksund Tunnel, Norway</em></td>
</tr>
<tr>
<td>12</td>
<td>Journey Event&lt;br&gt;<em>Fehmarnbelt Tunnel, Denmark / Germany (Proposed)</em></td>
</tr>
</tbody>
</table>
Improvements in the awareness and behaviour of road tunnel users over a ten-year period

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ABSTRACT

The safety of a road tunnel depends not only on its design and operation, but also on the users’ knowledge of the tunnel and how to behave within it. It is therefore important to assess both aspects.

In 2004, within the scope of a research project on human behaviour (ACTEURS project), the Centre for Tunnel Studies (CETU) contributed towards a qualitative survey which involved interviewing 600 road tunnel users in the Rhone Alps region (300 users of light vehicles and 300 professional drivers of heavy goods vehicles or coaches). The survey focused on users’ knowledge of the tunnel and its facilities, their awareness and understanding of safe driving behaviour in a tunnel, in addition to their knowledge of how to evacuate in the event of an incident.

Following this survey, several actions were implemented, including:

- modifications to signage and to equipment aimed at facilitating the self-evacuation of users, within the scope of major refurbishment programmes for tunnels in operation;
- the inclusion of questions on “safe driving in tunnels” in French driving tests, for professional and non-professional drivers;
- public awareness campaigns.

In order to measure the impact of the actions implemented, a similar survey was conducted in 2015. A similar panel of users was interviewed using the same questionnaire as in 2004. The tunnels concerned were the same as in the 2004 survey: two motorway tunnels and two cross-border tunnels. Additional questions were added to the initial survey, related to new equipment such as the road sign placed at a tunnel entrance, emergency exit signage and drivers’ awareness of the significance of the blue marker lights on side walls to help keep a safety distance.

In 2004, one out of every five drivers questioned considered driving through a tunnel to be a disagreeable experience. In 2015, this was seen as something trivial and 9 drivers out of ten declared that it did not bother them.

The users questioned in 2015 had a better awareness of existing safety facilities (emergency call stations, emergency exits, fire extinguishers). Almost 55 % of users spontaneously replied that the tunnel that they had just driven through had emergency exits. In 2004, this percentage was 38%.

In addition to drivers’ awareness of safety facilities, the questionnaire focused on their awareness of the behaviour to adopt in the event of an incident in a tunnel. The comparison of the results of the 2015 survey with those of the 2004 survey show that users are largely aware of the safety principles to adopt in the event of either a minor or major incident in a road tunnel.
Several scenarios were presented to users (a fire in the user’s own vehicle, a fire in a vehicle ahead, a
fire alert with a non-visible vehicle on fire). The analysis of the users’ replies enables their behaviour
to be categorized: those who actively seek to reach safety, those who adopt passive behaviour and
those who attempt to leave the tunnel with their vehicle.

The analysis of the replies of the 2015 survey shows that users are globally aware of the risk of fire in
tunnels and adopt safer behaviour in 2015 than in 2004. It can be seen that users are now aware of the
need to stop and to reach a place of safety in the event of a fire alert. This is particularly the case for
professional drivers, who are now trained in fire risks in road tunnels within the scope of mandatory
continuous training.

Nevertheless, the results show that in certain situations and notably when a vehicle ahead is on fire,
numerous drivers of light vehicles attempt to overtake the vehicle on fire, whereas in this situation
they are expected to stop and reach a place of safety, i.e. an emergency exit. At a national level, the
CETU is working on public awareness campaigns aimed at all drivers, in collaboration with operators
and road safety officers.

**KEYWORDS**: tunnel, safety, road sign, behavior, user acceptance, user understanding

**NOMENCLATURE**

CETU Centre for tunnel studies
1. INTRODUCTION

Tunnel safety has been the subject of considerable regulatory changes in recent years. The main provisions underpinned by these changes relate to technical aspects and the organisational dimension of safety management. Feedback from events in tunnels has moreover highlighted the crucial importance of paying attention to user behaviour in the design and operation of road tunnels.

These concerns are directly related to operational safety, and are the main focus of the work carried out as part of a CETU research project. The aims of this project may be summarised as follows: improving understanding of human and organisational factors and acquiring information which can be used to optimise infrastructure design and introduce the most appropriate measures for operation and user safety.

This article presents the results of two large-scale surveys carried out in 2004 and 2015 on users’ awareness and understanding of the regulatory safety equipment in road tunnels. The change in awareness of the safety distance and speed limits to be maintained in tunnels is also analysed. The study also looks at behaviour in crisis situations, in particular by comparing user reactions in different situations. These survey results were also compared with those of a similar survey conducted in Greece in 2012 via an on-line questionnaire (1,243 people replied at the time) [2]

2. THE ACTEURS PROJECT

In 2003, this work on the essential role of tunnel users led to an applied research project ([1]ACTEURS), which focused on the behaviour of users under normal circumstances and in a crisis situation.

Initiated by three alpine motorway concession companies, operating 11 tunnels in the Rhone Alps region, the aim of the project was to gain a better understanding of the interaction between users and tunnels, model users’ behaviour in normal circumstances and crisis situations and use this information to propose improvements to safety.

2.1. The large-scale survey

The ACTEURS project included a qualitative survey carried out in 2004, in which 620 tunnel users were interviewed. This survey provided information about users’ awareness of road tunnel safety and how they understood and used these structures.

For each tunnel, the questionnaires focussed on users’ knowledge of the tunnel and its equipment, their awareness and understanding of the rules for safe driving in tunnels and the behaviour they would spontaneously adopt in the event of an accident or fire alarm in the tunnel.

The results of this survey led to several actions targeting driver training and information:

- Several public communication and information campaigns on the specific nature of driving in tunnels were conducted by tunnel operators
- Since 2006, information on how to drive safely in a tunnel has been included in driver training and specific questions are asked in the theory test
- Training for professional drivers includes a module on driving in tunnels as part of both initial and continuing raining.

Other measures have been taken, directed at the infrastructure itself and the operator’s organisational practices, to make safety features more comprehensible to users. For example, indicating emergency exits by means of a green arch painted on the side wall and specific lighting systems enables users to identify and locate these safety facilities in normal traffic situations.

To measure the effects of these actions on awareness and behaviour, a new survey was carried out in 2015.
2.2. Survey methodology

The two surveys were carried out over equivalent periods of approximately three weeks in the same places, 5 motorway rest areas belonging to the three alpine motorway operators, by a service provider recruited as part of a public procurement contract. These rest areas are located near 4 tunnels, two of which are cross-border tunnels: the Mont-Blanc tunnel and the Frejus tunnel.

![Fig. 1 location of survey sites (source Google)](image)

The 2015 questionnaire was completely identical to the one used in 2004, with additional questions on training received by users, in light of the actions carried out between the two surveys. The questionnaire included closed multiple choice questions and open questions. In total, each user was asked some fifty open questions and multiple choice questions by a professional trilingual (French, English, Italian) pollster. Although the questionnaires took 20 to 30 minutes to complete, the two pollsters did not report any particular difficulty carrying out interviews.

Concerning equipment, questions about users’ understanding of the C111 tunnel sign and the blue marker lights for helping to maintain safety distances were added, as these safety devices did not exist in 2004. A question on awareness of emergency exit signs was also added.

2.3. Comparison of 2004 and 2015 results

Comparisons made within this document are considered significant in light of a confidence index of 95%.

2.3.1. Respondent profile

To ensure good comparison of the results of the two surveys, the specifications required the service provider to select a sample of users comparable with that of 2004, with about 50% of respondents being HGV drivers. Table 1 gives details of the samples of the two surveys.

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>2004 (HGV)</th>
<th>2015 (HGV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mont-Blanc</td>
<td>151 (104)</td>
<td>147 (100)</td>
</tr>
<tr>
<td>Fréjus</td>
<td>154 (137)</td>
<td>154 (136)</td>
</tr>
<tr>
<td>Vuache</td>
<td>164 (45)</td>
<td>171 (54)</td>
</tr>
<tr>
<td>Dullin / Epine</td>
<td>151 (27)</td>
<td>151 (27)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>620 (313)</td>
<td>623 (317)</td>
</tr>
</tbody>
</table>
Travel was mostly work related (63 % in 2004 and 68 % in 2015) for the predominantly regular users (60 % in 2015 compared with 55 % in 2004) especially those using a trans-alpine tunnel (Mont-Blanc and Fréjus), who made up two thirds of the users interviewed in each of the two surveys.

Table 2 shows the main nationalities of the drivers interviewed

<table>
<thead>
<tr>
<th>Nationality</th>
<th>2015</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>French</td>
<td>49%</td>
<td>73%</td>
</tr>
<tr>
<td>Italian</td>
<td>14%</td>
<td>12%</td>
</tr>
<tr>
<td>Romanian</td>
<td>6%</td>
<td>0%</td>
</tr>
<tr>
<td>Swiss</td>
<td>6%</td>
<td>2%</td>
</tr>
<tr>
<td>British</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>Bulgarian</td>
<td>2%</td>
<td>0%</td>
</tr>
<tr>
<td>Belgian</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>Polish</td>
<td>2%</td>
<td>0%</td>
</tr>
<tr>
<td>German</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>

The vehicle/nationality correlation, only possible in 2015, shows that most of the car drivers interviewed were French, Italian, Swiss or British. The other nationalities were mainly HGV drivers. Although totally absent from the 2004 survey, HGV drivers from Eastern European countries (Romania, Poland, Bulgaria) now make up a considerable proportion of the sample.

2.3.2. Respondents’ feelings when using a tunnel

In 2004, one in five people felt that using a tunnel was a demanding experience. In 2015, driving through a tunnel was seen as something trivial and nearly 9 out of 10 people felt indifferent to it. As in 2004, reasons given for finding tunnel use demanding were mainly related to stress and the narrowness of the tunnel. The length of the tunnel (Fréjus and Mont-Blanc) was not given as a reason by users, unlike in the 2004 survey.

The survey conducted in Greece in 2012 showed that 40% of users declared feeling anxious and ill at ease when driving through a tunnel.

2.3.3. Knowledge of tunnel equipment

Users were asked about the equipment available in the tunnel they had used. Compared with 2004, they knew more about the equipment provided in road tunnels. Nearly 55% of users spontaneously stated that there were emergency exits in the tunnel they had used. Compared with 39% of users in 2004, this is a statistically significant difference. As these were spontaneous responses and not presented to the user in a list or as a yes/no question, it might appear that users had really taken on board the fact that this equipment was present in the tunnels. In 2004, 12% of users mentioned the shelters compared with less than 5% in 2015. As users might have thought of shelters as emergency exits, it was necessary to compare (shelter + emergency exit) responses; between 2004 and 2015. In 2004, 311 users mentioned shelters or emergency exits, i.e. 50% of users. In 2015, 361 users mentioned shelters or emergency exits, i.e. 58% of users. The difference between 2004 and 2015 is statistically significant.
The main safety equipment available for users was mentioned by more than 50% of users.

- Telephones were mentioned by 50% of users, compared with 27% in 2004.
- Fire extinguishers were mentioned by 65% of users, compared with 45% in 2004.
- Evacuation route lighting was mentioned by 56% of users, compared with 24% in 2004.

Users were also more aware of CCTV cameras and ventilation systems. These differences are statistically significant. Traffic lights (red lights) and variable message signs were, on the other hand, mentioned less than in 2004. There is really no explanation in the case of traffic lights, which are present at each tunnel entrance but turned off.

Only 13% of users mentioned variable message signs in 2015, compared with 37% in 2004. This difference is statistically significant. Variable message signs are now very numerous on the motorway network, and it is therefore possible that users no longer perceive them as specific tunnel safety equipment. Furthermore, variable message signs are activated continually in the open air and only activated in tunnels when there is an incident. They are consequently less visible. Where other equipment is concerned, the differences are not significant.

Users were then questioned about their awareness of the existence of emergency exits. In 2004, 84% of users knew that emergency exits were provided in the tunnel they had just gone through. In 2015 this percentage was 99%. Furthermore, over 90% of respondents thought they would be safe using an emergency exit. The increase since 2004 (+ 20%) shows that users are more confident about the safety of road tunnels.

A question on how to identify emergency exits, which did not figure in the 2004 survey, was added to the 2015 questionnaire. As well as the regulatory measures (CE30 emergency exit sign in particular), the emergency exits in the 4 tunnels of the 2015 survey underwent measures to improve their visibility (green door surrounded by a green arch or an arch fitted with green neon lights or green cladding fitted with flashing lights). Almost 60% of users identified the colour green as part of a...
marker system. Users identified orange emergency recesses as places for calling the emergency services and not as emergency exits. 38% of users identified emergency exits by means of signs (CE30 emergency exit sign) located on the tunnel wall above the entrance to the emergency exit. Finally, nearly 98% of users identified the signs directing them to the emergency exits.

In the survey conducted in Greece in 2012, 8% of users declared that they had never noticed basic safety facilities such as emergency exits or emergency call stations. 28% of users declared that they would more easily identify an emergency exit if it were lit up and painted a specific colour.

2.3.4. Knowledge of traffic regulations

Concerning the speed limits in tunnels, 93% of users knew they existed in 2004, compared with over 99% in 2015. The difference is significant. More users knew about the speed limit in the cross-border tunnels than in the other motorway tunnels, in which it was often underestimated:

- In the Vuache tunnel, over 20% of users said the speed limit was 70 km/h, although it is actually 90 km/h
- In the Dullin and Épine tunnels 20% of users said 90 km/h, although the speed limit is actually 110 km/h.

In 2015, 96% of users thought it was easy to maintain this speed limit, compared with 86% in 2004. In 2004, users thought the purpose of this speed limit was to prevent collisions and to a lesser extent to reduce stopping distances (these objectives going together). In 2015, users mainly associated this speed limit with the reduction of stopping distances. This change can be explained by road safety campaigns.

Concerning the safety distance, 84% of car drivers in 2004 knew there was a minimum distance they had to maintain between their vehicle and the one in front. In 2015, it was 89%. Although there was an increase, the difference is not significant in view of the sample as a whole. On the other hand, the increase is significant for users (cars and HGVs) in the Dullin and Épine tunnels: 91% in 2015, compared with 74% in 2004.

As in 2004, regular users knew more about safe inter-vehicle distances in tunnels than occasional users. Almost 99% of HGV drivers knew of the existence of a specific safety distance in tunnels, this percentage was similar in 2004.

In 2015, nearly 97% of cross-border tunnel users knew what the safety distance was. In particular, more users of the Mont-Blanc tunnel knew what the minimum safety distance was in 2015, compared with 2004. In 2004, 18% of users underestimated this minimum distance. The difference compared with 2015 is significant. For users of the Fréjus tunnel, there was no significant change.

For the other motorway tunnels:
- 17% of users (almost all car drivers) of the Vuache tunnels underestimated this distance (35% in 2004). This is correlated to the underestimation of the speed limit. The difference is significant.
35% of users (almost all car drivers) of the Dullin and Épine tunnels underestimated this distance (44% in 2004). The difference is not significant.

In conclusion, we did not observe any significant change in the knowledge of cross-border tunnel users. Over 97% of them knew the distance they had to maintain. On the other hand, other motorway tunnel users’ awareness of the safety distance had increased. The percentage of motorway tunnel users knowing the exact distance increased from 15% in 2004 to 27% in 2015. There is a margin for improvement for car drivers using motorway tunnels though.

In 2015, 85% of users (68% in 2004) thought it was easy to maintain the safety distance. After 2004, blue marker lights were installed in tunnels to help users estimate the mandatory safety distance from the vehicle in front (2 blue lights for car drivers and 3 blue lights for HGV drivers). The disparity in speeds and heavy traffic were the reasons given by those who thought it was difficult to maintain this safety distance.

A specific question on blue marker lights was therefore added to the 2015 questionnaire. 93% of users said they had seen the blue marker lights and 89% of users knew that the blue lights were to help them maintain the safety distance.

The survey conducted in Greece in 2012 showed that recommended safety distances were not well known. In free-flowing traffic, 50% of users estimated that they were about 20 metres from the vehicle in front of them and 10% estimated that they were less than 20 metres away.

2.3.5. Results concerning safety equipment and traffic regulations

Compared with 2004, the results of the 2015 survey show that driving through a tunnel was considered as something trivial. Users had more awareness of the safety equipment and more confidence in it. They also had more knowledge of the regulations regarding safety distances and speed limits in tunnels.
3. BEHAVIOUR OF USERS IN CRISIS SITUATIONS

Users were asked about their spontaneous behaviour in a crisis situation. Several scenarios were presented to them, along with several types of reaction.

In the interests of readability and understanding, users’ answers were grouped into three categories:

- Drives away: this corresponds to one of the following reactions: I keep going to get out of the tunnel, I make a U-turn, I overtake the vehicle, or I keep going but call the emergency services or I keep going to see what is happening;
- Stops and adopts active behaviour: this corresponds to one of the following reactions: I get out of my vehicle to try to put out the fire, try to reach a place of safety, get my passengers to a place of safety, call the emergency services, or give assistance;
- Stops and adopts passive behaviour: this corresponds to one of the following reactions: I wait for the emergency services, wait for instructions from the tunnel operator, I signal to other drivers so they will come to my assistance, or I look to see what the others are doing.

3.1. If the user’s own vehicle catches fire

3.1.1. Cross-border tunnels

The Fréjus and Mont-Blanc tunnels are very long. When their vehicle catches fire, users of these tunnels are asked to stop and get to a place of safety if they are more than 1 km from the exit.

Compared with 2004, we see a real difference in behaviour since more than 90% of cross-border tunnel users said they would stop and adopt active behaviour (get to a place of safety, try to put the fire out, call the emergency services, give assistance). The percentage that would drive away is almost nil. Statistically, the differences are significant.

![Table: Cross-border tunnel behaviour comparison](image-url)

**Fig. 4: fire in user’s own vehicle – cross-border tunnels**

3.1.2. Motorway tunnels

The three motorway tunnels taking part in the survey are tunnels less than 5000 m in length. For these tunnels, when their vehicle catches fire, users are asked to try to drive out of the tunnel. If this is not possible, a good reaction is to stop and get to a place of safety.

In France, 5000 m is the threshold above which the fire and emergency services have to be placed near two-way tunnels with daily traffic of more than 2000 vehicles on average per year in at least one
direction (Technical Directive, 2000). Stopping a vehicle on fire enables the emergency services to get to the scene rapidly and the operator to make optimum use of the smoke extraction system.

First instinct:

<table>
<thead>
<tr>
<th>Motorway tunnel</th>
<th>User’s own vehicle catches fire</th>
<th>All vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vuache</td>
<td>Dullin/L’Epine</td>
</tr>
<tr>
<td>Drives away</td>
<td>2015: 12%</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>2004: 29%</td>
<td>28%</td>
</tr>
<tr>
<td>Stops and adopts active behaviour</td>
<td>2015: 85%</td>
<td>83%</td>
</tr>
<tr>
<td></td>
<td>2004: 63%</td>
<td>67%</td>
</tr>
<tr>
<td>Stops and adopts passive behaviour</td>
<td>2015: 3%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>2004: 8%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Fig. 5: fire in user’s own vehicle (behaviour on first instinct) – motorway tunnels

Like cross-border tunnels, the difference compared with 2004 is significant. The majority of users state that they would stop and adopt active behaviour (get to safety, try to put the fire out, give assistance).

Second instinct:

Users were then asked what their second instinct would be if the first was not possible. In 2015, 90% of motorway tunnel users whose first instinct was to drive away would stop and adopt active behaviour as a second instinct.

In this scenario, in the 2015 survey more users said they would stop and adopt active behaviour (get to safety, try to put the fire out, call the emergency services, give assistance), thus reducing the number of users trying to drive away or leave the tunnel. The increase is more marked in HGV drivers.

For users of the motorway tunnels involved in the study, the expected appropriate reaction as a first instinct is to drive out of the tunnel with the vehicle on fire. This is not always possible however (user stress, panic, or the user thinks the vehicle is no longer drivable) and as a first instinct, users predominantly favour stopping and adopting active behaviour, by using the safety equipment present in the tunnel. This should be correlated with increased awareness of the equipment in road tunnels.

The survey conducted in Greece in 2012 showed that in this situation, 38% of users would continue driving in order to exit the tunnel. 62% of users would stop their vehicle and engage in proactive behaviour (to extinguish the fire, alert emergency services, evacuate), similarly to the users questioned in France in 2015.
3.2. Vehicle ahead catches fire

When a vehicle ahead catches fire, the user is expected to stop and reach a place of safety by going to an emergency exit. He may also try to call the emergency services or give assistance. Under no circumstances should he stay in his vehicle.

<table>
<thead>
<tr>
<th>Vehicle ahead catches fire</th>
<th>type of vehicle</th>
<th>Car users</th>
<th>HGV drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drives away</td>
<td>2015</td>
<td>57%</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>37%</td>
<td>30%</td>
</tr>
<tr>
<td>Stops and adopts active behaviour</td>
<td>2015</td>
<td>39%</td>
<td>73%</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>61%</td>
<td>69%</td>
</tr>
<tr>
<td>Stops and adopts passive behaviour</td>
<td>2015</td>
<td>4%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>2%</td>
<td>1%</td>
</tr>
</tbody>
</table>

Fig. 6: vehicle ahead catches fire

Compared with 2004, a larger percentage of car users would try to drive out of the tunnel by overtaking the vehicle on fire.

The change in behaviour of HGV drivers is less marked. Nevertheless, we note that among HGV drivers the instinct to drive away was lower than the other two categories. This difference is statistically significant. As in 2004, nearly 70% of HGV drivers would stop to adopt active behaviour. This result shows that even more users (and an even greater increase for car drivers) would overtake the vehicle on fire. Their first instinct is not to get to safety in the emergency exits.

Users were then asked to describe their second instinct if the first was not possible. In 2015, 90% of car users whose first instinct was to drive away would stop and adopt active behaviour as a second instinct. The same behaviour was observed in HGV drivers in 2015. In 2004, the majority of users (all tunnels combined) whose first instinct was to drive away, would stop and adopt active behaviour as a second instinct.

Finally, a considerable difference in behaviour was observed in this scenario between cross-border tunnel users and motorway tunnel users. 60% of motorway tunnel users would try to drive away, compared with 20% of cross-border tunnel users.

In motorway tunnels (twin one-way tubes with several lanes in each direction), users can easily overtake the vehicle on fire, if it does not block all the traffic lanes. This explains the marked difference in behaviour between cross-border tunnel users and motorway users, as the majority of motorway tunnel users would try to overtake the vehicle on fire and leave the tunnel. Conversely, in cross-border tunnels, overtaking a vehicle on fire is only possible by breaking the no-overtaking rule and risking a head-on collision with vehicles coming in the opposite direction.

Compared with 2004, the majority of car users would try to overtake the vehicle on fire. This behaviour is particularly true in motorway tunnels, which have two lanes in each direction. HGV drivers have hardly altered their behaviour between the two surveys. As a whole, they were more compliant with instructions in 2015 and therefore fewer of them would try to overtake a vehicle on fire.

The survey conducted in Greece in 2012 showed that 27% of users declared that in this situation they would overtake the vehicle “with caution”, 25% would stop and then proceed to evacuate (proactive
behaviour) and 25% would stop and try to extinguish the fire. 18% of users would adopt passive behaviour: stop and wait in their vehicle. Finally, 5% of users would make a U-turn.

### 3.3. Alarm with no visibility of the vehicle involved

In this scenario, a fourth type of reaction was added: incredulous users who make no change to their behaviour when an alarm is sounded and carry on driving.

<table>
<thead>
<tr>
<th>fire alarm</th>
<th>type of vehicle</th>
<th>2015</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drives away</td>
<td>Car users</td>
<td>11%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>HGV drivers</td>
<td>40%</td>
<td>21%</td>
</tr>
<tr>
<td>Stops and adopts active behaviour</td>
<td>Car users</td>
<td>67%</td>
<td>67%</td>
</tr>
<tr>
<td></td>
<td>HGV drivers</td>
<td>46%</td>
<td>55%</td>
</tr>
<tr>
<td>Stops and adopts passive behaviour</td>
<td>Car users</td>
<td>22%</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>HGV drivers</td>
<td>9%</td>
<td>21%</td>
</tr>
<tr>
<td>Incredulous</td>
<td>Car users</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>HGV drivers</td>
<td>5%</td>
<td>3%</td>
</tr>
</tbody>
</table>

*Fig. 7 Fire alarm, all tunnels*

While in 2004, in the event of a fire alarm, many users would continue driving (flight behaviour and incredulity), the number was much less in 2015. Users seem to be aware that they should stop. On the other hand, nearly 25% of users (HGV and cars) would stop and adopt passive behaviour. The appropriate behaviour would be to make for the emergency exits and get to a place of safety.

In 2015, only 2 users were incredulous compared with 26 in 2004.

No significant change in behaviour has been observed between regular and occasional tunnel users.

**According to the type of tunnel**

<table>
<thead>
<tr>
<th>fire alarm</th>
<th>Cross-border tunnel</th>
<th>Motorway tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drives away</td>
<td>2015 8%</td>
<td>2004 20%</td>
</tr>
<tr>
<td></td>
<td>2015 64%</td>
<td>2004 54%</td>
</tr>
<tr>
<td></td>
<td>2015 28%</td>
<td>2004 24%</td>
</tr>
<tr>
<td></td>
<td>2015 0%</td>
<td>2004 2%</td>
</tr>
</tbody>
</table>

*Fig. 8 Fire alarm – behaviour according to type of tunnel*

In both tunnel types we see an increased number of users stopping and adopting active behaviour compared with users who keep going. The change between 2004 and 2015 is particularly marked in motorway tunnels where the number of users stating they would drive away is almost 4 times fewer.

In this scenario, nearly 90% of users in 2015 would stop and over 60% would try to get to a place of safety. In 2004, more than 30% would try to drive away and could consequently put themselves in danger. There is therefore increased awareness among users who would stop more systematically in the event of a fire alarm in a tunnel and try to get to safety.
The survey conducted in Greece in 2012 showed that in this situation, only 24% of respondents would stop and seek information or evacuate. The other respondents declared that they would slow down and continue driving.

4. CONCLUSIONS

Conducting two surveys by interview, eleven years apart and in an identical context, has made it possible to measure the change in road users’ awareness of safe driving behaviour in road tunnels and the change in behaviour in crisis situations.

The results of the 2015 survey of road tunnel users, compared with those of 2004, show that:

- Driving through a tunnel is considered as something trivial
- Users have increased awareness of safety facilities
- 99% of car and HGV drivers know there are emergency exits in the tunnels they have used
- Users have more confidence in the safety equipment
- Users have more awareness of safety distance regulations and speed limits to be maintained in tunnels.

The results of the 2015 survey also show that behaviour in crisis situations has improved, as detailed below.

In a fire in their own vehicle:

- Users have taken on board the specific features of cross-border tunnels: less inclination to drive away and a greater tendency to stop and adopt active behaviour (get to safety, call the emergency services, help other users)
- On the other hand, in motorway tunnels, the user is expected to drive out of the tunnel. Yet, responses show that users (cars and HGVs) favour stopping and adopting active behaviour over driving out of the tunnel.

When a vehicle ahead catches fire:

- We see appropriate behaviour in HGV drivers but more car drivers would be inclined to drive away, more than 50% of them would try to overtake the vehicle in order to get out of the tunnel (particularly motorway tunnels).

When there is a fire alarm with no visibility of the vehicle involved:

- We note that users are aware of the need to stop and get to safety.

In the last two scenarios the user is expected to stop and get to a place of safety by going to an emergency exit. The survey results and feedback from recent events in French tunnels show that user behaviour is inappropriate. This is particularly true for congested urban tunnels experiencing heavy traffic. In these tunnels, crisis situations requiring users to get to safety immediately are not necessary understood by the user.

This is why CETU is working to implement measures to inform all drivers in France and in collaboration with tunnel operators and road safety bodies. Measures have been taken in partnership with transport companies and professional training bodies. A training module on tunnel driving has been created. In France, this training module is included in mandatory training for professional drivers (HGVs and coaches). Available in English, it has also been distributed to member states of the European Commission.
Finally, CETU is making animated films on tunnel safety and appropriate behaviour in normal situations and crisis situations. These films will be distributed in 2018 via social networks and on dedicated accident prevention and road safety sites.

5. REFERENCES


Evaluation of road tunnel evacuation route marker light designs

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KEYWORDS: emergency escape lighting, evacuation route marker lights, evacuation, road tunnel

INTRODUCTION
The Swedish regulations regarding safety in road tunnels prescribe evacuation route marker lights not higher than 1,5 m above the carriageway level on at least one of the tunnel walls in Swedish road tunnels [1]. Recommendations on the design of these are provided in EN 16276 [2] on evacuation lighting in road tunnels, which was approved in December, 2012. Among other things, the following is stated about evacuation route marker lights (which is part of the overall evacuation lighting concept) in the standard:

To enhance the visibility in smoke, the minimum maintained luminous intensity of each marker, in all directions from which it could be seen by a fleeing pedestrian, shall be determined by their spacing. The minimum maintained luminous intensity shall be 0,1 cd for each meter of spacing between markers, with a minimum luminous intensity of 1 cd.

EXAMPLE For a distance of 15 m between two markers, the minimum maintained luminous intensity is 1,5 cd.

Within the Swedish Transport Administration, there is a concern that this minimum requirement is too low to fulfil the overall objective of evacuation lighting in road tunnels during events of failure of the ordinary power supply in general, and during fire emergencies in particular. A joint research project was therefore initiated in the end of 2016 in order to, firstly, define which performances road tunnel evacuation route marker lights should meet, and secondly, to evaluate different route marker light designs based on this and the recommendation in EN 16276 [2]. In this extended abstract, the preliminary findings of that project is presented. For a more extensive presentation, the reader is referred to the technical report produced within the project [3].

PERFORMANCE REQUIREMENTS
The main function of evacuation lighting in road tunnels is to provide guidance and visibility for people leaving their vehicles and evacuating the tunnel as pedestrians [2]. This type of lighting should function during an interruption in the ordinary power supply, but most importantly, the assistance provided by the lighting should function also in the event when there is smoke in the tunnel. Based on the findings of a literature review carried out within the project, it is concluded that evacuation route marker lights should be designed so that:

1. evacuees can orient themselves with help from the lighting, and
2. the lighting illuminate the evacuation route to a safe location.

Some information on appropriate illuminance levels are available in the literature, and is typically expressed in the interval 0.5-5 lux. These are, however, based on empirical evacuation trials carried out in building environments with no smoke. Furthermore, no information on necessary luminous
intensity levels for evacuees to be able to orient themselves with help from the lighting in a smoke exposed tunnel are available in the research.

EVALUATION OF DIFFERENT DESIGNS
In order to evaluate different evacuation route marker lights, a pilot experiment was conducted in a approximately 40 meter long and smoke filled tunnel in Revinge, Sweden. Three different point light designs and three different continuous lanelight designs were evaluated under various experimental conditions relating to luminous intensity, presence of smoke, colour of the smoke (when applicable), standby lighting, etcetera. Evaluations were made by a test group of five individuals, including the authors of this extended abstract. The evaluations were based on a pre-defined grading template including questions regarding visibility of the lights, ability to orient and move in the environment, interpretation of the lights, visibility conditions, etcetera.

The main conclusion is that evacuation route marker lights designed according to EN 16276 [2] risk not fulfilling the above performance requirements regarding orientation and illumination. In a smoke free road tunnel environment, the performances may be met, but even in this situation illumination of the evacuation route is poor. Because of the findings of this pilot experiment, it seems critical to define levels for luminous intensity as well as illumination at which these lights will provide guidance and visibility for people leaving their vehicles and evacuating the tunnel as pedestrians. Another conclusion based on the evaluations made is that continuous lights overall seem better in terms of facilitating evacuation in a road tunnel, particularly when smoke-filled. This is partly because they performed better in terms of illuminating the evacuation route, partly because they were continuous and always could be spotted, also in a smoke-filled environment. Still, the conclusions need to be verified in a full scale experiment, as the pilot experiment only provides an indication of the results. Previous experiments have, for example, revealed the benefit of point light sources along the evacuation route in a smoke filled tunnel [4].

FUTURE RESEARCH
It is recommended that future research establish explicit performance level requirements regarding both luminous intensity and illumination for evacuation route marker lights. These experiments must involve uninformed test subjects. A first step must, however, be to coordinate the current definitions both of central terms such as evacuation route, safe location, etcetera, as well as lighting terms such as evacuation lighting, evacuation route marker lights, etcetera. Currently in Sweden, these terms have different definitions depending on the regulatory framework being addressed.

REFERENCES

Analytical and Numerical Evaluation of Fire Events and Initial Aero-Thermal Conditions in Tunnels

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KEYWORDS: flow reversal, tunnel climate, natural draft, rail tunnel, tunnel fire

INTRODUCTION
Most of the existing high-speed rail tunnels in Europe have the following features:
- Not equipped with mechanical ventilation systems or intermediate ventilation shafts
- Uniform, monotonic inclination
- Single-tube, twin-track layout

In such inclined rail tunnel tubes, the flow direction of air is influenced by different pressure phenomena, for example by pressure differences induced by moving trains, by outside wind acting on the portal, by meteorological pressure differences across mountain rims, by thermal draft due to different average temperatures inside and outside the tunnel. Together, these pressures may lead to an up- or downflow of air in the tunnel during normal operation.

In case of a “hot incident” in an inclined tunnel, the draft caused by the fire leads to an upwards directed thermal pressure force. This pressure superposes with the aforementioned pressure phenomena and, depending on the strength and direction of the different pressure forces, the fire may have the following effects:
- Enforcement of the initially prevailing up-flow of air/smoke
- Weakening of the initially prevailing down-flow of air/smoke
- Turning of down-flow to up-flow of air/smoke

The air/smoke flow direction in tunnels affects the evacuation, rescue and fire-fighting activities in the tunnel. Ideally, the flow-direction does not change in an uncontrolled manner during an incident as the change of the flow direction is highly critical for the following reasons:
- Previously tenable egress and access paths are getting filled with smoke.
- Occupants and emergency services become disoriented and cannot identify the proper egress and access direction.
- The change in flow direction might lead to high flow velocities which disturb the smoke stratification in the incident tunnel.

OBJECTIVES
The likelihood of changing flow directions during a tunnel fire in a rail tunnel with monotonic inclination and without mechanical ventilation shall be presented. The effect of several parameters such as tunnel length, tunnel slope or cross-sectional area shall be statistically investigated.
Moreover, the typical tunnel length in which stratification and three-dimensional effects prevail shall be investigated to allow for a better evaluation of the hazards presented by flow reversal, as well as to obtain an insight into reliable ways of combining 1D and 3D simulation codes.

**APPROACH**

An innovative coupling between two one-dimensional validated flow software codes has been developed to allow for a calculation covering the short-term (fire thermal draft) as well as the long-term effects (climate) on flow conditions prior to and during a fire incident in a rail tunnel. Results are based on one-dimensional simulations of the tunnel. The typical daily and annual change of the aero-thermal conditions of tunnels is therefore included and accounted for in the analysis. The statistical distribution of flow is analysed regarding flow velocity and direction under the influence of the daily and annual variation of outside temperature and train induced pressure changes. The typical length of tunnel in which three-dimensional effects prevail is also studied using a validated three-dimensional flow computation (CFD) software package.

**RESULTS**

The 1D sensitivity study of properties of typical European high-speed rail tunnels demonstrates that during up to about 40% of the annual operation time, downwards directed thermal drafts may prevail leading to the critical potential for suddenly changing flow directions of smoke during the rescue phase of fire incidents. 1D and 3D fire simulations show in addition that the pre-existing flow conditions dominate the smoke propagation during several minutes, after which a sudden flow reversal due to the fire-induced thermal draft endangers evacuating users.

A key finding for naturally ventilated tunnels is that the stratification of smoke prevails for a considerable distance along the tunnel, leading to heterogeneous flow conditions and to a reduced performance of 1D flow computation in specific cases. The combination of 3D and 1D numerical tools was tested but found to be unpractical for the typical length of the single-tube tunnels in question. In untypically long tunnels and/or tunnel networks the combination of 3D and 1D numerical tools appears to be more reasonable.

In conclusion, the study to be presented allows for a better insight into the flow conditions prior to fire and the resulting likelihood and risks linked to changing flow directions during an incident.

**REFERENCES**

SES Study of Evacuation of Pollutants from Diesel freight trains at Pajares (25Km.) and Pontones (6.7Km.) tunnels

Dr. A. Ruiz-Jimenez, A. Matas
TD&T

INTRODUCTION
This is a Best Practice study, included in the Design Tunnel Ventilation System of Pajares and Pontones Tunnel HSR and Freight Diesel trains, achieved by TD&T. Pajares tunnel’s length is 24,646 Km. long, being the second longest railway tunnel in Spain, and the seventh longest in the world. This tunnel is bi-tube with a grade of 1.685%. Also, there is another tunnel close to Pajares, with the same alignment, under the name of Pontones (6.7Km. long), included in the study. The tunnels are used for HSR trains and Freight (Diesel) trains.

Ventilation design was achieved using SES (Subway Environmental Simulation) v.4.1. Because of TD&T’s special dedicated tools for Post-Processing, it has been possible to get NOx results for Diesel Freight trains. CO values have not been considered critical, as NOx values are more restrictive. Pollutant emissions rates are given, for freight trains, so emissions have been calculated. (The concentrations of NOx emitted by an engine corresponding to 10 times the concentration of NO2).

A number of pairs of jet-fans, along both tubes, including tunnels entrances was proposed, in order to achieve comfort and emergency situations in both tunnels.

RESULTS
When Diesel freight trains pass through the tunnel, it is needed to the amount of pollutant particles emitted has been obtained, after SES simulations.

A pollution study has been done according to the tunnel length, and air velocities produced by jet-fans. Particles need to be addressed out of the tunnel, but NOx concentrations get stacked in the long tunnels.

SES program provides results of NOx, when freight Diesel trains go through the tunnels. Trains headways and jet-fans velocities are changed and combined, to do the analysis. European Regulations dictate maximum value of 28 ppm for an hour. Results are displayed at tunnel exit, where the greatest accumulation of pollutants happens.
SIMULATION 3
FREQUENCY: 4 trains each 30 minutes
NO JET-FANS
SIMULATION TIME: 2 hours (7.200 seconds)

SIMULATION 7
FREQUENCY: 4 trains each 30 minutes
PAIRS OF JET-FANS (Q = 40.8 m³/s): each 800 meters
SIMULATION TIME: 2 hours (7.200 seconds)

Figure 3 Results for Pontones Tunnel.

Table 1 Summary of results for Pontones Tunnel.

<table>
<thead>
<tr>
<th>SIMULATION</th>
<th>Rate of fan</th>
<th>Distance between jets</th>
<th>Time it takes for NOx to go out of the tunnel</th>
<th>Velocity of the NOx</th>
<th>NOx Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>-</td>
<td>-</td>
<td>NOx doesn't go NOx gets stacked inside</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Q = 20.6 m³/s</td>
<td>200 m.</td>
<td>790 s.</td>
<td>7.56 m/s</td>
<td>6.10 ppm</td>
</tr>
<tr>
<td>5</td>
<td>Q = 20.6 m³/s</td>
<td>400 m.</td>
<td>1175 s.</td>
<td>5.08 m/s</td>
<td>5.23 ppm</td>
</tr>
<tr>
<td>6</td>
<td>Q = 20.6 m³/s</td>
<td>800 m.</td>
<td>1595 s.</td>
<td>3.74 m/s</td>
<td>5.23 ppm</td>
</tr>
<tr>
<td>7</td>
<td>Q = 40.8 m³/s (Higher air flow)</td>
<td>800 m.</td>
<td>885 s.</td>
<td>6.72 m/s</td>
<td>6.10 ppm</td>
</tr>
</tbody>
</table>

- The higher the air velocity inside the tunnel, the faster is the output of pollutants.
- When pollutants spend less time in the tunnel, their concentration gets higher.

SIMULATION 9
FREQUENCY: 12 trains each 20 minutes
JET-FANS: JZR-6 each 800 m (4 sequenced groups)
SIMULATION TIME: 4 hours (14.400 seconds)

SIMULATION 12
FREQUENCY: 16 trains each 30 minutes
NO JET-FANS
SIMULATION TIME: 8 hours (28.800 seconds)

Figure 4 Results for Pajares Tunnel.

- Using sequenced operation of pairs of jet-fans pairs (as shown in first graphic, in Figure 4), is the best way to get concentration out of the tunnel.
- If no jet-fans are used high concentrations (over 28ppm) will be accumulated in the tunnel exit.
- Table of results, for different simulation cases is provided at Poster (different headways, fans) inside the tunnel.
Rescue of passengers with reduced mobility – Experiments in underground stations

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KEYWORDS: passengers with reduced mobility, underground stations, fire brigade, evacuation, rescue operation

INTRODUCTION
For the evacuation of underground stations empirical research and methods for calculating the egress are available. These methods are dealing with self-evacuation of passengers who are able to use stairs and escalators. The rescue of wheelchair users and other passengers with reduced mobility may require the help of other passengers, personnel or fire crews. In this field much less data exists [2] and the need for further research has been recognized in scientific projects [3]. The Munich fire brigade ran a series of tests in August 2016 to better understand this issue with regard to the design of new stations.

TEST SETUP AND METHODS
Each test setup consisted of one wheelchair user on the platform who had to be rescued by a fire crew of 5 professional firefighters (1 officer and 4 firefighters) equipped with breathing apparatus. As wheelchair users, people with real disabilities took part voluntarily. For every test, a different fire crew was called. Three metro and suburban rail stations with depths of 11,5 m, 18 m and 24,5 m had been chosen. Two stations had a complex mezzanine level with walking distances of 85 and 110 m between the stairs. In the 18 m deep station with a small mezzanine level also test setups with a standing escalator and the aid of additional equipment (rescue sheet, stokes stretcher, non-electric wheelchair) were conducted. In total the series consisted of 20 single experiments in 10 setups. Each setup was run twice to detect potential spread.

The tests started with the operational order by the incident commander to the fire crew on ground level outside the station. The wheelchair user waited on the platform. The test ended with the test person rescued to ground level. Times for driving from fire station to incident scene, reconnaissance (getting first informations on the incident after arrival) etc. were not included. No smoke has been used. This was considered acceptable because according to german regulations, in new stations a low-smoke layer must be maintained until the 30th minute after ignition.

The following data were documented: (split) times, air consumption, age and pulse immediately after the test. The firefighters filled a questionnaire after the test to get information about the subjective exertion. Experienced fire officers watched the experiments and documented their observations.

RESULTS
Regarding physical exertion, the ascending rescue was challenging. The main factor for the exertion was the height difference between platform and ground level. The tests in the 11,5 m deep station were considerably easier to perform than in the 18 m deep station although the horizontal walking distance was approximately 70 m longer one-way and orientation was more difficult. In the lowest station one firefighter had a pulse of more than 90% of his maximal heart rate while in the 24,5 m deep station 4 of 10 firefighters exceeded that value after the experiment. The maximal air consumption on the way from platform back to ground level ranges from 94 l/min (at depth 11,5 m) to 136 l/min (at depth 24,5 m). As a comparison: at german fire schools 80 l/min are teached as a guide value for “very heavy work”. Also the questionnaire and the observations indicate a critical physical
strain at the 24.5 m deep station.

The analysis of the split times showed a high proportion of fixed times, e.g. for the operational order, for talking to the wheelchair user or for fixing a rope for securing the escape route. Vertical speeds were lower at deeper stations (see Tab. 2). Significant differences in horizontal speed on platform and mezzanine level could not be observed. For most engineering purposes it was found suitable to consider mean split times for the way to platform and maximal times for the return. Due to the different setting compared to usual fire training and a rather polite behaviour facing the test person, average times are not considered as unsafe assumption before the test person is being carried back. Estimated rescue times based on the experiments’ split times can be seen in Tab. 1.

All auxiliary equipment made the rescue slightly easier, especially the wheelchair (nearly impossible with an electric wheelchair).

Rescue over the 1 m wide standing escalator was possible with reduced vertical speed. Using the escalator was a bit more exhausting than over stairs of the same height.

<table>
<thead>
<tr>
<th>depth</th>
<th>small mezzanine level</th>
<th>complex mezzanine level</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.5 m</td>
<td>7.8 min</td>
<td>10.3 min</td>
</tr>
<tr>
<td>18.0 m</td>
<td>8.7 min</td>
<td>11.2 min</td>
</tr>
<tr>
<td>24.5 m</td>
<td>10.4 min</td>
<td>12.9 min</td>
</tr>
</tbody>
</table>

Table 1   Estimated rescue times beginning with the operational order without additional safety factor.

<table>
<thead>
<tr>
<th>Value of NFPA 130 as comparison (not applicable for this purpose)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test A</td>
</tr>
<tr>
<td>0.00</td>
</tr>
<tr>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 2   Vertical speeds in m/s at different stations.

CONCLUSIONS AND FUTURE WORK

Rescue from underground stations cannot be calculated as the evacuation of passengers who are able to walk on stairs. Nevertheless the experiments could help to judge the possibilities of rescue by fire services from underground stations. As these possibilities are very limited with persons who are unable to walk and in deeper stations, two mitigation strategies are possible for underground station design (also combined if necessary):

- Measures of self-rescue for persons with reduced mobility, e.g. lifts with extension of operating times in the event of a fire [4] to minimize the number of people who need the help of emergency teams
- Measures to facilitate the rescue by other passengers or fire services, e.g. still operating escalators in the escape route and firefighters lifts (EN 81-72 [5])

Currently different stakeholders are working together on recommendations for firefighter lifts in underground stations, also using the results of these experiments.

REFERENCES

Experimental study on smoke characteristics of tunnel fire under water mist system combined with longitudinal ventilation

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KEYWORDS: Tunnel fire, smoke characteristics, water mist, longitudinal ventilation

INTRODUCTION
With the development of the economy and the progress of the technology, large numbers of tunnels characterized by super length and large cross-section are being constructed and coming into service. The tunnels bring convenience to people’s daily life, but the corresponding fire hazards cannot be ignored. Tunnel fire has attracted an increasing amount of attention since it will cause heavy casualties and huge economic losses. The problem of tunnel fires is one of the most complex and interesting areas of modern fire research. In order to meet the demand of fire suppression and prevention in tunnels, water mist system and longitudinal ventilation system are utilized gradually. There have been some studies on the design of water mist system and its fire suppression performance within tunnels. Water mist manufacturers and researchers have performed numerous large-scale tests using water mist systems in tunnels[1-5]. Small-scale experiments and numerical studies have also been done to study water mist fire suppression under different conditions[6-9]. However, very few studies considered the condition of water mist system combined with longitudinal ventilation. Therefore, in this study, a series of small-scale test data was obtained under the combined effect of water mist and longitudinal ventilation, providing relating reference for tunnel fire suppression and prevention.

EXPERIMENTAL SETUP
In this work, the smoke characteristics of tunnel fire with the combined effect of longitudinal ventilation and water mist system were studied in a small scale tunnel (16.5 m length×1.3 m width×0.6 m height). The gasoline pool fire (0.16 m×0.16 m) was used as fire source and it was set in the middle of the tunnel. The smoke temperatures beneath tunnel ceiling along the longitudinal direction were measured by K-type thermocouples in different experimental situations:

<table>
<thead>
<tr>
<th>Number</th>
<th>Pool size (m)</th>
<th>Heat release rate (kW)</th>
<th>Wind speed (m/s)</th>
<th>Water mist</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>0.16 ×0.16</td>
<td>63.24</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>02</td>
<td>0.16 ×0.16</td>
<td>63.24</td>
<td>0</td>
<td>Yes</td>
</tr>
<tr>
<td>03</td>
<td>0.16 ×0.16</td>
<td>63.24</td>
<td>0.5</td>
<td>Yes</td>
</tr>
<tr>
<td>04</td>
<td>0.16 ×0.16</td>
<td>63.24</td>
<td>1.0</td>
<td>Yes</td>
</tr>
<tr>
<td>05</td>
<td>0.16 ×0.16</td>
<td>63.24</td>
<td>1.5</td>
<td>Yes</td>
</tr>
</tbody>
</table>
RESULT AND DISCUSSION
when the water mist operates without mechanical air supply, the maximum smoke temperature occurs
at the position above the fire source, and the smoke temperature distribution beneath the tunnel ceiling
follows the nature exponential decay laws from the position above the fire source.
When water mist and air supply act cooperatively, the upstream smoke temperature reduces obviously
and tends to be smooth. Meanwhile, the upstream smoke temperature rises up suddenly in the near
field of fire source and increases along the downstream direction until reaches the maximum value at
the downstream position close to the fire source. And then, the smoke temperature reduces linearly
and becomes steady gradually.
Compare the results we can find that: The air supply speed will affect the efficiency of smoke control,
too low air supply speed causes thicker upstream smoke layer and lower visibility, while too high air
supply speed reduces the efficiency of mechanical exhaust. By the comprehensive analysis, the best
air supply speed range is from 0.5m/s to 1.5m/s.

ACKNOWLEDGEMENTS
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Experimental study of different screening test methods for determination of fire spalling of concrete

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KEYWORDS: Fire spalling, screening test

INTRODUCTION
Under the umbrella of the international committee RILEM TC 256 SPF [1] one aim is to define a suitable screening test method for the determination of the fire spalling sensitivity of different concretes with a small scale method. The aim of using a screening test method is mainly to sort out suitable mixes for further tests in a larger more realistic scale. The screening test method can also be a tool for research for investigations on correlations between parameters influencing fire spalling of concrete.

MATERIALS
In the experimental campaign, described more in detail in [2], three mixes were used. Two previously known for being sensitive to spalling and one with the addition of 1 kg/m$^3$ PP fibres. The mixes uses are presented in Table 1.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Water [kg/m$^3$]</th>
<th>Aggregate 0-8 mm [kg/m$^3$]</th>
<th>Aggregate 8-16 mm [kg/m$^3$]</th>
<th>PP fibres 18 μm [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix A</td>
<td>510</td>
<td>168</td>
<td>796</td>
<td>1</td>
</tr>
<tr>
<td>Mix B</td>
<td>510</td>
<td>168</td>
<td>796</td>
<td>-</td>
</tr>
<tr>
<td>Mix C</td>
<td>430</td>
<td>168</td>
<td>866</td>
<td>-</td>
</tr>
</tbody>
</table>

FIRE TESTS
Seven different test methods were used in the studie. Larger slabs with a thickness and reinforcement layout from the Swedish tunnel “Norra länken” in Stockholm and six screening test methods from research groups in Sweden, Scotland, Poland and Japan [2]. The screening test methods consisted of reinforced and unreinforced small slabs, ring shaped specimens moulded in a steelpipe and concrete with a tapered cross section heated from two sides. In total 41 fire tests were performed. The poster will include pictures and short descriptions of all test methods used as well as diagrams showing all spalling results.
CONCLUSIONS
The main conclusions from the study was that spalling results from large slab specimen tested without load or restraint cannot be used for a general assessment of spalling beyond the reinforcement layer if loading or restraint of the elements are expected in the real case. If the reinforcement is exposed during a fire test the stress profile is dramatically altered and the concrete will crack due to the loss of stiffness of the reinforcing steel. This may not be the case in a real tunnel where the surrounding cold structure acts as a restraint also when the reinforcement is exposed, i.e. spalling may continue through the section beyond the reinforcement layer.

Very rapid spalling of the concrete cover was shown during HC fire exposure of large slabs for the two mixes without PP fiber addition. During these tests on large slabs (see specimen in figure 1) the 50 mm thick concrete cover was lost after less than 10 minutes of fire exposure.

Spalling occurred in all specimens of the two mixes without PP fibers except for one of the mixes tested with the ring-shaped specimen moulded in steel pipes. In that case no spalling happened which indicates that this method was not giving equivalent results compared with the other methods. Based on this limited study all small scale test methods except the ring specimen predicted spalling as in the large scale test but the methods shall still be labeled screening test methods, i.e. methods for sorting out suitable mixes for further tests in a larger more realistic scale. It shall be noted that the amount of spalling was different in the examined methods. The test results will be submitted to the international comitee RILEM TC 256 SPF [1] as reference material for making recommendations regarding test methods.

ACKNOWLEDGEMENTS
Main financial support comes from Trafikverket (the Swedish transport administration) and SBUF (the Swedish construction industry's organisation for research and development). The main part of the tests, as well as manufacturing of all test specimens, have been performed by RISE. Also international partners contributed to the project by performing tests and are greatly acknowledged: Gunma University in Japan, The University of Edinburgh in Scotland, UK, and Cracow University of Technology in Poland.

REFERENCES
The influence of external wind in tunnels - simple expressions

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KEYWORDS: Tunnel, wind effects, semi-empirical expressions

INTRODUCTION
In tunnels air movements are of great importance, both in case of fire and in normal situations, and can affect both technical installations such as fans as well as organizational actions for the fire brigade. External winds will affect air movements in the tunnel and the impact will be larger for short tunnels compared to longer ones. The air movements in tunnels can be of crucial importance to the fire development, the visibility and toxicity. Also, the normal ventilation in tunnels will be affected by external winds. The best way to estimate wind effects is to measure air movements in situ. However, wind impact in tunnels can also be simulated with CFD calculations. But there is also a need for using simple hand calculations to estimate the resulting air movements in tunnels. The results have previously been published in a thesis [1].

METHOD
The poster describes simple semi-empirical expressions to estimate the influence of wind on flow in tunnels. In wind tunnel tests performed in a model tunnel influences from variation in design of the tunnel mouth and different wind directions have been investigated. A simplified semi-empirical equation based on the pressure coefficient was obtained based on the experiments and earlier results.

RESULTS AND DISCUSSION
The pressure coefficient is the ratio between the dynamic pressure and the stagnation pressure in the opening of the tunnel. Pressure coefficients included in the developed correlation were determined based on empirical data including a mix of model scale tests and full-scale tests shown in figure 1. These results are valid for short tunnels where the losses in the opening are dominating over the losses caused by friction from the tunnel walls.

Based on the model tests the following curve approximation was developed, \( C_p = 0.45 \cdot (1.5 \\alpha) \), where \( \alpha \) is the wind angle.
$C_p$ is the pressure coefficient, $\alpha$ the wind angle. Wind angle $0^\circ$ corresponds to a wind direction straight into the tunnel opening. The equation can be simplified to a function based on a wind velocity $u_{\text{ref, stg}}$ (the air velocity in the stagnation point)

$$u = \sqrt{\frac{u_{\text{ref, stg}}^2}{0.45 \cdot \cos(1.5\alpha)}}$$

where $u$ is the resulting air velocity in the tunnel. In figure 2 the resulting air velocity in the tunnel is described as a function of different wind directions.

![Figure 2. The resulting air velocity, $u$, in a tunnel as a function of different external wind angels and free stream velocities.](image)

With the results from equation and Figure 2, the resulting air velocity in a short tunnel can be estimated.

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Experimental study of diagnostic in order to detect risks for fires in Underground Mines

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KEYWORDS: Fire, Underground mines, Early diagnose, Sensors, Overheating, Ventilation, Energy optimization

INTRODUCTION
There is a major interest to early diagnose problems in the mines’ underground facilities. A special demand is the early detection of risks of fire, such as overheating of equipment, cables or similar. Around 40 fires occurs per year in Swedish mines where the greater part is started by vehicles moving in mines [1]. This is subject to strain the mining production. Placing sensors both in the plants and on mining vehicles with continuously transmitting signals from these to a central diagnostic systems one can early detect risks for overheating from types that leads to that plastics begins to emit thermal decomposition products. This will soon be possible when Swedish mines are being equipped with e.g. 5G. Following temperature, hydro carbons, CO2 concentration, CO concentration, relative humidity, flow and combine them with dynamic simulation models one can follow the development of the mine and compare the simulations to measurement data. This is then used as input to a decision tree system to assess the risks of such fires, but also to determine toxic gases that can be dangerous to humans and the machinery (corrosion). Oil mist in the air from leaking hydraulics is another issue that we want to detect. If a fire is a fact the approaches for how to extinguish the fire in mines varies. The process can be enhanced especially if the ventilation is shut down in the mine shaft where the fire occur. In best cases the fire could then be self extinguished. Ventilation in tunnels has shown in many cases to aggravate the fires. The fire safety issues in underground hard rock mines are in many ways very similar to the issues faced in tunnel construction projects [2]. What ABB is looking at is with smart mine ventilation to control the ventilation in such a way that it is being shut down during extinguishing the fire and then restarted in order to increase the possibility of venting out bad air as fast as possible. Today 49 % of energy consumption in mines is related to ventilation [3]. How different ventilation strategies affects the consumption is another area of the study.

MATERIAL AND CONDITIONING
To investigate the suitability of different sensor types for early detection of fire condition (or risks for fires) in mines, tests have been performed with a number of different sensors. Ten different cable types that are today mounted on Atlas Copco’s vehicles were tested, see figure 1. The material of the cables varied from e.g. PVC to halogen free. The thinnest cable was 0,75 mm² and the thickest 2, 5 mm². Cables with high current and voltage above 400 V can be found quite protected 1,5 -2 m above the ground on the vehicles. Signal cables are mounted close to the floor, which is 0,3 m above the ground and on low built machines and up to 7-8 m above the ground at the end of the drilling machines – booms with limited protection. Also oil mist was produced in some experiments.

![Cables on Atlas Copcos vehicles](image)

INSTRUMENTATION
The sensors need to be resistant to the mining environment and thus be able to distinguish between normal mining air or if fire is about to evolve due to e.g. soot, oil mist (hole in hoses). Therefore
different measurement methods were important elements of the tests. With the tests we wanted to determine if the sensors were sensitive enough; in other words, what they react to or what they are disturbed by to find out which ones are hypersensitive and thus not suitable for further tests in the project. Figure 2 shows the sensors that were tested at RISE, SP Brandteknik’s facilities in Borås.

**TESTS**

The sensors were mounted on a frame construction with wheels, see figure 3. In this way it was possible to move forwards and backwards at the same time, thus observing at what distances the sensors reacted on emissions from the cables and the oil mist. See figure 4 the set up of the lab equipments in Borås. The angle of the equipment could also be varied and thereby simulate inclines on the mine road. Also a fan was mounted in order to test how ventilation affected the sensors capabilities to respond.

**ADDITIONAL TESTING**

Future tests will focus on sensors that may be suitable for placing on rock walls and humans and the possibilities with 5G installed in order to test logging of data. Other risks that can cause fires e.g. overheated engines as for oil mists is also planned to be tested.

**RESULTS**

We could see from the experiments that Fotovac, a method determining organics after ionization, could determine emissions from the cables when the current was approximately 50% higher than nominal at a distance of some 0.5-1 m as it sucks air through the detector. It also reacted to oil mist. The SICK smoke detector started to react when there was significant smoke but also on oil mist. The thermos camera had a function determining maximum temperature in the picture, and could determine a temperature increase already under normal operations of the cables and this can be used already from several meters distance and by setting a temperature limit an alarm can be set. The other sensors were to insensitive to use directly, but CH4 sensors could be used if gas could be sucked to the detector probably.

**DISCUSSION**

In the poster a compilation of the results from the tests will be presented and a discussion of the possible diagnostic as for detection of risk for fires will be performed. The focus will be to determine suitable sensors and discuss possible placing in order to minimize number of fires caused by vehicles in Swedish mines.

**REFERENCES**

Emergency medical care in major tunnel incidents – an integrative literature review

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KEYWORDS: major incidents, tunnels, emergency medical care, prehospital care extreme environment

INTRODUCTION
There are several types of tunnels; road tunnels, train tunnels, and also tunnels under construction. The access routes into these tunnels are often long and sometimes in several levels which in case of a major incident with several injured persons, indicate a difficult emergency operation. The complex environment in underground tunnels impact the work of rescue teams, who often represent different organizations (e.g. rescue service, ambulance and Swedish transport administration). The rescue service perspective on rescue operations in tunnels has been studied [1]. However, the description of methods and tactics used in emergency medical care during rescue operations is mostly lacking. The aim of this study was to provide an overview of the medical emergency care during major incidents in tunnels, but due to a lack of material it is also including some aspects of rescue operations in tunnels of importance for the medical emergency care.

METHOD
The search for literature was performed in PubMed as well as an extended literature search for reports using the keywords: pre-hospital care, emergency care, rescue operation, injury incidents, major incident and tunnel. The references in the articles found were further reviewed for more articles. In total, 94 articles and reports were found of which 47 were included. The excluded literature was not relevant according to the aim of the study and e.g. dealt with technical matters. Only preliminary results are available as the analysis will be performed during the spring of 2018.

RESULTS
Preliminary result show that the findings are mostly based on retrospective data from incidents and fewer from preventive and prospective initiatives. The studies focusing on the medical emergency care are few and predominantly focus on case descriptions, e.g. the terrorist attack on London’s underground trains [2, 3] or bus crashes occurring in tunnels [4, 5]. These articles describe emergency care and give a more detailed description of the injured and the provided care. They describe the difficulties associated with underground rescue and emergency medical operations e.g. the passengers escaping in different directions emerging from two underground stations, which made the rescue and emergency crew believe there were two different incidents, as well as difficulties in communication and transportation of injured due to the access route of the site. The result also showed long hours of effort and resource-intensive work. During one of the bus crashes the rescue operation took eight hours before the emergency care reached the injured persons and more than 200 people were estimated to have been involved in the rescue operation [6]. Other factors important to take into consideration regarding the emergency medical care are risks (e.g. in smoke-filled tunnels, combustion gas heat or where in a tunnel the risk of incidents is highest), evacuation safety measures, e.g. exit portals and alarm systems [7], evacuation behavior [8], challenges in evacuation and rescue operations and the importance of collaboration during rescue operations in tunnels.
DISCUSSION/CONCLUSION
There is a lack of studies regarding the emergency medical care during major incidents in tunnels. Most often, the studies focus on preventative measures reporting previous injury incidents, the number of people killed or injured [9] and subsequent rescue operation by the rescue service. There is a need to increase the knowledge of emergency medical care during major incidents in tunnels to optimize the survival rates and health for the injured, as well as providing a safe and effective work environment for the rescue and ambulance organizations. We need to further investigate specific challenges regarding information exchange, negotiations and initiatives for knowledge transfer between actors to provide emergency care. There is also a need to pinpoint how to establish joint efforts in the emergency medical care (specifically during the initial phases of a rescue operation), exchange of staff during extensive work etc.

The future will bring even more complex tunnels of different types, and the existing knowledge and situation regarding tunnel safety is unclear and fragmented [10]. These questions need to be explored both from both pre- and post-phases; knowledge from past incidents as well as through exercises/training to better prepare involved actors for joint effective tactics and new knowledge in future operations with regard to emergency medical care. Very little is prepared and practiced with regard to emergency medical care in major tunnel incidents, where a more offensive medical intervention is very faraway in Sweden today.

REFERENCES
SUVEREN - Safety of New Energy Carrier Vehicles in underground transportation facilities

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KEYWORDS: New Energy Carrier, battery fire, gas fire, emerging risks, Smart Cities, underground transportation, evacuation, firefighting systems, simulation

INTRODUCTION
Due to the fact of global warming and in order to reduce CO2 emissions, vehicles with new energy carriers like batteries, compressed natural gas, and hydrogen as well as different types of biofuels will gather a growing share in the composition of our society’s means of transportation. These new energy carriers will increasingly be found in urban infrastructure environment and in public transportation vehicles, too.

Today’s safety concepts, guidelines and standards are based on design parameters like heat release rates, fire mitigation measures and evacuation concepts that result from the “old” conventional energy carrier risks of vehicles with combustion engines (ICE vehicles – internal combustion engine vehicles). But using new energy carriers will lead to emerging risks like battery fires, flashes from pressure vessels or distribution of inflammable or explosive gases. We may assume that these changing risks will also result in new safety challenges for our society and buildings. A holistic underground infrastructure safety approach [1] requires investigating these new developments.

MAIN OBJECTIVES OF SUVEREN
Together with the Bundesanstalt für Materialforschung und –prüfung, BAM and the Studiengesellschaft für Tunnel und Verkehrsanlagen e.V., STUVA, FOGTEC Brandschutz GmbH & Co. KG will develop and investigate both new technologies and new concepts to improve the safety level of underground transportation facilities – taking into account risks and boundary conditions emerging from New Energy Carrier vehicles.

New technologies comprise hardware for fixed fire suppression systems as well as simulation and detection tools [2] adapted to the special needs and risks brought by batteries, CNG, hydrogen pressure vessels or biofuels into tunnels of today’s and tomorrow’s transportation facilities. The new concepts will one the one hand side lead to new guidelines for tunnel safety design, and on the other hand side result in training courses for a target group including owners, operators and designers of underground transportation facilities like – both urban and rural – tunnels, car parks, or subsurface storage spaces.

WORK PLAN
SUVEREN is organized in 6 work packages as follows:
“WP1 – Safe use of New Energy Carriers in underground urban space” will identify actual and future risks relating to specific properties of New Energy Carriers and lead to new design scenarios.
“WP2 – Case Studies” will be carried out in close collaboration with operators of relevant facilities. Methods of managing the risk of fire will be investigated including a comparison of the state of the art with what the future will demand.

In the frame of “WP3 – Technologies to mitigate damages” measures will be developed to improve safety of underground urban spaces in case of fire [3]. Based on results from WPs 1 and 2, functional as well as non-functional requirements to technical installations will be derived.
“WP4 – Development and Validation of models” will calculate different risk scenarios for evacuation [4] and also validate model calculations with experiments [5]. The result from “WP5 – Safety concepts for underground urban spaces” will be a summary of the other work packages’ findings. A Handbook with recommendations for equipment and operation of underground infrastructure will be elaborated together with different stakeholders. Finally, “WP6 – Standards, regulations and trainings programme” will take care of disseminating the project results to the relevant groups of stakeholders including active participation in standardization committees and carrying out a trainings course for designers, owners, and operators.

FIRST RESULTS
Whereas ICE vehicles and corresponding risks have a long tradition and are well known in urban environment, the new mix of energy carriers like fuels, different types of gas, batteries and – in terms of storage – pressure vessels lead to changing or new risks and risk perception. Gases with relative densities different from air will accumulate either on the ground, possibly flowing into sewer systems, or below ceilings as we investigate urban underground transportation facilities. Gas leakage without fire will require new safety concepts with the need for new detection systems and perhaps new countermeasures. The question of flashpoints, explosive limits, auto-ignition temperatures and relative density will heavily influence new scenarios to be developed.

In order to develop these new scenarios, different boundary conditions of tunnels versus garages will be taken into account including the composition of vehicles in operation, ventilation concepts, persons involved (users, operators, first responders), and escape routes. New risks like gas leakages or spread of smoke with other than ICE known temperatures will lead to different risk situations in tunnels or garages. The selection of the most relevant scenarios will be the result of discussions with experts and operators based on case studies, and simulated and validated with real scale tests.

CONCLUSIONS
Recent discussions about combustion engines in vehicles definitely push car manufacturers towards developments of alternative engines and the use of New Energy Carriers. SUVEREN makes an important contribution to our urban underground transportation safety on an applied research level following an interesting series of underground safety and security research projects [6] of the last more than 15 years.

REFERENCES
Resilient and sustainable strategies for emissions control in road tunnels

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KEYWORDS: pollutant emission, emission control strategies, tunnel safety, energy efficiency, decision making.

INTRODUCTION
One of the main objectives of tunnel operators is to manage their assets to be resilient and sustainable, maintaining an appropriate level of safety while optimising operating costs. In normal operation, a critical activity is to maintain pollutant concentration (CO, NO₂, PM) below the specified limit levels to provide drivers with a comfortable and safe driving environment [1].

There are several ways to achieve this emission control in road tunnels and it is important to understand their relative performance in specific tunnel configurations to enable optimisation. This will allow the minimisation of power consumption used to operate the ventilation system, reduction of the recovery time to acceptable pollutant concentration, extension of equipment life and reduction of maintenance costs (by reducing the number of activated fans as well as the number of switches on-off).

In this analysis, it is intended to carry out the analysis and comparison of three different emission control strategies in terms of resilience (response, recovery) and sustainability (energy efficiency, operational cost) concepts. The first emission control strategies will be based on Standard Emission Control strategies, SEC. The second one will be based on Fuzzy Logic Emission Control concepts, FLEC and the third one will be based on Predictive Emission Control concepts, PEC [2, 3].

Results will be compared to provide a quantitative understanding of the potential benefits of the different emissions control strategies to support decision making in the design and implementation for road tunnels.

REFERENCE ROAD TUNNEL DEFINITION
The main characteristics of a reference road tunnel will be defined, based on a representative 2-lane unidirectional tunnel with a longitudinal ventilation system comprising jet fans evenly distributed along its length. The traffic characteristics, fleet composition and vehicle emission rates will be based on PIARC recommendations [1] and the traffic flow will be considered variable with time.

EMISSION CONTROL STRATEGIES
Three different emission control strategies will be analysed. The first one, SEC, is based on the comparison of the current pollutant concentration in the tunnel with predefined threshold values and states. The emission control strategy will be to increase or decrease the number of activated jet fans. The second one, FLEC, is based on the comparison of both the pollutant deviation from a set point and the deviation rate of change. Depending on these values, different fuzzy logic rules will be applied to increase, maintain or decrease the number of activated jet fans. The third one, PEC, provides an alternative approach based on the prediction of the traffic density and meteorological conditions that will allow the estimation of the concentration of pollutants inside the tunnel. Estimated values of pollutants may then be used for calculation of outside air volume demand and, therefore, the number jet fans.
required to adequately ventilate the tunnel. The assessed number of activated jet fan may then correct accordingly the SEC or FLEC estimation [2, 3, 4, 5].

**NUMERICAL MODELLING**

After the set-up of the reference road tunnel and the definition of the emission control strategies, the emission concentration inside the tunnel as well as the emission control strategies are implemented in a 1D simulation tool [6]. A series of simulations, taking into account the effects of piston effect, meteorological conditions and pressure losses, will be used for analysing the performance of these approaches in terms of power consumption, reduction of the recovery time to acceptable pollutant concentration and extension of equipment life.

**DISCUSSION**

In the final paper, a compilation of the results obtained by applying different emission-pollutant control strategies will be presented. Special attention will be given to understanding the pros and cons of these strategies from a tunnel operator’s point of view (asset management and normal operations) allowing the selection and development of the most suitable strategies for different scenarios.

**REFERENCES**

Estimation of Total Heat Release Rate of Multiple Components in a Railway Tunnel

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KEYWORDS: Heat release rate, thermal properties, heat transfer, mass loss rate, cone calorimeter, railway, tunnel,

INTRODUCTION
The predominant strategy for fire safety in tunnels and in particular rail tunnels, is to restrict the threat posed by fire by way of material control. Typically this implies limiting the composite materials of tunnels and their contents to those designated as low to non-flammable. Although significant research effort has been carried out to study combustion of individual materials, less attention has been given to methodologies to derive a combined heat release rate (HRR) for multiple components installed in the environment and geometry of a railway tunnel. Practical requirements beyond those associated to fire safety mean that not all components in the tunnel are non-combustible, thus there is a need to explore the magnitude of the combined heat release rate of these items. This is so they can be compared to a typical carriage vehicle fire to establish how significant the additional HRR brought about by the inclusion of these items is. The poster will outline a method for approximating the combined heat release rate of a collection of items installed within a typical railway tunnel, considering how one burning item may cause ignition of other items depending on the locations of the installed components in relation to the fire source and to each other. This method was devised without the need for specific fire tests to be performed on equipment or for large scale tests replicating the environment.

Amongst the typical installed components in the railway tunnel discussed are power cables, communication cables, cable joints, cleats, radio antenna, catchpit frames, emergency exit signs and tunnel luminaires.

DETERMINING THE HEAT RELEASE RATE OF A SINGLE ITEM

Investigations carried out for this study established that the likelihood of ignition could be assessed by considering the critical ignition temperature and the critical heat flux for ignition. The accuracy of using these two parameters was evaluated against empirical data [1].

The properties that affect this combustion reaction include the heat of combustion, characteristic flame spread rate and mass loss rate [2]. Tests that identify these parameters were investigated. Cone calorimetry tests provide values for the heat of combustion due to a given heat flux. Thermogravimetric analysis (TGA) provides the data required to calculate the mass loss rate. Cone calorimetry test and TGA experiments for materials at various heat fluxes were found in scientific literature and papers [3].

Using the empirical data, a method of calculating the heat release rate for a material was carried out by establishing a characteristic fire growth rate property, \( \alpha \), for the materials in the tunnel. \( \alpha \) is a characteristic material property that encompasses the mass loss rate, flame spread rate and heat of combustion. The value characterises the fire growth of a material, and can be used to estimate the HRR at any given time.
ESTIMATING THE COMBINED HEAT RELEASE RATE

A number of fire scenarios were considered and the resulting sequence of ignition and combustion were investigated. For example, in a railway tunnel, a fire can arise from a burning train carriage, or from an item of tunnel equipment burning. The heat that is transferred from the fire to its neighbouring objects, depending on the environment, is in the form of conduction, convection, and radiation. For example, the smoke released by the fire causes a radiative heat flux to be applied onto nearby installed components [4].

If the resultant heat flux applied to an object was greater than its critical heat flux, it was assumed that ignition would occur. It would therefore release heat which would apply an additional source of heat flux to other items potentially causing those to ignite as well, and cause a chain reaction of ignitions. The combined heat release rate determined at a given point in time is the sum of individual heat release rates of the individual components.

DISCUSSION

The methodology of estimating the combined heat release rate of multiple installed components for a given environment, namely a railway tunnel will be presented. Amongst the typical installed components considered will be cables, emergency exit signs and tunnel luminaires. With a worked example, the poster will discuss the possible influence of the investigated parameters and limitations to the calculations. It was discovered that the combined heat release rate of all present components in the tunnel is not necessarily negligible when compared to the fire load of the train carriage itself.

REFERENCES

Development of a full probabilistic risk and smoke spread model for assessing ventilation system performance in tunnel fire safety

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INTRODUCTION
In tunnel fire safety engineering, the concept of risk analysis plays an important role in the creation of a fire safety design which meets the objectives and boundary conditions set by the different stakeholders. Quantitative risk based methods provide a possibility to dimension fire safety systems and take the variety of these boundary conditions (infrastructure, occupant and environmental) and possible scenarios into account [1]. Due to the critical nature of these underground infrastructures, it is of fundamental importance to analyse the whole spectrum of possible outcomes which can contribute to the spread of the effluents of a fire. Therefore, a significant number of fire scenarios should be investigated in order to have a good representation of the risk posing in the tunnel. In this paper, a probabilistic one dimensional tunnel model is presented which gives a good representation of the flow field in tunnel and takes the uncertainty and variety of the different input parameters into account.

KEYWORDS: Ventilation, 1D modelling, probabilistic risk assessment, QRA

DETERMINISTIC TUNNEL MODELLING
The design of ventilation strategies and the analysis of the flow field in tunnels is commonly done by means of two approaches: one dimensional (network) modelling (1D) [2] and three dimensional CFD modelling (3D) [3],[4]. Both approaches solve the equations of Navier Stokes, but in different ways. 1D models assume that the properties of the fluid are uniform over the tunnel’s section. In 3D models, the properties vary in 3D location. The 1D model cannot correctly represent the regions with a three dimensional flow, but it solves the flow field significantly faster than the 3D model. The lack of accuracy of the 1D model in a design phase can be acceptable since many simulations are required for the quantitative risk assessment (QRA). In this paper, the flow field along the tunnel is studied with an in-house developed model that allows to simulate a single branch tunnel. The model solves the equations of Bernoulli in steady state conditions for a given tunnel configuration and it allows to calculate the longitudinal velocity in the tunnel. The energy equation is not explicitly solved in the model, but the temperature profile is imposed based on the equations proposed by Ingason in [5]. A more accurate modelling is out of the scope of the current paper, but in principle the current analysis can be performed also with other 1D models.

BOUNDARY CONDITIONS AND MODEL VARIABLES
The purpose of the model is to determine the ventilation performance for different operating conditions and fire scenarios. The scenarios are expressed by means of different combinations of input parameters. The model is able to take into account four different variables. These are: the position of the fire (Uniform), the power of the fire (Lognormal), the wind (direction and speed) at the portals (Weibull) and the failure probability of the ventilation system. The first three variables are considered continuously distributed [6], Figure 1. These variables are analysed using a full probabilistic risk method. The the fourth variable is considered discrete and is studied with an event tree approach. The position of the fire in the tunnel is considered to be a uniform distribution since the probability of a fire to occur in every position of the tunnel is equal. The wind effect is modelled based on the speed and the direction at the tunnel site and calculating a pressure distribution at the portals. The fire power distribution is calculated based on the data coming from the literature [7] and interpolating the results basing on the traffic and accident information. Other boundary conditions such as the inclination of the tunnel can be taken into account.
QUANTITATIVE RISK ASSESSMENT

A quantitative risk assessment methodology is proposed by means of the Sobol sampling technique [8]. The sampling technique is based on the Sobol sequences which are quasi-random low-discrepancy sequences. With this approach we can have a better spread pattern [9] with respect to random sampling.

The Sobol technique is suggested over other methods such as Latin Hypercube Sampling [10] because it shows a good sampling pattern. Secondly, the method shows the advantage to add extra samples in case an insufficient number of support samples are chosen. In this way, an initial set of samples can be analysed and the result can be verified for convergence. If the result does not converge, additional samples are added to the total sample pool. Because of the Sobol algorithm, the new pool of samples still represents the full spectrum in an equal probabilistic manner. In the paper, a full flowchart will be elaborated to describe the probabilistic applied technique. The results are presented by means of a total failure probability. The following formula is given to determine the failure probability for a full event tree technique with multiple scenarios:

\[
P_f(FID \geq 1) = \sum_{i=1}^{n} P(FID \geq 1 | scen_i) P(scen_i)
\]  

DISCUSSION

The current study presents a holistic view of the longitudinal ventilation system in a tunnel. The approach takes into account several scenarios in order to represent correctly the reality. Taking into account only the worst case scenarios can be applicable in a design phase, however these represent only a small portion of cases which can occur. Moreover, in the design phase some assumptions are required in order to limit the variability of the input parameters and of the boundary conditions. The current approach can overcome the problem providing a comprehensive response of the tunnel especially taking into account multiple variables at the same time. The large combination of input parameters might prevent the ventilation system to provide the critical in front of the fire, but this gives a realistic estimation of the failure probability of the system.

REFERENCES

Risks associated with alternative fuels in road tunnels and underground garages

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ABSTRACT
This research project focused on a literature review about the risks involved in using gaseous fuels and electric vehicles in road tunnels and underground garages. Alternative fuels pose new risks that we, due to our greater familiarity with liquid fuels, are unused to. In particular this relate to gaseous fuels and pressure-vessel explosions, and the release of toxic gases such as hydrogen fluoride from Li-ion batteries undergoing thermal runaway.

INTRODUCTION
Due to environmental considerations, much current transportation policy development is aimed at increasing usage of renewable energy sources. In the future, a large number of road vehicles will not be powered by fossil fuels, and in order to prevent incidents in connection with such a change in the transportation sector, regulations and practices should stay one step ahead. Therefore, a project was approved by the Nordic Road Association (NVF) that was intended to review and update current knowledge regarding alternative fuels, provide guidelines for the operations of rescue services, and offer recommendations for the creation of regulations [1-2]. The project ran during 2016 and involved two workshops, one aimed at underground garages and one focusing on road tunnels, to which interested parties were invited. The project was limited to commercial gaseous fuels in Sweden (liquefied petroleum gas; LPG, DME, methane, and hydrogen gas) and electric vehicles. The research method was based on a literature review and analysis from a risk perspective.

GASEOUS FUELS
Gaseous fuels can be compressed, liquefied-compressed or cryogenically frozen. The storage and handling of methane takes place in the form of both compressed gas (CNG) and cryogenic gas (LNG). Hydrogen gas is primarily handled in compressed form, whereas LPG and DME are normally handled in liquefied form.

An explosion is a rapid release or creation of gas under pressure. The keyword here is ‘rapid’ so that a blast wave occurs. Examples of such an explosion include the rupturing of a pressurised tank, i.e. a pressure vessel explosion, and a chemical reaction (combustion, for example) that results in a rapid increase in pressure such as occurs when a combustible gas-air mixture is ignited. The portion of the gas that is in liquid form (only relevant for LNG, LPG and DME) during a pressure vessel explosion may lead to a BLEVE when the liquefied gas rapidly evaporates in the warmer environment outside of the tank. For a BLEVE to occur, the liquid must be heated around 100 K above normal storage temperature, i.e. heated by a fire. A gas container explosion can inflict fatal damage in not only the immediate vicinity but further away, as parts of the tank can be propelled a great distance.

According to European guidelines, CNG containers are to be inspected at regular intervals, but these are currently ignored entirely in Sweden. Two CNG pressure vessel explosions have recently occurred during refuelling at 230 bars in Sweden. This is about half of the design pressure for the gas container. There could be many more CNG vehicles on Swedish roads with gas containers that currently operate with narrow safety margins.

Standardized testing should ensure that pressure relief devices activate in case of fire. Despite, there are many cases when they have been unable to prevent a pressure vessel explosion due to the increased pressure inside the container and the weakened material following the fire. One reason is that the fire can be either more powerful or local compared to the fire in the standard. Another is poor maintenance and inspection of CNG containers and systems. Taken altogether a pressure vessel
explosion followed by a BLEVE (for LPG, LNG, DME) or fire ball (for CNG, hydrogen) as a result of a vehicle fire must be accounted for.

**ELECTRIC AND HYBRID-ELECTRIC VEHICLES**

At least part of the energy that powers electric vehicles is stored in a battery. Li-ion-based technologies are the most common on the market at present. The energy that is released during the combustion of a battery is moderate in relation to that of the rest of a vehicle, and contributes less to the fire load as compared to a traditional petrol tank. In order to prevent battery failure as a result of both external impact and internal error, batteries are equipped with technical safety systems. If the damage sustained nevertheless causes high temperatures or internal short circuits, the battery may suffer failure and undergo thermal runaway.

The fire load of an electric vehicle is thus no greater than that of one with a more conventional fuel, but does involve different risks. The electric system of a traction battery must be taken into account during a rescue operation, particularly when a car is charging. Traction batteries do not increase fire-risk if appropriate tactic is taken by rescue services. During a thermal runaway, however, the production of highly flammable and toxic gases may become considerable. When thermal runaway takes place in connection with a fire, the gases produced do not exacerbate the situation as the fire gases from the fire are themselves toxic. If no fire occurs, however, the production of large amounts of toxic gas, such as hydrogen fluoride, may go unnoticed.

Fires in batteries take a long time to extinguish. A great deal of cooling is required to stop a thermal runaway. Thus, a fire suppression operation involving an electric vehicle should focus on extinguishing the fire around the battery, and preventing fire propagation from it. The thermal runaway process of damaged Li-ion batteries may re-start and/or continue for more than 24 hours after the damage occurred.

**CONCLUSIONS**

Current approaches to handling petrol and diesel are well-tested and relatively safe. Nevertheless, petrol (in the aftermath of vehicle incidents) causes many vehicle fires. Alternative fuels, in the form of either gas or electricity, will likely lead to fewer vehicle fires in general but offer new types of risks. In the final report [1-2] several recommendations for guidelines and future research was offered.

The risks (in terms of both probability of occurrence and consequences) associated with use of alternative fuels in road tunnels are relatively low, and there is no need for special regulations or measures to be established. Rescue operations, however, are critical in both underground garages and tunnels. There are significant uncertainties concerning how the rescue service should deal with fires in gas vehicles: should containers be cooled? When should an offensive or defensive tactic be used? In garages, people generally have sufficient time to evacuate prior to a fire causing a jet flame or pressure vessel explosion. A jet flame can, however, increase the risk of fire propagation to adjacent vehicles in garages, where cars are often parked close to one another. Explosions generally do not have any serious effect on the structure of a tunnel, as the amount of gas is too small in relation to its ventilation, size and load-bearing capacity. In underground garages, however, the risks posed by gas vehicles are more critical. The uncertainties in our understanding of vehicle fuel container pressure vessel explosions in different kinds of underground garages are considered to be substantial. Critical building types, i.e. those in which there is a strong risk of collapse, can likely be identified. This issue falls between the cracks of Swedish government authorities: the National Board of Housing, Building and Planning refers to the Civil Contingencies Agency, who refers to the Traffic Administration, who in turn refers back to the National Board of Housing, Building and Planning.

Gas container systems should be designed to be better able to resist a pressure vessel explosion resulting from a fire than they are at present.

**REFERENCES**


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