Proceedings from the Seventh International Symposium on Tunnel Safety and Security, Montréal, Canada March 16-18, 2016

Edited by Anders Lönnermark and Haukur Ingason
ABSTRACT

This report includes the Proceedings of the 7th International Symposium on Tunnel Safety and Security (ISTSS) held in Montreal, Canada, 16-18th of March, 2016. The Proceedings include 59 papers given by session speakers and 9 extended abstracts presenting posters exhibited at the Symposium. The papers were presented in 17 different sessions. Among them are Emergency Management, Passive Protection, Case Studies, Safety Levels and Acceptable Risks, Fixed Fire Fighting Systems, Security and Safe Operations, Regulations, Testing and Design, Risk Analysis, Ventilation, Evacuation and Fire Dynamics.

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 Alexandre Debs, Ministère des Transports du Québec, Canada, Gary English, City of Seattle Fire Department, USA, Tony Cash, Transport for London, UK, Ahmad Kashef, National Research Council of Canada, George Hadjipathoulous, Carleton University of Canada and Harold L. Levitt, The Port Authority of New York and New Jersey, USA. We are grateful that the keynote speakers were able to share their knowledge and expertise with the participants of the symposium.

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PREFACE

These proceedings include papers presented at the 7th International Symposium on Tunnel Safety and Security (ISTSS) held in Montreal, Canada, 16-18th in March 2016. 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 an overview of emerging research and regulatory actions coupled to state-of-the-art knowledge in the field of safety and security in underground structures.

This ISTSS regularly attracts over 230 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 active fire protection has become a major field of interest. Further, risk and engineering analysis continues to be an area that attract many papers. Also the interest in new energy carriages (vehicles with new type of propellant) in tunnels increase and will in near future become one of the most important research fields. Numerous renowned researchers and engineers have contributed to these and other topics at this symposium for which we are very thankful. Fire related issues still attract many presentations but the focus has shifted towards technical solutions that can mitigate the fire development should a fire occur. The enormous costs for underground structures forces engineers to design alternative solutions. The sessions that have greatest focus on mitigation of fire development include those dealing with the effects of ventilation systems, active and passive fire protection, fire fighting and human behaviour.

We received nearly 100 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, 59 abstracts were selected, based on their high scientific quality, for paper presentations. The poster session contain 9 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 fifteen of the symposium papers were selected to candidate as full journal papers in Fire Technology, 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 Technology. 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 Event Partner, Ministére des Transports du Québec (MTQ) in Montreal, for their co-operation and help. Special thanks to Alexandre Debs at MTQ for his assistance and help in the planning of this symposium. We also would like to acknowledge Stefan Zmigrodzki and Hubert Dubois at CMIA+ in Montreal for their initial help in realizing this symposium.

Haukur Ingason
Chair of Organisation Committee

Anders Lönnermark
Chair of Scientific Committee
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Challenges Related to Maintenance, Operation and Safety Management of Urban Road Tunnels in Montréal

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ABSTRACT

In Montréal, approximately 10 km of urban highway pass through tunnels such as pont-tunnel Louis-Hippolyte–La Fontaine, which runs under the St. Lawrence Seaway, and tunnel Ville-Marie, an underground interchange that passes through the heart of downtown Montréal. These tunnels, built in the 1960s and 1970s, allow road users to circulate safely and comfortably in a well-lit, scrupulously monitored environment that is sheltered from harsh weather conditions.

After a brief historic description of the two most important road tunnels in Canada, this paper will present issues related to operation and safety management, including emergency planning, training and inspection. It will also present challenges related to periodic preventive and corrective maintenance.

This paper will show why tunnel designers should learn from past experience and always take into account tunnel operations, since the aging of this type of infrastructure requires extensive maintenance in a challenging environment with very limited possibilities of interrupting traffic. This would allow tunnel designers to make judicious choices with respect to tunnel geometry, materials and equipment to optimize efficiency from a structural, mechanical, functional and safety standpoint.

HISTORIC OVERVIEW

Pont-tunnel Louis-Hippolyte–La Fontaine opened in March 1967 and is the oldest of the two tunnels. It is a 1.8-km long underwater gallery running beneath the St. Lawrence River and comprising 7 concrete components that were built in dry dock and then towed, submerged, and assembled on the riverbed (Figure 1a). The tunnel consists of two (2) traffic tubes with three lanes each and a central section that is used for service and rescue purposes.

The Ville-Marie and Viger tunnel complex is more recent. Its concrete structure was constructed in a trench in an ancient riverbed, and subsequently covered over (Figure 1b). It entered into operation in several stages: tunnel Ville-Marie was opened in 1974, tunnel Viger was opened in 1986 and, in 2002 and 2003, three buildings that comprise the Quartier international de Montréal were constructed. The complex now constitutes an underground freeway interchange totalling 6.8 km of traffic tubes varying from one to five traffic lanes, along with several kilometres of evacuation corridors. Other sections of the depressed highway between Ville-Marie and Viger are scheduled to be covered by 2016.

Without a doubt, tunnels Ville-Marie and Louis-Hippolyte–La Fontaine are essential pieces of the Montréal Metropolitan road network, ensuring daily mobility for hundreds of thousands of motorists. Infrastructures of this scale require continuous efforts to ensure user safety and security by efficient operation and periodic maintenance.
Tunnels are considered to be road infrastructures consisting of asphalt pavement along with structural and drainage components. However, they are also complex industrial installations, with hundreds of systems and sub-systems that must operate under extreme weather conditions. This is particularly true of the mechanical and hydraulic systems (fans, motorized louvers, pumps, motorized valves, compressors, elevators, hoists, winches, etc.), the electrical and electronic systems (circuit breakers, isolating switches, cables, generators, batteries, UPS systems, motors, transformers), the lighting and dynamic signalling systems (traffic lights, variable message signs, illuminated signs), the heating systems (heating cables, coils, radiators, thermostats), and the surveillance and safety systems (cameras, fire protection, gas detectors, telephones). Some tunnel features are summarized in Table 1 below.

Systems equipped with electronic devices are very sensitive to aggressive and corrosive environments and require particular attention. Others systems are better suited to tunnels in a northern environment and are more resistant to extreme winter temperatures.

In order to prevent freezing and ice clogging, and to promote drainage, the water-supply lines for the fire-protection system, the gutter expansion joints, the wall drains, the drains under the pavement, and the various trenches and culverts are heated by electrical cables. Rigid copper cables encased in a plastic material are used in pont-tunnel Louis-Hippolyte–La Fontaine. The heating cables in tunnel Ville-Marie Viger are made of neoprene covered with a rubber material. These have proven to be less resistant than expected and, in some cases, have been replaced by the same type of cables used in pont-tunnel Louis-Hippolyte–La Fontaine. The heating cables serve as a partial mitigation measure for the problem of icicle formation, which is mainly caused by infiltration through expansion joints, especially specific joints that have been known to be susceptible to this since the tunnels were opened. In addition, all of the fire cabinets have heaters in order to prevent freezing of the fire protection equipment, including the valves, ducts, extinguishers, and other equipment, such as extinguishing foam for hydrocarbons. This equipment is constantly monitored by temperature sensors, which trigger alarms when necessary.

A large number of remote surveillance and monitoring devices are installed in the tunnels, including sampling gas analyzers, surveillance cameras installed in pressurized climate-controlled housings in order to prevent contamination by salt spray.
Table 1  Tunnel features

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<tr>
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<th>Tunnel Ville-Marie</th>
<th>Tunnel Viger</th>
<th>Tunnel L.-H.-La Fontaine</th>
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<tr>
<td><strong>Opened</strong></td>
<td>1974</td>
<td>1986</td>
<td>1967</td>
</tr>
<tr>
<td><strong>Cost of construction</strong></td>
<td>$120 million</td>
<td>$35 million</td>
<td>$75 million</td>
</tr>
<tr>
<td><strong>Duration of construction</strong></td>
<td>3 years</td>
<td>2 years</td>
<td>5 years</td>
</tr>
<tr>
<td><strong>Number of traffic tubes</strong></td>
<td>8 (including six ramps)</td>
<td>2 (main tubes)</td>
<td>2 (main tubes)</td>
</tr>
<tr>
<td><strong>Length of main tubes</strong></td>
<td>2.2 km</td>
<td>0.5 km</td>
<td>1.8 km</td>
</tr>
<tr>
<td><strong>Cumulative length of tubes</strong></td>
<td>6.3 km</td>
<td>1 km</td>
<td>3.6 km</td>
</tr>
<tr>
<td><strong>Number of traffic lanes per tube</strong></td>
<td>1 to 5 (depending on the tube)</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td><strong>Lane width</strong></td>
<td>3.65 m</td>
<td>3.65 m</td>
<td>3.65 m</td>
</tr>
<tr>
<td><strong>Overhead clearance</strong></td>
<td>4.42 m</td>
<td>4.42 m</td>
<td>4.42 m</td>
</tr>
<tr>
<td><strong>Number of vent shafts</strong></td>
<td>7</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Number of fans</strong></td>
<td>43 (air intake)</td>
<td>8 (air intake)</td>
<td>8 (air intake)</td>
</tr>
<tr>
<td></td>
<td>31 (exhaust)</td>
<td>6 (exhaust)</td>
<td>8 (exhaust)</td>
</tr>
<tr>
<td><strong>Pumping station</strong></td>
<td>5 pumps ( x 120 l/s)</td>
<td>4 pumps</td>
<td>6 pumps ( x 150 l/s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 pumps ( x 50 l/s)</td>
</tr>
<tr>
<td><strong>Security</strong></td>
<td>65 escape doors</td>
<td>8 escape doors</td>
<td>36 escape doors</td>
</tr>
<tr>
<td></td>
<td>144 hydrant points</td>
<td>18 hydrant points</td>
<td>48 hydrant points</td>
</tr>
<tr>
<td></td>
<td>288 lane telephones</td>
<td>36 lane telephones</td>
<td>48 lane telephones</td>
</tr>
<tr>
<td><strong>Generating sets</strong></td>
<td>4 sets ( x  800 kW)</td>
<td>Connected to Ville-Marie</td>
<td>4 sets ( x  400 kW)</td>
</tr>
<tr>
<td><strong>Number of cameras</strong></td>
<td>62</td>
<td>20</td>
<td>20</td>
</tr>
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SAFETY MANAGEMENT

Two monitoring centers dedicated to the tunnels provide continuous remote traffic surveillance; they are designed to detect incidents, control various electromechanical systems, such as ventilation, pumping, lighting, electrical power supply and activate and execute emergency procedures in case of an incident.

In general, tunnel operators receive a five-day training before they are allowed in the control room center, where they are coached by the team leader of a group of six operators. During the first month, new operators are assigned to highway surveillance and traffic management (not tunnels) to familiarize themselves with the tools, software and other equipment available in the control room center.

Reference manuals, emergency plans and ventilation scenarios are updated regularly. Basic training focuses on the operating organization, the road network and its specifics, all technical assets of the facility, all systems related to the facility, normal operating procedures, and emergency procedures. Basic skills are phone reception, keyboard control, and computer use. Theoretical training on the basics of fire engineering in tunnels with the participation of the Montréal Fire Department is also provided to all operators.

All operators are retrained once a year and are asked to participate in debriefings for incidents in which they have been involved. Maintenance staff and other partners involved (firefighters, police
department, etc.), may be asked to participate too. Usually, a second debriefing with external participating agencies is organized.

A theoretical training material for fire engineering and dynamics in road tunnels has been developed and included in the cursus of several fire academies in Montréal and Québec. The ministère des Transports participated in developing the content of this course and allows students to come visit the tunnels and participate in fire drills. Content of the course includes smoke behaviour in tunnels, how and to which extent smoke movements can be controlled with ventilation, what is the critical velocity and why it is important in longitudinally-ventilated tunnels, and fundamentals of different types of ventilation systems available in tunnels. Practical training consists in fire tests with 3 to 5 MW propane-generated fire and exercises in a training center for underground intervention.

Training program and annual exercises allow constant validation of the ventilation strategies with respect to keeping an appropriate longitudinal flow, limiting temperatures, facilitating routing of first responders, and accelerating access to the tunnel. These exercises (Figure 2) allow the ministère des Transports to identify improvements and refurbishment needs for the existing tunnels.

As an example, in past years, in case of fire, operators had to take care of each fan individually using the SCADA tunnel control system (Supervisory Control and Data Acquisition system), and manage all communication tasks related to the emergency procedure. But since 2006, a major improvement allowed them, by the touch of a button, to activate an initial smoke control strategy, leaving more time to other urgent tasks such as communicating with first responders and following the tunnel closure and evacuation procedures. Other recent improvements include the balancing of ventilation dampers in pont-tunnel L-H-La Fontaine and improved signage to the evacuation route with respect to the ventilation strategy implemented.

![Figure 2. Fire tests in tunnels Ville-Marie (to the left) and Viger (to the right).](image)

Proper safety management is also achieved by continuous visual safety inspection and functional tests. Every system must be tested daily, weekly or monthly.

Visual safety inspections are scheduled and performed by maintenance staff to detect any anomalies and to ensure continuous knowledge of the condition of all systems. This is done to initiate preventive or corrective action that is usually the responsibility of the maintenance staff. Some functional tests are scheduled and performed by the control centre personnel and include ventilation systems (fans, dampers, etc.), pumping stations (fire and drainage pumps, etc.), dynamic signs (DMS, illuminated signs, etc.), and redundancy systems (power outage, etc.).

Many tests are programmed to operate automatically. In case of an anomaly, the operator must report it through a web-based system. Telecontrolling, telemetering and telesurveillance of mechanical and electrical parts of the tunnels are carried out by means of a shared SCADA computer-operated system installed in the tunnel control centre and in the maintenance centre of each tunnel.
When a fault is detected on equipment, the control centre personnel use a web-based management application to inform the maintenance personnel and initiate a work order. This makes it possible to quickly share information on the condition of each piece of equipment in order to initiate corrective maintenance if necessary. Other functional tests must be done manually and are performed by the maintenance personnel on a regular basis on components such as the ventilation systems (local control), pumping stations (local control) and redundancy systems (local control).

Other more specialized tests are performed by private contractors, such as testing of the fire protection systems to comply with NFPA and calibration of CO/NO-detection systems. Many tests are scheduled and performed during planned maintenance tasks, such as cleaning.

Tailor-made emergency intervention plans have been adopted in respect of each tunnel. Traffic controllers rely on special software to guide their response when incidents occur. The software takes into account each tunnel’s vulnerability and includes several scenarios of accidents and incidents. The software (Aide à la Gestion des Interventions en Tunnel, or AGIT) proposes an intervention plan geared to the site (camera) and traffic conditions (smooth or congested). Among other things, it includes smoke-removal and traffic-management scenarios. AGIT serves as a reminder of the measures to be adopted in an emergency and is an excellent training and simulation tool.

Order in Council 674-88 is a preventive measure that prohibits vehicles transporting hazardous materials such as compressed gas and flammable, explosive, oxidizing, radioactive or corrosive materials from using pont-tunnel Louis-Hippolyte-La Fontaine and tunnels Ville-Marie and Viger.

MAINTENANCE AND REPAIR WORK

A maintenance centre has been set up in the northern vent shaft of pont-tunnel Louis-Hippolyte-La Fontaine and another one in shaft No. 9 of tunnel Ville-Marie. Maintenance crews encompassing several trades are maintained at both centres, which have parts stores and specialized vehicles such as elevator-equipped trucks, for work carried out above ground, and sweeper trucks. Certain tasks require highly specialized staff. Most specialized equipment is linked to the computerized control and monitoring system, thus facilitating the detection of failures, which appear instantly on the operator’s screen. The operator transmits the information to the head of maintenance so that the necessary repairs can be carried out.

In general, there are two types of road maintenance in Québec: summer maintenance and winter maintenance. In addition to the seasonal distinction, the summer maintenance refers to routine and periodic maintenance of a preventive nature, while winter maintenance refers to all winter maintenance activities. These activities are required in order to keep roadways clear and safe following weather disruptions, including snowstorms or extreme temperatures that reduce tire grip. Although primarily preventive in nature, routine maintenance can also include a remedial component involving minor repairs or replacing equipment.

**Summer maintenance**

In tunnels, summer-type maintenance is carried out throughout the year. Much of this work is cyclical and repetitive. The purpose of this preventive maintenance program is to ensure the safety of users by keeping the tunnels and their systems at their planned safety level and in compliance with design standards. The various activities include cleaning (walls, signalling devices, light standards, drainage, cameras, etc.), replacing parts (lamps, filters, and other hardware), changing fluids (motors, pumps, fans), lubricating and tightening connections (motors, louvers, vents, etc.), and calibrating sensors and alarm levels (detection, probes, etc.). The cleaning of tunnel walls, safety equipment and signage is performed all year around. A specially designed vehicle equipped with a brush and two rinsing vehicles perform the work in summer. In
winter, when there is a warm spell, the walls, signage and traffic signals are cleaned manually using a water jet (Figure 3).

Maintenance of the lighting system is also crucial, and priority is given to the periodic replacement of lighting fixtures. Fluorescent lights at tunnel entrances are replaced every two years and other lighting fixtures, every three years. A truck equipped with a hydraulic platform is used to carry out the work.

Maintenance work on shoulders is similar to that required on any open urban autoroute. Drainage ways are checked regularly and retention basins are cleaned every three months. Water is sprayed into the drains in the fall in order to clean them.

Specialized firms carry out maintenance on specialized equipment such as generating sets, elevators, electrical substations, pumping stations, ventilation equipment, cameras, control and monitoring centres, and back-up units.

Winter maintenance

The main goal of winter maintenance in tunnels is to restore the appropriate safety level of the road in the tunnel and its approaches after a specific meteorological event (mild weather or intense cold) or after a major storm. The constraints imposed by the impact on traffic are significant. However, the urgency of these interventions means that they must be carried out quickly.

Snow and ice removal operations are initiated on the basis of the monitored weather conditions and forecasts. During precipitation events, performance criteria specify a maximum tolerance of 5 to 7 cm of snow. Traffic lanes must be completely cleared within 3 to 5 hours after the end of the precipitation event. Tunnel entrances and exits are critical areas that require special attention (Figure 4). When precipitation is heavy, these zones represent areas of sudden change in terms of both visibility and road surface conditions (snow accumulation). In light of this, these areas receive particular attention in terms of snow removal and salt spreading.
Removal and hauling of snow at tunnel portals is carried out after the storm and requires the complete closure of the tunnel. This operation has a substantial impact on the free traffic flow of the Metropolitan area and is carried during the night after a storm. It involves picking up the snow that has accumulated at the entrances, because tunnels do not have any space to contain the accumulation of snow at the portals. With this in mind, it would be quite beneficial to plan for such a space at entrances during the design stage for tunnels in northern environments.

The monitoring and removal of icicles and ice patches resulting from infiltrations is an operation that is carried out on a continuous basis and governed by clearly defined intervention criteria. Pont-tunnel Louis-Hippolyte–La Fontaine is inspected at 1:00 a.m. and 1:00 p.m. every day. To facilitate the inspection, one or two lanes are blocked in mobile roadwork mode. Tunnels Ville-Marie and Viger are inspected only once a day, at 1:00 a.m. If icicles or ice patches are detected on the pavement, a team is mobilized and must intervene as soon as possible, ideally before the morning rush hour, which starts around 5:00 a.m., or the evening rush hour, which starts around 3:30 p.m. This type of intervention often has a major impact on traffic.

**Challenges and repair work**

Tunnel maintenance poses several problems stemming from the complexity of mechanical and electrical facilities and Montréal’s rigorous winter climate. In particular, mention should be made of the rusting of electrical conduits, short circuits in alarm system cabling, corrosion of fans, water seepage and the blocking of equipment by ice, debris and dirt. Other obstacles relate to the initial layout of the project and the geometry of traffic lanes. The following section will give an overview of the major challenges encountered, the solutions implemented and recommendations for future tunnel designers.

**Traffic disruption**

Tunnel closure for repair work causes major traffic disruption in the Metropolitan area and public dissatisfaction. This is why work is always scheduled by night, during off-peak hours. In addition, taking into account the particular context of visibility in tunnels, work can only be carried out when the traffic tube is completely or partially blocked over its entire length, because lane changes are not permitted inside the traffic tube.

**Ventilation**

In pont-tunnel Louis-Hippolyte-La Fontaine, no provision was made for access to facilitate fan maintenance and repair. Doors have now been added, but workers must be suspended from ropes to gain access to the motors.
Problems were encountered with the fan flaps in tunnel Ville-Marie, which were often obstructed by debris and damaged by rust. The fan motors were not protected by metal casing, as is the case in tunnel Louis-Hippolyte-La Fontaine, which made them more vulnerable, especially as regards manual brakes. In tunnel Ville-Marie, the fan flaps have been replaced six times. Moreover, the fan flaps had to be mounted on ball bearings and all metal parts had to be treated to protect them from salt. The fan motors and manual brakes were also protected by a metal casing and included their own ventilation system. These considerations were taken into account for the design of tunnel Viger, greatly improving maintenance and access to the fans.

Water infiltration from joints

Less than a year after pont-tunnel Louis-Hippolyte-La Fontaine opened, a letter from its designers reported leakage of water in joints running perpendicular to the tunnel’s axis, particularly at the last two special joints. These joints were concreted in the springtime, rather than in the winter, altering the tunnel’s stress environment and producing tension in the joints during winter cold spells. The joints had originally been designed to permit movement without leakage. To prevent such leakage, a chemical substance that swells on contact with water was injected during the winter, while the joint was under maximum tension. Over the past three years, encouraging results have been observed, with a substantial decrease in leakage from the joints. The remainder of the water is drained off into culverts that are heated by electric cables. Although the issues of ice accumulation and icicle formation persist, they have been reduced significantly.

Similar problems were encountered in tunnel Ville-Marie. The slightest imperfection in the concrete or in the manner in which sealants were installed results in sweating or slight leakage. A number of interventions were carried out to inject cement and polyurethane grout starting in the first few years of operation. These injection methods yielded only partial and temporary results. Repeated freezes combined with the quality of the concrete resulted in the development of microcracks, which spread over time, permitting additional leakage. In light of this, another approach was adopted: Rather than trying to stop the leakage, the water was redirected to the drainage system, as long as the tunnel could maintain its full hydraulic capacity.

Power supply

Redundancy of the two 12 000-V power transmission lines that supply electricity to the tunnel is provided by generators. Tunnels Ville-Marie and Viger are equipped with four 800-kW generators and pont-tunnel Louis-Hippolyte-La Fontaine, with four 400-kW generators. A static inverter was installed in pont-tunnel Louis-Hippolyte-La Fontaine to provide electrical power until the generators could operate at full capacity, when an outage occurred. The static inverter, used for the first time in Québec, required considerable maintenance and spare parts were not available. It often failed during outages and was eventually abandoned. Rectifier-equipped back-up batteries are now used, as is the case in tunnels Ville-Marie and Viger. This system supplies roughly one-sixth of the normal lighting capacity and essential control and monitoring equipment; it is much more reliable and demands less maintenance.

The supply of equipment and spare parts, such as cables and electrical conduits which, because they are exposed to intense cold, have been replaced by PVC connectors (the latter resist humidity better than galvanized steel) is also a problem. Impermeable cabling is also used.

Emergency equipment

The tunnels are equipped with heated fire-hose cabinets that house fire extinguishers, hoses and hydrants. In pont-tunnel Louis-Hippolyte-La Fontaine, fire-hose cabinets are accessible through traffic and emergency lanes, which is not the case in tunnel Ville-Marie, because of the geometric complexity of the lanes. The fire-hose cabinets are only accessible through traffic lanes, which hampers maintenance operations. In tunnel Ville-Marie, there are two main types of cabinets, one
containing only a dry chemical extinguisher and the other containing an extinguisher, a hose and two water taps, which are heated in order to prevent freezing. The two types of cabinets alternate at 45-m intervals. Foam tanks were recently installed in each fire-hose cabinet of pont-tunnel Louis-Hippolyte-La Fontaine to accelerate intervention by firefighters.

Rust has been a major problem on original emergency equipment such as escape doors and fire-hose cabinets, parts of which are made of ordinary steel. All such equipment has gradually been replaced by stainless steel equipment.

Some fire hoses frequently burned or hardened because of their proximity to the heating system, a problem that was solved by rolling them up instead of hanging them, to keep them away from the heating system. Furthermore, sheathed neoprene hose, recognized for its resistance to cold, has been used in both tunnels.

**Monitoring equipment**

Carbon monoxide detectors ensure monitoring and control of air quality in the two tunnels. At the outset, a hopcalite sampling device was installed in pont-tunnel Louis-Hippolyte-La Fontaine, although it demanded extensive maintenance and was hard to calibrate. Furthermore, the pumps used to draw air samples inside the compartments tended to overheat and it was thus necessary to install them outside the compartments. Even then, maintenance and monitoring were difficult. This carbon monoxide detection system was soon abandoned and replaced by an infrared system similar to the one used in tunnels Ville-Marie and Viger, which is simpler and provides more accurate readings.

**CONCLUSION**

This article discusses the complexity of tunnel operations, based on case studies of tunnels Ville-Marie and Louis-Hippolyte-La Fontaine. The first part of the document deals with safety management, including emergency planning, training and inspection, and the second part provides an overview of different preventive and corrective maintenance activities and of repair work.

Experience has shown that a substantial part of maintenance costs and difficulties are the result of decisions taken during the design and construction phases of a tunnel project. Unfortunately, those involved in these phases of a project often have only limited experience with the factors that affect maintenance costs. This demonstrates that it is of utmost importance to take tunnel operations and maintenance requirements into consideration during the planning and design of a road tunnel.

In order to achieve the best results, it is important that operators be consulted and allowed to give advice during the whole planning process. This may result in a higher investment cost, but in a lower whole-life costing.

Experienced maintenance staff must be involved and life-cycle cost criteria must be used when choosing between various solutions or options. Making informed decisions based on past experiences will be of the greatest benefit when balancing the maintenance requirements against the cost of constructing a tunnel.

As this article shows, a tunnel designer must always take into account tunnel operations, since the aging of this type of infrastructure requires extensive maintenance. It is essential to consult operators of other tunnels to take advantage of previous experience, thus avoiding potential problems and reducing monitoring and maintenance costs. In this way, judicious choices can be made to optimize the tunnel’s efficiency from a structural, mechanical, functional and safety standpoint, while respecting its geometry, materials and equipment.
All Hazards Approach to Tunnel Safety and Security

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ABSTRACT

Considerable research in tunnel fires has changed our understanding about fire as a hazard, and dramatically changed how tunnel fires are addressed. Yet, there are many other current and probable future tunnel hazards which have not received the same level of attention but which could have major negative impacts to the tunnel operations and structure. This paper points out hazard areas needing further understanding and recommends an ‘All Hazard Approach’ to tunnel safety and security based upon the viewpoint of emergency responders.

KEYWORD: Tunnel, Hazard, Terrorism, Dangerous Goods

OVERVIEW

Modern tunnels are far safer due to the combined efforts of many disciplines. Science which has informed us of extraordinary fire growth and energy release, engineering which has expanded upon this knowledge to design and build safer tunnels, owners and operators who can know be assured today's tunnel fires can be stopped by modern suppression systems, smoke managed by the greatly improved and more efficient ventilation systems.

We, the fire service, are grateful that this evolution has occurred as our lives and most importantly, the people we are sworn to protect are safer. Yet, the world and more specifically the underground world has changed while we worked to understand and contain tunnel fires.

The fire service command have readapted to new challenges beyond fires. The fire service and other responders spend considerable energy in identifying, planning, and preparing for the multitude of possible hazards that can occur above ground in the building world, and therefore are more ready to respond to face newer hazards. Not only those that occur naturally, or accidentally, but those events that occur with malicious intent.

The tunnel community should be constantly adapting and planning for the range of possible hazards beyond fires. To be ready, the fire service has adopted an ‘all hazard approach’ and encourages those responsible for tunnel safety and security, from designers, engineers, owners and perhaps most importantly the researchers to adopt the same all hazard approach.

Although transit properties in the US have hazard analysis guidelines for developing this approach, road tunnels are not required to meet the same rigorous requirements. Using a critical and catastrophic hazard analysis can form the framework for this process and yield a prioritized list of hazards based upon probability and outcomes that can be mitigated. It is important to understand the process of identifying hazards, determining the risks by careful analysis and testing, should provide the necessary knowledge to design for safer new tunnels and retrofits of existing tunnels. However, developing the complete hazard analysis process for tunnels is beyond the scope of this paper. This
paper concentrates on identifying road and rail tunnel hazards as seen from the fire service perspective, and identifies areas that will need additional research.

**HISTORY OF ‘ALL HAZARDS APPROACH’**

The first common use of the term, ‘All Hazards Approach’ was likely in the USA Civil Preparedness efforts of the 1960s and 1970s, “The emphasis of the Defense Civil Preparedness Agency will be to help local governments improve their readiness for any type of emergency. This includes an all-hazards approach to emergency planning with consideration of all contingencies that a disaster may generate, including sudden or gradual onset of the disaster.” (1) (Underline added for emphasis)

This early definition identified; ‘readiness’, and ‘emergency planning for all contingencies from a disaster’, which during this period may have been possible nuclear war. This early all hazard approach has been greatly expanded and debated among governments, responders, hospitals, and politicians. There are now several definitions. Of the several current definitions, the following most closely meets the needs for this discussion.

“The All-Hazards Approach to preparedness means we need to weigh the likelihood and consequences of a broad array of threats. These include, but are not limited to: extremes in weather, industrial hazards, viral pathogens, and of course, terrorism that can take many forms.” (2) The use of an all hazards approach should be strategic, and plan for the full range of hazards. This wide scope, can be very technical, and can entail especially detailed hazard analysis, risk identifications and impacts. Explaining this is beyond the scope of this paper. However, we can overview how an All Hazard Approach for the Fire service has evolved from a single mission, fighting fires, to a strategic approach to most hazards. From this basis we can identify the challenges hazards create in tunnels and identify research needs.

The modern Fire Service has a lengthy history of adapting to challenges. Although for many years the fire service concentrated solely on extinguishing fires, our mission was expanded over time. Many believe our mission changed when we expanded into emergency medicine, and disciplines close to fires, such as extrication from collapsed buildings. However, more importantly was the recognition that simply responding to fires was a losing proposition, i.e. a reactionary position. But thinking of fires a hazard and concentrating on preventing fires, through planning, regulations and inspections resulted in far fewer fires, i.e. a proactive stance. Our prevention approach to fires has expanded to include an all hazard identification and prevention approach where we have been proactive in identifying hazards, preventing them were possible and being ready if necessary. Some hazards are outside the responsibility of the fire service in most communities, specifically criminal acts and terrorism. Tunnel should consider how interagency cooperation could assist tunnels understand and prevent hazards.

We, the tunnel community, have learned hard lessons from the tragedies that have occurred in tunnel fires, this same community should now adopt an all hazard approach recognizing our tunnels, and in fact, the underground world, is a far more difficult environment in which to address what are perceived to be minor surface hazards, but which underground can be severely life threatening. The underground of the future will be far more than underground transit stations, interconnected pedestrian walkways and the occasional shopping strips built to move ‘out of the weather’.

The demand for more usable space in the urban centers will eventually cause policy makers to recognize there is massive available space in the underground. Add to this the climate change impacts resulting with extreme weather. Unfortunately our underground safety regulations are simply not
ready for a massive move to the world beneath our feet and certainly not ready for the challenges an all hazards approach will identify.

The world has long faced dangers besides fires. These include environmental hazards such as sudden weather extremes, geologic hazards such as earthquakes, and manmade hazards in the forms of war, and more recently a global shift to utilize terrorism as a weapon to attain political and personal agendas. Although the natural disasters appear to be occurring with greater frequency and severity due to climate change, the human caused hazards are growing exponentially. The combination of all of these hazards has presented new challenges for the emergency responders at all levels and of all types.

The fire service and other responders spend considerable time planning the 'what if scenarios' that can occur to the world we must respond to. This planning process has forced us to face new challenges not only due to accidental fire, unplanned hazardous materials spills, larger scale traffic accidents with multiple casualties, but more recently a range of intentional acts aimed at harm, disrupting operations and instilling fear in the people. This has ranged from relatively minor nuisance actions by disgruntled lone individuals to well-coordinated militaristic actions designed to instill fear and distrust in addition to the very real deaths and destruction. The tunnels are readily available to the public and will continue to be used by terrorists.

It has taken the fire service decades to fully adapt to an 'all hazards' approach, the tunnel world might not have the luxury of this time line given the proliferation of terrorism and environmentally driven incidents.

BEYOND FIRE - AN EVOLUTION FOR RESPONDERS (Possible Research)

Prevention

Initially the fire service only fought fires. We did not concentrate on fire prevention, but realized early in the history of the fire service that prevention saves lives and property and became a higher priority. In the 1970s, the America Burning programs identified the deaths and destruction caused by fires was extensive. “In 1971 alone, 2,512 million fires killed 12,200 people, and the nation had incurred a property loss of some $2.8 billion.” (3) Prevention became a hallmark of the fire service. With this emphasis towards prevention there has been remarkable success. Major cities with a history of active fire prevention are finding the number of accidental fires remaining relatively constant against a growing population.

For comparison some of our worst fires in tunnels might be are readily preventable. The 2007 Interstate 5 truck underpass fire N of LA resulted in three deaths, destroyed 31 vehicles, caused 25 million in damage and closed this critical freeway for three days while temporary repairs were made. On investigation the truckers reported there had been several unreported accidents attributed to sight problems and high posted speed. After the accident the speed limit was reduced 10 mph to 45 mph.

Emergency Medicine

Over time, the fire service was tasked with more and larger expectations to provide public safety, and we took on the role of emergency medicine. This was largely pioneered in a few US cities with Seattle, USA becoming an international model of success. The number of emergency medical calls (many related to motor vehicle accidents) is growing for many fire service agencies, or for
independent emergency medicine response groups. The volume of emergency medical response is now more than triple the number of fires in many urban areas.

Dealing with emergency medical response, or perhaps more correctly, the medical hazards, is a cornerstone of many emergency responses agencies. A key is the emergency responders cannot ‘fix’ the patient, only stabilize them for treatment at a hospital. Time to access to the patient and transport to a hospital become critical.

Per NFPA 1710, 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, there are several objectives, including, “480 seconds or less travel time for the arrival of an advanced life support (ALS) unit at an emergency medical incident,” … “provided a first responder with AED or basic life support (BLS) unit arrived in 240 seconds or less travel time” (4)

This is very difficult objective to reach in tunnels due to limited access points and typical traffic congestion resulting from the incident. The tunnel itself is not the hazard, but the fundamental design creates the challenge. Many current designs are using ‘cross passages’ in lieu of egress/access stairs. The lack of surface access can mean accessing the patient and transporting them nearly the entire length of the tunnel. This drastically increases time to arrive at the patient and extricate them to the hospital. For lengthy tunnels, alternate transportation should be provided. The Chunnel is one of the known tunnels with this feature. If improvements are not made to allow rapid patient access and removal from the tunnel, an alternate medical approach should be considered. Could emergency physicians, with minimum equipment be dispatched to the scene for medical intervention? Alternates need to be considered.

Hazardous Materials, Dangerous Goods

The increasing and widespread use of ever increasing chemicals has resulted in more frequent incident of greater size and impact AND with far greater complications due to the higher toxicity.

Responding to Hazardous Materials, (Dangerous Goods), (HM(DG)) has become a separate discipline in some fire agencies where a dedicated HM(DG), full time emergency response team is used. The need for this separate team is a combination of the frequency incidents, technical knowledge necessary to identify and correctly respond, and the necessary equipment to approach, identify and mitigate the incident. Since many of these HM(DG) incidents are a result of transportation accidents, ‘A Guidebook for First Responders During the Initial Phase of a Dangerous Goods/ Hazardous Materials Transportation Incident’ or ERG, was developed internationally with a new 2016 version out shortly. The ERG uses required vehicle placarding information, or information from shipping papers, to direct the responder to a ‘guide page’ in the ERG which has information common to group of chemicals based upon the hazard classification. For example ERG Guide 114 describes actions, hazards, and isolation distances relative to certain groups of explosives. Toxicity information is also included on other pages which typically provides greater isolation distances and distinguishes between upwind and downwind (plume).

HM(DG) transportation in tunnels is lightly enforced in many areas. In the US, the individual states set regulations, however, even when regulations are enforced, the typical penalty for illegally using a tunnel is often not much more costly than the fuel to drive around the tunnel. A worthwhile gamble for drivers who move HM(DG). We can expect increasing demand to transport HM(DG) via tunnels due to transportation costs to bypass the tunnel. Some tunnels are restricting HM(DG) to off peak
times which reduces but does not eliminate the risks to the public. The Eisenhower Tunnel in Colorado installed a $25M deluge sprinkler system to allow heavy goods vehicles to use the tunnel versus the alternate, i.e. long waits until designated times, or driving a very long alternate route.

For rail tunnels, passenger trains and freight trains (which commonly have HM(DG as part of the consist) routinely share tunnels. The potential for disaster is very real; however, the number of derailments is still relatively low in tunnels. Seattle is expecting to see 30 additional, one mile long oil trains per day, on top of the approximately 50 freight trains (which includes HM(DG) in their consists) daily. These trains are frequently in the one mile tunnel under downtown Seattle daily.

Oddly, there are some advantages to HM(DG) spills and releases in tunnels. The impact of an airborne release above ground can rapidly spread to surrounding populations and is predictable by ‘plume patterns’ of who will be harmed. In a tunnel, the same hazard might be contained within the tunnel by use of the tunnel ventilation to achieve a zero air movement. Fire suppression systems might be used to purge the airborne gases or dilute liquid spills. If tunnels are used for HM(DG) simultaneously with passenger rail, changes may be needed. Drainage in tunnels can be designed to contain liquid spills. Tunnel access of HM(DG) can be controlled using technology similar to marine ports where full truck scanners identify potentially dangerous chemicals. Some jurisdictions’ require HM(DG) to follow a prescriptive route through their areas, including tunnels, and follow the vehicles electronically to ensure compliance. More research is needed in these areas.

Technical Rescue

For decades the average firefighter and law enforcement officer took only common sense precautions before attempting confined space rescues, often with abysmal results. For a time the number of rescuer deaths exceeded those who died in the confined spaces. US Federal regulations were initiated to prescribe minimum steps for entering confined spaces as either a worker or a rescuer. The tunnel ‘back of house areas’, utilidors, and drainage areas can be confined spaces requiring special training and equipment to enter for work or during a rescue.

Accidental or intentional acts using explosives can create traffic and rail mayhem. Vehicles can be severely damaged, trapping riders or motorists and preventing their own self rescue. The term ‘heavy rescue’ is used to describe the hazards and challenges posed to safely extract humans from crushed vehicle and or industrial accidents. For tunnels this becomes even more of a challenge as the tools used to move large vehicles, such as mobile cranes, simply do not fit in the confines of a tunnel.

Seattle is undergoing emergency response planning to identify means and methods to shift overturned large trucks in the limited space of a tunnel. Technical rescue teams have developed ‘lifting bags’ which can move even the heaviest motor vehicles and train cars, unless they are pinned against a tunnel wall. Using cutting torches to remove parts of vehicles for emergency extrication and which can be readily deployed above ground with adequate ventilation create their own hazards in a tunnel environment due the gases released and sparking, i.e. ignition sources. Rail vehicles damaged in tunnel accidents can create extraordinary challenges for heavy rescue where the only access is from either end and lifting the vehicles is dangerous. Determining best practices for vehicle (road and rail) technical rescue in tunnels is missing and could be researched to identify best methods and equipment.
Terrorism

Although terrorism has been known for centuries, the modern availability of exceptionally deadly weapons, coupled with religious/cult fanaticism, mentally deranged individuals has directly impacted tunnels. The range of weapons available to use in tunnel is wide. These terrorist weapons are defined by the acronym CRBNE. Chemical, Radioactive, Biological Nuclear and Explosives.

The array of options for CBRNE uses in tunnels is many. We saw a limited application of this in the Sarin Gas attacks in Tokyo in 1995. This single incident changed the way many view terrorism in passenger rail tunnels. The use of gas attacks in tunnels is more effective than above ground given the geometry, high concentration of riders, and limited space for gas diffusion.

Tunnel bomb attacks to subways have dramatic results. Madrid, London, Moscow and others have suffered from these terrorist acts which not only impact those directly involved but create fear in the riders, exactly what terrorism is designed to accomplish.

Even a small bomb can cause inordinate damage as simply damaging a piece of tunnel rail track can result in derailing a train moving at speed with devastating results. The kinetic energy from a derailment is distributed to the fixed tunnel structure as a train impacts the sides, walls, and ceiling of a tunnel. The kinetic energy imbued to the human body is enormous, yielding fatalities and injuries on a larger scale. Responding to a tunnel can be very time consuming. For example although 1998 Eschede, Germany high speed rail disaster resulted in 101 fatalities. Many more might have died if this had occurred in a tunnel simply due to lengthy emergency response times to provide emergency medicine and extrication to victims.

A key part of The Metro Project tested the vulnerabilities of passenger rail cars to internal explosives. Recommendations from the tests were eye-opening to responders when they realized the damages would preclude self rescue by any survivors due to damage to the doors, and, prevent emergency responders from readily reaching the survivors by both the damaged doors and the heavy frame construction. The construction makes using commonly rescue tools very time consuming. Cutting open a lightweight automobile is simple compared to the cutting heavy steel frames of trains. Research into best methods to extricated victims from a heavy gauge passenger rail car is needed.

Coupling all hazards with risk assessment can bring understanding of potentials. For tunnels through mountains or under bodies of water, simply damaging the surrounding structure can have serious complications. For example damaging an underwater tunnel can flood not only the immediate tunnel but allow flooding throughout large underground areas. Port Authority of New Jersey New York and the US National Institute of Standards and Technology developed robust ‘tunnel plugs’ designed to reduce or stop flooding.

The tunnel authorities and law enforcement have responded to the threat of terrorism with increased security by using point of entry control methods. E.g. camera recognition to identify known terrorists is far more widely used today. Newer forms of CBRNE detectors have been deployed with limited success given the slow detection processing times. Research is ongoing to develop real time CBRNE detection.

Use of biological agents in tunnels has great potential as airborne releases can spread quickly. Tests performed documented spread through wide areas of major metro systems in minutes due to natural ventilation and piston effect. The ability to quickly and effectively stop air movement could be used to prevent further spread if rapid detection becomes available. Zero air velocity presents the ‘reverse’
challenge to tunnel ventilation experts who have strived to optimize ventilation efficiencies. If Zero velocity is not possible, using mechanical ventilation to exhaust possible airborne chemicals or biological agents to specific, lower risk areas should be considered. However, much further study is needed to be able to make a command decision whether using the typical response of isolating and identifying a suspected HM(DG), OR, quickly exhausting the hazard to an unsuspecting neighborhood results in the least harm.

Natural Disasters

When considering tunnel hazards we cannot discount natural hazards. Weather is not often considered a threat to tunnels, yet major storms can flood tunnels. Extreme storms such as Hurricane Sandy resulted in tunnels being flooded in the New York area. The cost to retrofit systems (especially electrical) damaged by water is significant and could be preventable, either by preventing water infiltration or designing for possible water damage. Flood gates have been installed in some tunnels. The Alaska Way Viaduct tunnel in Seattle designed their utilidor as a water holding area to contain water from fire suppression and fire hand lines. This greatly reduced the size of pumps, and related power supplies and pump discharge lines. The cost benefit of analysis of waterproofing the electrical systems in the utilidor demonstrated this was considered a good tradeoff.

Unlike weather emergencies, earthquakes occur without warning. Typically earthquakes do not cause major damage to tunnels. Major tunnel damage can occur without warning and could derail trains, or cause motor vehicle accidents. Early warning technology for earthquakes is promising but does not provide predictable levels of security needed to stop traffic prior to the quake energy striking the tunnel. Geology plays a key role in earthquake risk and the recent opened Turkey Marmaray rail tunnel project crosses between tectonic plates, which arguably could be the location of more frequent and greater earthquake ground movements. Extraordinary engineering was used to create a flexible ‘joint’ across the plate fault line. This is expected to successfully withstand any earthquake reasonably predictable.

Multiple Hazards

With a better understanding of known, existing hazards we can contemplate the potential for multiple hazards, or incidents occurring at the same time. First we need to recognize the fundamental assumption by fire and safety codes is we must only design and construct for a single hazard at one time, one fire, one flood, etc. This simplified approach does not realistically address what can happen either above or underground and especially in tunnels if multiple hazards occur simultaneously.

Most responders recognize that more than one ‘bad thing’ can happen as a result of the initial incident. For example, a car accident can result in both injuries and fire. Above ground the relatively easy access from all sides of the accident makes mitigating the two challenges difficult but not impossible.

In a tunnel, the limited access to the incident, long distances to the incident from access points, dependency on systems, such as ventilation, lighting, etc., multiplies the complexity and the need for additional resources.

Quantifying the complexity is difficult. Many would simply assume a single incident with multiple hazards occurring would not add too much difficulty. In practice, this can be a gross underestimation. Taking the accident with fire and injuries, the presence of both changes many elements of a successful rescue. Typically individuals injured in an accident are rapidly triaged to determine degree of injury.
and which patients need advance care and rapid transport first. Safely removed an injured person from an automobile is not technically difficult, but needs to be done correctly to avoid further injury. The responder resources of a single unit with four persons can remove a patient that is not trapped in a few minutes. Typically we would remove one person at a time as the resources are limited and several people are needed to move an injured person correctly. If more than one person is severely injured, additional resources can be called but their response time can be several minutes.

If there is a fire, some of the initial responders are used to prevent the fire from spreading and hopefully to extinguish the fire. Taking one person from a four person responder crew can slow the successful removal of the first and subsequent patients. If the fire cannot be quickly brought under control the patient’s life may be in jeopardy and rapid extrication might be necessary. This can jeopardize the patient health, but the choice of further health issues versus death is not a difficult choice.

In a tunnel this would not seem too difficult unless the time to reach the incident has allowed the fire to grow to a point where extraordinary efforts are needed to stop the fire growth. Rescuing a patient from inside a car which heavy fire impingement requires coordinated actions by the responders. Perhaps multiple fire hose lines, more personnel etc. The time it takes to access an incident in a tunnel can more than add difficulty; the delay can compound the problem.

Multiple hazards can occur from a single action. A train derailment at speed can cause injuries, fires, and require technical rescue to even access the patients, along with fire suppression, on scene advance life support etc.

Any tunnel incident that involved HM(DG) almost always compounds the difficulty responders face. HM(DG) fires on the surface are usually addressed as defensive actions, i.e. prevent the incident from growing. This defensive posture works well on the surface where building occupants have multiple exit points. In a tunnel the nearest exit can be far away and if a fire is involved, the fire growth rate can be extraordinary and the smoke extremely toxic.

In more practical terms, the more hazards involved, the more challenging in terms of time, resources, etc. Keep in mind the longer time to mitigate, the lower probabilities for survival.

FUTURE HAZARDS

We must not limit the all hazards approach to these known tunnel hazards. Tunnels are changing as society, demand for tunnels, and technology changes.

We are still using the tunnels built in the late 19th and early 20th century, some are over 100 years old. Tunnels built today are also expected to function for a full century or longer, i.e. 2116+. Although we may marvel at this engineering success, we should recognize the rapid societal changes we are undergoing and what this could mean for hazards. What changes, and therefore what new or more complex hazards will we face in the next 100 years that will not contemplated in today’s designs.

Perhaps looking backwards will frame our perception of the future. Initially tunnels were constructed to overcome topographic obstacles. Rail tunnels for materials transport was possibly the first modern use of a constructed tunnel transportation tunnel. Although since the tunnels were built, there were obvious tunnel related hazards such as collapse, fire, derailments, etc. these risks were acceptable by
society and not addressed to the degree we do so today. This isn’t to say there was no effort for risk management, but perhaps surprisingly this was not necessarily concern about human risk.

A good example is the Hoosac, Massachusetts, rail tunnel opened in 1875 after a difficult, lengthy and deadly construction. The tunnel was considered quite advanced for its time and was the longest tunnel in North America until 1915. In 1889, “85-90 trains passed through the tunnel daily. Rear end collisions happened as a result of the smoke from the coal fired train. Some collisions proved to be fatal. Ventilation was so poor that train crews had to lie on the floor to find breathable air. Boiler fires would die down to the point that the crews had to stick broom sticks out and against the wall to determine if they were still moving.” (5) A 16 foot fans were added at the central shaft to exhaust smoke and therefore reduce train slowdowns caused by lack of visibility or low levels of oxygen.

In 1910, in the New York train terminal area (North River Tunnels) used the first US electrified locomotives (via traction power) with a 650v DC third rail system installed to reduce exhaust smoke. In 1915 an overhead catenary with 1100 v 25 hertz ac was established in the Philadelphia terminal area. Overhead catenary is still widely used between cities and in tunnels. The efforts to reduce exhaust smoke, added a new, and sometimes deadly hazard as most recently demonstrated by the January 2015 WMATA fatality as a result of traction power electrical arcing.

With the demand for automobiles and trucks to move people and goods, the Holland road tunnel in New York was opened in 1929. This tunnel was special as considerable efforts were made to understand the CO exhaust from cars and trucks and its effect on humans. This tunnel pioneered the full transverse ventilation system. The Holland road tunnel and North River rail tunnels are still in use.

Notoriously, the Holland Road tunnel was the site of the 1949 hazardous materials tunnel fire which injured 66, caused one fatality, damaged over 500 feet of ceiling. After the fire over 650 tons of debris was removed. The fire caused over $7.5M damage (in today’s dollars) Inadvertently the transverse ventilation system designed to manage carbon monoxide was at least partially successful in controlling the smoke from the hazardous materials fire when the fire burned a large hole in the ceiling exhaust plenum. This larger hole allowed the smoke to be extracted by the large fans in the exhaust towers. The heat was so intense the exhaust fans were cooled by firefighter hose streams.

Fortunately the history of HM(DG) fires in tunnels is relatively rare. However a missile fuel fire, propane tanker BLEVE, several flammable liquid fires in road tunnels, and of course major hazardous materials fires in rail tunnels have occurred and have resulted in deadly consequences.

We might ask, if in 100 years, the modes of transportation; walking, bicycles, cars, buses, and trains will continue relatively unchanged. We should expect continuing efforts for ever increasing volumes of people in existing and future tunnels. More simply, we can expect a demand for greater capacity either in new larger tunnels or in existing tunnels. Increasing the number of people in an existing tunnel might seem innocuous, however, without changing either the egress capacity or the ability to prevent and control fires will compromise the ability for people to safely exit, i.e. a new hazard created by changes not included in design.

For example, although train tunnels that use longitudinal ventilation can realistically only have one train in a ventilation zone due to fire/smoke hazard, this principal has already been disregarded. In New York, the practice of putting more than one train in the same ventilation zone in a tunnel occurs daily. This poses a hazard to riders as we can expect a fire to occur somewhere in the midpoint of a tunnel on one of the train cars. Pushing smoke in either direction will endanger all passengers.
downstream. Adding more trains in one ventilation zone is a ‘new hazard’ not envisioned by the tunnel designer.

Multiple trains in one ventilation zone are a direct result of need for greater capacity. With limited funds for new tunnels, we can expect increasing requests for more capacity in existing tunnels. Science and engineering will be asked to increase this capacity. Although faster trains and higher speed limits in road tunnels will seem an easy approach, more likely we will see requests for more people in a tunnel in the form of higher densities, or more people per vehicle. To improve fire safety, we can envision faster on board suppression. Ultra fast fire detection and suppressions systems already exist and could be modified for passenger rail tunnels. This could reduce design fires dramatically.

We can also expect mode combinations as well. We have seen a few examples of combined bus and passenger rail in Seattle and Boston. We can expect cars, trucks and heavy freight trains in the not too distant future. We should expect to see all forms of ground based transportation in our future tunnels. These might not be neatly separated by fire walls; rather we could see bicycles, pedestrians, and freight trains sharing the same ventilated spaces. The complexity of design will be difficult, but not likely impossible.

Looking forward we can expect not only higher capacity demand for existing tunnels but alternatives to fuels, and transportation modes. We are already seeing a significant shift to other fuels; biodiesel, and to a limited degree alternate fuels such as hydrogen powered vehicles are becoming common. Fires have been reported on natural gas powered buses in Australia tunnels.

Although we are still heavily dependent on hydrocarbons, we are attempting to wean ourselves off this dependency which might take the form of highly efficient batteries. What hazards do these pose? Perhaps the airline industry has already pointed to battery hazards. Shipping lithium ion batteries resulted in two plane crashes a UPS plane in 2010 and an Asiana plane in 2011. Four significant battery fires occurred in new Boeing 787s in 2010. These are cautionary tales. But lend credence to approaching new technologies in tunnels with care. Having truck or train cargo composed of densely packed newer batteries or some ‘yet to be developed’ energy system might create both a fire and explosion risk.

Rather than carrying power sources on the vehicles, we can expect ‘simpler’ versions of traction power, i.e. without catenary or third rail. This might take the form of broadcast power, either generally across large areas, or linearly with buried inductive systems. This could extend to heavy rail as well. Perhaps this change will result in a reduction in hazards in the tunnel.

Road transportation will also change with the advent of digitally connected cars and ‘car trains’. Connected cars could allow remote coordination of vehicles to improve transportation and could be coordinated with fire protection and life safety systems to move the car (and occupant) to the safest place in the event of an emergency. Perhaps ‘car trains’ will allow higher capacity use of tunnels. Car trains allow near zero spacing between vehicles and allow higher speed as well.

One possible new mode might be ‘vehicle less’ transportation in tunnels in urban areas. People movers are prevalent in airports, but could be used on a grander scale in tunnels. High speed people movers with equal speed air movement might make people movers an option.

Climate change is already predicted to be so severe in the Middle East the surface areas will become uninhabitable due to intense heat. We can expect efforts to move underground on a large scale as
climate change impacts expand. Migration away from areas with extreme heat to other, more temperate climates will occur in the near term. This might cause growth predictions for urban centers to be underestimated resulting in an even greater demand for increased capacity.

We already have fire protection and life safety systems which can be connected wirelessly. In tunnels this could save substantial cost by reducing or eliminating hard wire control cables. This is similar to the ‘connected cars’. We have seen hackers take remote control of connected vehicles, bringing up the specter of wholesale control of vehicles, control systems and fire protection systems by cyber attacks as a newer, wholesale form of terrorism.

**Probability**

With increases in number of tunnels, increasing the miles (kilometers), and simply more vehicles we can expect greater frequency of incidents unless changes are made to the vehicles and tunnels. If we recall the Chunnel prediction of the probability of one fire per 500 years has been discounted with three major fires (1996, 2008, and 2015) in 21 years.

If we continue to build ever longer tunnels with multiple vehicles in the tunnel at the same time, we should expect to have more than one fire occur at the same time. If we ask the firefighters if it is possible to have two car fires at roughly the same time in a 5 mile tunnel, they will agree this is not likely but certainly possible. The challenge is tunnels are typically not designed for multiple fire scenarios. However, the lack of requirement does not prevent a second fire from occurring. The Tunnel Operator might be faced with more than one tunnel incident occurring simultaneously, but be limited in the ability to successfully mitigate both incidents. The ‘only one fire’ design belief is an extension of fundamental assumptions from the building, fire codes and standards which are tasked with some very large buildings, but not buildings that are several miles long as we are seeing in tunnels. The lack of requirement to simultaneously address more than one incident should be clearly stated in the basis of design. Where possible the basis of design should specifically address more than one incident, and incidents of varying types.

**Tunnel Operator Response in the Future**

We are already seeing a major move to include fire life safety systems in tunnels which adds considerable complexity. When the typical new tunnel emergency response plan is reviewed there are often well over a dozen steps expected of the tunnel operator when an incident occurs. This often includes correctly identify the fire location, notify motorists, emergency responders, initiate ventilation and fire suppression for the correct zone, etc. Many tunnel operators are also expected to notify tunnel crews, and their supervisors. Expecting a tunnel operator to correctly make these choices and take the relevant actions is perhaps asking too much from one or two people, especially if they are also witnessing (via camera) multiple individuals injured by the incident. The chances of operator errors are worth consideration. To avoid the errors the use of SCADA (Supervisory Control and Data Acquisition Systems) are becoming much more popular.

SCADA allows semi automatic activation of a pre determined ‘emergency scenario’. For example a scenario might be a motor vehicle stopping in a tunnel. This could result in lane closures, notification to tunnel incident response team, change in lighting, etc. All of these steps can be taken by SCADA with tunnel operator supervision. Currently, the more complex scenarios revolve around fire responses. In that regard adapting the ‘positive alarm sequence’ (PAS) method as specified in NFPA 72 for managing an incident adds both reliable systems initiations and full operator control.
PAS provides a short time for a Tunnel Operator to acknowledge an alarm, before anyone other than the operator is notified. After acknowledging the alarm, the operator has three minutes to verify the alarm is genuine or abort the preprogrammed emergency scenario. This maintains complete control of the systems by the tunnel operator. However, if the tunnel operator is unavailable to acknowledge the alarm, or fails to take any action within the three minute investigation phase the preprogrammed scenario is initiated. Even after initiation, the tunnel operator can stop the scenario at any time.

Also, there is limited tunnel operator training and most of this is tunnel specific. Tunnel operators are a key resource to correctly managing an incident, and in fact, become the initial incident commander for many jurisdictions. To be successful the Tunnel Operator should not only be conversant in incident command and daily traffic nuances, but fully understand the basis of design for the various tunnels systems, what options are available if one or more of the systems fail, and understand the probable results of HM(DG) releases, either accidentally or intentionally. There are many skill sets the Tunnel Operator should possess especially if we consider the complications of multi hazards.

**TUNNEL ASSUMPTIONS**

The Runehammer and Metro Project full scale tests demonstrated the previously assumed fire growth rate and heat release rates in road and rail tunnels have been underestimated. This might be considered a new hazard of significant proportion, but in fact was a hazard created by misunderstanding tunnel fire assumptions. The result of these tests have demonstrated the ventilation systems in most tunnels are likely not adequate to deal with smoke from a large scale fire.

Passenger rail emergency evacuations are based upon the previously assumed slow fire growth rate and low maximum heat release rate. The ventilation systems may be undersized, and the time for successful self rescue may be too generous.

Another incorrect assumption is the erroneous belief that fire suppression systems (sprinklers and mist) are bad. Excessive steams, explosions, are often cited as ‘reasons’ why suppression systems won’t work and are dangerous. However, modern tunnel fire and vehicle fire tests are proving these are incorrect assumptions. We should understand there are hundreds of thousands of these systems in buildings around the world whose performance record is outstanding. An NFPA study identified frangible head sprinkler systems fail to operate correctly .018% of times due to component errors. The basis for the steam and explosion belief is the 1965 Ofenegg test. These tests erroneously allowed the fire to burn uncontrolled for an extended period of time resulting in excessive steam when the suppression system was allowed to operate. Delaying operation is not the recommended practice. Additionally the test pan fire was not correctly controlled to prevent flammable vapors after extinguishment. The vapors from the heating fuel found an ignition source resulting in a sudden and explosive reignition. This was also an incorrect operation of the sprinkler system.

There is an assumption that smoke from fire will always stratify, forming a nice, even layer at the tunnel ceiling. Many jurisdictions rely on stratification as a key portion of their egress strategy. Ventilation modelers might also rely on stratification to extract the smoke layer at the top of the tunnel. This reliance may be misplaced. From practical experience we know smoke from a fire does not ‘always’ have enough buoyancy to rise up and away from a fire and linger near the ceiling. There are circumstance where smoke is produced (pyrolysis) without a free burning, open flame fire. Smoke produced in this manner might be only marginally more buoyant than the ambient air conditions and can quickly cool and spread across the tunnel cross section. Fires with extremely high heat release rates can produce prodigious quantities of smoke. This smoke may have enough pressure
to displace the cooler air near the fire, i.e. the stratification layer is from the ceiling to the tunnel floor if the fire air supply is coming from one side. It is understandable the tunnel community has the believe of stratification as nearly all the test fires use fuel sources with known properties for heat, and more specifically smoke production to test the ventilation systems.

However, watching a multitude of pan tests does not accurately reflect all the real fires we see in tunnels. In fact, smoke from a tunnel fire has similar ranges of buoyancy as found in building fires. Some smoke is very hot and retains its buoyancy for considerable distances away from the fire. Some smoke might be relatively cool and therefore not nearly as buoyant. This cooler smoke simply fills the air space below the ceiling, leaving a narrow band of fresh air at the floor where oxygen rich air is pulled to the seat of the fire. Assuming ‘all smoke will always stratify’ poses another hazard as this can create an erroneous assumption for exiting and for smoke extraction.

Tenable smoke is also a non valid assumption in tunnels. NFPA allows people to be in smoke for a limited time based upon the toxicity of the smoke. For NFPA tenable smoke is presumed to be the byproduct of a fire where the fuel is relatively benign. Typically this would include organics, such as wood, cotton, paper. In tunnels the common approach to smoke toxicity is to measure certain gases, commonly produced by fires. If the gas level is below a certain threshold, the smoke toxicity might be considered not ‘too bad’. However, in tunnels the smoke can be almost instantaneously lethal depending on the product being burned. In road tunnels a heavy goods vehicle can be carrying legal ordinary cargo, or, illegal hazardous materials which, if burned in a vehicle accident is deadly. For rail tunnels, the risk is not on passenger trains, but combined freight and passenger tunnel where, if a freight train fire occurs, the smoke can be very toxic exposing the passenger train occupants.

**SUMMARY**

Although historically the hazards associated with using tunnels have been largely discounted, the use of tunnels today comes with greater expectations of safety. For many years this expectation was focused on reducing the hazards presented by tunnel fires. However, fire is not the only hazard we face in the underground.

The tunnel community should realize the other, non fire, hazards ranging from weather induced, such as flooding; to very real threats of terrorism which could cripple regional economies need to be addressed. This paper has identified many hazards needing additional research; much probable future challenges and outlined briefly the potentials associated with multiple hazards interacting in a tunnel.

We can anticipate continued and increasing demand for more tunnels and a push to use existing tunnels at much greater capacity levels, simply put, more people in tunnels at the same time. This seems an inevitable evolution in tunnels unless new tunnel construction costs are reduced or funding for major tunnel infrastructure projects is increased.

We can congratulate ourselves in developing a better understanding of fire potential and planning to use this knowledge for the safety of the public, responders and protecting the tunnel assets. However, we cannot stop the quest to understand tunnel hazards, either those we are aware of, or those that will be presented in our futures and perhaps we should be looking at a wider scope beyond tunnels, the public use of the underground.
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Safety and Security Issues in Complex Underground Infrastructures

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ABSTRACT

There is an unnecessarily pessimistic tension between safety and security in underground infrastructures. A good balance is essential because it is not possible for one to exist without the other. This paper seeks to identify good practices in safety and security, explaining why it is important to have both in equal measure.

KEYWORDS: safety, security, underground, ISTSS, scientific paper, tension

INTRODUCTION

New challenges, new technology, new processes and new lessons learned from past experiences all combine to drive the evolution of rail fire safety standards. The ongoing process of modernisation, along with new rolling stock designs and changes to rail networks as new lines are added or existing ones are extended, means that ensuring passenger safety is all about chasing ever-moving targets without compromise.

It has been said that the last twenty years have seen the most joined up approach to fire safety ever. The biggest changes came in the late nineties and early noughties, when the industry consolidated its knowledge of construction materials and greatly improved interoperability between rail networks. There are many diverse companies operating rail networks and getting them to agree on harmonised standards has been hard. These last few years have seen an unprecedented, joined-up approach in Europe with the publication of the Technical Standards for Interoperability and a revised European Norm for the fire safety of rolling stock in EN-45545 Parts 1 to 7. The work that has been done on improving fire safety for buildings and infrastructure is not necessarily also applicable to trains.

The process has not been without its difficulties, especially as each of the major European nations had its own unique testing methods and local specifications, all of which will eventually be superseded by EN45545. It is for that very reason that progress along the long and hard road to the right formula has had to have been driven by an understanding that common standards are in everyone’s best interests. It is laudable to have the same level of safety across Europe. Passengers joining a train that leaves the northern tip of Norway and travels to southern Spain must have confidence in the level of safety for the entire journey.

Conferences like this play an important role in collecting together industry professionals from the whole global industry to look at safety issues. The bridges that have been built and the cementing of relationships between interested parties is now especially important as the industry embarks on the new dawn of a massive investment in new trains and the refurbishment of existing rolling stock.

There is, however, an unnecessarily pessimistic tension between safety and security in underground
infrastructures. A good balance is essential because it is not possible for one to exist without the other. This paper seeks to identify good practices in safety and security, explaining why it is important to have both in equal measure.

First, two definitions:

- **Safety** – The condition of being protected from or unlikely to cause danger, risk, or injury.

- **Security** – The state of being free from danger or threat.

It is only by careful consideration of the interfaces between fire safety and network security that successful safety and security strategies can be assured.

**SECURITY THREATS**

With over four million passenger journeys a day, it is vitally important to keep London Underground premises and services safe and secure. This is done in a number of ways, and all staff have a key role to play, as do contractors, cleaners, tenants and customers. LU security procedures have been developed over a number of years and are based upon advice given by the police and UK Transport Security & Contingencies Directorate (TRANSEC).

LU security procedures can be broken down into two main areas:

- Network Security
- Station Security

**NETWORK SECURITY TEAM**

LU’s specialist Network Security Team offers support and advice to the business in all matters relating to physical security of the network and security from terrorism.

This involves working with Transport Security Inspectors from the Department for Transport in order to ensure that minimum security standards are always met. The team also provides advice and guidance to projects and commercial developments in order to ensure that best security practice is complied with.

In addition to this, strong working relationships exist with the Community Safety & Crime Prevention Unit who advise the business on matters relating to Crime Prevention and Section 17 of the UK Crime and Disorder Act, and regularly collaborate in order to ensure that crime and terrorism is considered as part of the design phase of projects. As one example, new or existing street level secure buildings are designed to be unobtrusive and blend in with natural surroundings. Physical barriers are designed with security and the environment in mind.

Strong working relationships have been forged with police and other government departments involved in security and counter-terrorism. The team is fully embedded within LU’s Command & Control structure, and support the business in terms of putting in place measures to reduce incidents of vandalism, graffiti and cable theft. The steps taken in order to reduce disruption to the railway have meant that London Underground is able to assist in providing a safe, secure and reliable service.

Prevention is only one part of the story; the ability to evacuate, when necessary, is essential, while at the same time, keeping undesirable elements out is vital. There is always a balance to be struck and in certain other premises, overzealous security measures mean people cannot escape in a fire situation or fire brigades cannot approach and gain access because of bollards and barriers. This is not the case
within London Underground. Success lies in having an “open” transport system with vigilant staff and passengers. Crime rates may be low but perception can often make this appear worse than reality. The importance of visible staff and a strong police presence cannot be over-emphasized – herein lies the operational staffing strategy of TfL and London Underground and it includes the role of the British Transport Police (BTP).

UNATTENDED OR SUSPICIOUS ITEMS

To deal first with the “routine”. Over 160 items of lost property are dealt with every day, by Underground staff using the “HOT” procedure (defined below). Of these, very few are considered suspicious and require the attendance of the BTP. The HOT procedure has been successfully used on UK railways for over 15 years and has been adopted by other agencies in the UK and abroad, including Australia, Eurostar, USA and other international metro systems.

The HOT procedure was devised in the early 1990s. The origins of HOT stem from the analysis of over 5,000 unattended bag incidents and police incident reports. It enables rail staff to evaluate the risk associated with the discovery of unattended items.

HOT is designed to enhance staff and customer safety whilst avoiding disruption and risk caused by stalled trains elsewhere on the network. HOT is based on the premise that unattended items are:

- not Hidden and are found in public areas in plain view
- not Obviously suspicious
- are Typical of what is regularly encountered

HOT is an integral part of the initial assessment process and has a well defined application. It is a first response measure for dealing with items identified as unattended and discovered within public spaces. It should be used every time an item is identified as unattended.

EVACUATION PROCEDURE

If after applying HOT, staff decide the item is suspicious, they move away and initiate the evacuation procedure.

Returning to the subject of access and egress, LU has procedures in place to prevent access by unauthorised/unqualified persons - including contractors - into any area where they have no jurisdiction or where they could place themselves or others at risk. Keys are only available to essential users and contractors via specifically authorised and identified individuals. Intervention points are designed to prevent and deter trespass by members of the public while ensuring that fire authority requirements for emergency access and evacuation are fully met. Robust standards ensure the Intervention Points are always operationally secure and fit for purpose.

STATION SECURITY

There are a variety of other, less mundane, security threats on the London Underground network, including:

- Active shooter
- Hostile surveillance and suspicious behaviour
- Bomb Threats
- Chemical and biological threats
ACTIVE SHOOTER

'Active shooter' is the term given by police to an attack consisting of one or more people using firearms. This form of attack in a busy place like the Tube, a shopping centre or another crowded place is considered to be one option that could be utilised by terrorist groups. London Underground regularly provides its staff with specific security guidance on threats such as this. For obvious reasons, this guidance won’t be detailed in this paper.

HOSTILE SURVEILLANCE AND SUSPICIOUS BEHAVIOUR

Terrorists and other criminals use surveillance techniques to help plan attacks. This will include reconnaissance and testing out the security measures at potential targets on and around the system. It's during this preparation that the best chance of spotting suspicious behaviour exists, when the terrorist is at their most vulnerable to being exposed.

If staff see something that is out of place they can engage effectively by offering customer service. More often than not it will be innocent activity such as someone lost or in need of assistance. Perhaps it is people taking videos or photos: does it look like regular tourist photography or something out of the ordinary? LU staff behaviour is in keeping with the advice given to customers: “If you suspect it, report it”.

Notifying the BTP of any concerns helps build up a network-wide intelligence picture. This information will then feed into the Metropolitan Police specialists who will analyse the intelligence and they will take action if necessary. Staff know the station and tunnel environment best, so LU depends and trusts on them to follow their instincts. Even if the activity or behaviour ends up not being suspicious, the information is still worthwhile. Joint working with the emergency services, mutual respect and complementary emergency and contingency plans all contribute to excellence in safety, security and fire prevention.

BOMB THREATS

Bomb threats are a regular occurrence for the UK rail network. Bomb threats can be communicated by telephone, in person or even by email or social media. The vast majority are made with mischief in mind and may be from schoolchildren, intoxicated people or others who perhaps hold a grudge against public transport and it is important that they do not generate any unnecessary safety risk by overreacting to all threats.

Safety is the top priority though and the BTP have had a process in place for twenty years that lets them assess each threat and for them to then provide advice to rail operators. When a station has been mentioned in such a threat, a police inspector will carry out an assessment and the actions that staff should follow will come from a BTP police officer, the London Underground Control Centre or from Service Controllers.

SAFETY AND SECURITY DURING CONSTRUCTION WORKS

Drawing on the importance of safety in tunnels under construction, the opportunity arises to share some experience of the work behind the scenes at London Underground’s Bond Street Station Upgrade Project. Some of this subject matter has been presented internally and to the Transport Special Interest Group of Institution of Fire Engineers at the IFE Annual General Meeting, in London, during the summer of 2015 but it hasn’t been widely broadcast.

The IFE SIG comprises approximately 25 fire safety engineering professionals and has elaborated on such issues as flame spread in façade glazing due to the flammability of ablative layers of Polyvinyl butyral ("PVB") resin used in ballistic glass [PVB is prepared from the reaction of polyvinyl alcohol]...
with butyraldehyde; tunnel safety and the peer-review of documents such as the UK Fire and Rescue Service Operational Guidance on Railway Incidents.

Some of the most complex tunnelling undertaken in the UK if not Europe has been the tunnelling in Central London, driving tunnels between existing London Underground assets, with potential impacts on the Underground, Thames Water (including sewers), the (now redundant) Post Office tunnels as well as the buildings above. The depth of shafts ranges from 18m to 24m and tunnels weave their progress between many existing utilities. The longest tunnel run is approximately 450 metres. A large contribution towards personnel safety has been made by the use of video clips of site activities when inducting new staff. Acquisition of skills, knowledge, training & experience has been assessed before the issue of competency certificates. Frequent checks are made of operative capability and a strict adherence of a zero tolerance towards the abuse of drugs and alcohol ensures alertness and compliance with procedural safeguards. Crane team & plant operators’ induction is frequently reviewed to include on-site assessment: possession of a card on its own does not confer capability. There’s a strong focus on behavioural safety including the use of role playing and interactive learning sessions to reveal any shortcomings in human performance.

RISK MANAGEMENT IN TFL

Risk is defined as ‘an uncertain event or set of events that, should it occur, will have an effect on the achievement of objectives’. The effect can be positive (opportunity) or negative (threat).

TfL manages risks by looking at threats and exploiting opportunities.

TfL faces many different types of risk, such as

- Strategic risks
- Operational risks
- Programme and project risks
- Information risk
- Health, safety and environmental risks
- LU Asset risk

TfL has a continuous and systematic approach to managing risk by proportionally addressing the risks surrounding the organisation's activities. Risk management is part of TfL's culture and staff are required to comply with TfL's risk management policy and risk management procedure.

RISK REGISTER

A project risk register has been implemented and workshops include the use of “bowtie” modelling construction phase risk assessment. The origins of bowtie can be found in the simplified fusion of fault and event tree methodologies. In the 1990’s the oil and gas industries founded and developed the practical application of bowtie as a tool to facilitate a better understanding of how risks were being managed. The benefits of the methodology have since been recognised in numerous other industries including defence, medical, financial and the aviation industry. If, like the author, readers have had any experience of aviation, they will be familiar with Professor James Reason’s model, referred to as the ‘Swiss cheese’ and bowtie is a barrier-based structure illustrating this approach. Bowtie achieves reductions in risk by not only identifying the controls (or barriers) in place but also looking at control failure mechanisms (as escalation factors) and in turn how these are managed (as escalation factor controls). Based on these considerations, insights are gained into an organisation’s risk mitigation strategies and therefore into the appropriate management of safety resources. The main strength of the barrier approach is as a qualitative tool, which is of tremendous benefit where statistical information on quantitative losses may be unknown or where the numbers of losses have been so low that the veracity of quantitative data cannot be relied upon.
FIRE PRECAUTIONS

Fire Prevention Controls and Station Emergency Planning

The prevention of fire is always viewed as a prime objective. Both the environment within which a fire can start, and the processes within that environment shall be controlled, e.g. the minimising of ignition and fuel sources. A number of technical and managerial controls are to be applied during the various phases of the project.

RESPONSIBILITIES

Responsible Person

In the United Kingdom, the definition and responsibilities of the ‘Responsible Person’ are defined in the Regulatory Reform (Fire Safety) Order 2005. In terms of LU the ‘Responsible Person’ is the corporate entity, not an individual person. Where there are multiple occupants on a premises, or where a fire on one premises would affect another, there is a duty to consult and co-operate between all interested parties, the results of which would normally be recorded by the principal landlord.

Competent Person

The definition and responsibilities of the ‘Competent Person’ are outlined in the Regulatory Reform (Fire Safety) Order 2005.

PREPARATION OF A FIRE STRATEGY

A Fire Strategy is prepared as part of the design process for all new buildings, stations, and railway facilities. “Lessons learned” capture good custom and practice and any number of solutions used in the past, as an aid to the development of a robust fire strategy. For work on existing premises a Fire Risk Management Impact Assessment shall be completed. It’s a mini version of a fire strategy. The Fire Strategy should address the means of escape from the premises (in case of fire) for able bodied and persons with restricted mobility; the means of giving warning in case of fire (fire detection and alarm systems: public address / voice alarm systems (PA/VA)); automatic fire suppression or extinguishing systems, which may be provided either for safety reasons or for asset-protection purposes; the provision of fire-resisting construction, to provide fire and smoke separation or containment (often known as 'compartmentation') or to provide structural fire resistance. ‘Compartmentation’ refers to a fire rated elements of construction (including all elements of walls, floor and ceiling) segregating areas of risk. Fire separation refers to fire rated construction provided to protect the means of escape from fire and smoke.

As important as these factors described above are, robust control over the reaction-to-fire performance of the materials used in construction and fit-out (including flame spread, combustibility, smoke and toxic fumes) is fundamental in securing fire safety on LU; London Underground adopts stringent controls to ensure prevention remains at the heart of its strategic approach.

Where passive measures cannot by themselves satisfy, the provision of manual fire suppression / extinguishing systems (both fixed and portable) for use by the occupants of the premises supplement the design.

The provision of emergency lighting and illuminated escape signage (including Emergency Do Not Enter signage) facilitates the management of staff, contractor and passenger flows. Access and facilities for firefighters, including protected fire-fighting access, fire brigade communications and fire-fighting water supplies are provided by reference to good custom and practice, being discussed with the fire authorities where the constraints of the premises might mean code-compliance isn’t fully achievable.
The preparation of a Fire Strategy (or impact assessment in the case of minor alterations) is always done by a competent Fire Engineer and will be checked and approved by another LU-accredited Fire Engineer.

**FIRE PROTECTION: ENGINEERING SYSTEMS**

Fire protection systems are incorporated into premises according to statutory requirements and with any further conditions imposed by other parties (such as Insurers, Fire Authority and the Office of Rail & Road). The strategy is to ensure that life safety and property protection risks are managed. ‘Critical Systems’ may require additional fire protection equipment and these will be identified in the Fire Strategy e.g. signal rooms and control rooms. The identification of such systems should be performed with reference to the relevant asset-specific “Category 1” standards (principally signalling and communications) and agreed with the relevant discipline engineers, the asset steward(s) and the operators.

**Automatic Detection and Warning of Fire**

Sub-surface stations and certain surface stations have fire detection and alarm systems for the early identification and warning of fire. Other premises and some key installations (e.g. Signal Equipment Rooms), will have fire detection and alarm systems installed subject to the risk to persons or criticality for business continuity.

Where there are other premises adjacent to or associated with station premises then it should be considered whether a fire in that premises could pose such a risk that the station requires a link (sometimes called a “Grey Link”) between the fire alarm in the premises and the station alarm. This is the approach that was taken in the construction activity at Bond Street tunnels. Similarly, if a fire on the station may result in significant risk to the other premises then a link may also be necessary. In all cases where such links are being considered it must be subject to a risk assessment undertaken by a competent fire engineer, and links should only be implemented when warranted by the risk. In general where there is no access to, from or shared with the station, where the premises do not share power or other building services with the station or the railway and where there is imperforate fire resisting separation between the premises in accordance with Building Regulations, then such links should not normally be necessary.

**Fire Suppression Systems**

Suppression systems are provided at Sub Surface Stations in specified non public areas to meet the requirements of The Fire Precautions (Sub-Surface Railway Stations) (England) Regulations 2009. They are also provided as part of an engineered solution on these stations and other premises to deal with specific fire safety or asset protection issues. They consist of sprinkler systems supplied by town’s mains and ‘stand alone’ water fog systems which have their own limited water supply. Specially designed sprinkler protection systems are also provided for all escalator installations. The designs used by London Underground do not meet the British or European standards as full coverage of the station is not specified (nor is it necessary) and the protected and unprotected areas are not fire separated to the relevant standards. The Fire Strategy will identify any new requirements for suppression including any extension or modification to the existing system. If it is recognised through the design process, that consideration should be given to the installation of such a system where one does not exist at present, or to the extension or modification in any way of an existing installation, this should be identified in the Fire Strategy. Where sprinkler removal is proposed due to a change of room use (i.e. a significant reduction in fire risk) it may be necessary for pipe-work to continue to pass through the area to feed heads positioned elsewhere. Similarly, where changes may not be permanent, then it may be prudent to retain the sprinklers in order to provide flexibility in future room use. In such cases it may be preferable to leave the sprinklers in place as an alternative to removing the heads and fire insulating the pipe-work. The contents of the room will, of course, need to be considered.
Smoke Control and Extraction Systems

Where installed, ventilation systems should be designed to contain or control smoke, maintain safety on enclosed escape routes, aid evacuation and purge smoke from certain areas once evacuation is complete. It must be simple to operate both centrally from a control centre and locally at the station. Passive measures for smoke control are dealt with under compartmentation.

Note: on some stations, areas exist which could serve as smoke reservoirs in the event of a fire. As so far as reasonable practicable, these should be maintained and consideration should be given to the provision of vertical containment barriers (down stands) where appropriate.

Ductwork and Fire / Smoke Dampers

Fire resistant ductwork and provision of fire resistant insulated dampers will be co-ordinated within the design to ensure that all compartmentation and separation is maintained. Fire dampers are installed in such a way to allow easy access for maintenance. The number of fire dampers required may be reduced by using fire resistant ducting. On premises with fire detection systems, the fire damper will be operated from the fire system. On constrained, below-ground installations, insulated fire/smoke dampers are normally used. This keeps the cause and effect simple. The cause and effect is programmed to limit the number of dampers that close to those in the vicinity of the fire and to shut off associated fans. This should take into consideration the criticality of rooms in the area that may be required to continue in operation where not specifically affected by the fire. Notwithstanding the above, care is required where smoke could affect the means of escape.

Station Controls and Fire Service Facilities

Where adjacent or nearby stations are affected by nearby tunnelling works, Station Operations Rooms (SOR) or Station Control Points (SCP) are places where the station’s main fire control panel is located and where the CCTV is monitored and the PA is operated. It is the place to where the ‘grey link’ that was mentioned earlier terminates – on the station Main Fire Control Panel. In general, these rooms have a protected route from fresh air or a second means of access / egress. Where this is unachievable or impracticable, a fireman’s microphone is installed at or near the station RVP and training provided to the station staff in its use, and on any stations with Fire Detection and Alarm installed, a fully functional networked fire panel is also installed at or near the RVP and training provided to the station staff.

Fire Prevention Controls and Station Emergency Planning

The prevention of fire is always viewed as a prime objective. Both the environment within which a fire can start, and the processes within that environment shall be controlled, e.g. the minimising of ignition and fuel sources. The following are some of the technical and managerial controls that are applied during the various phases of the project.

Fire Safety Management

The Regulatory Reform (Fire Safety) Order requires all premises (covered under the order) to have a Fire Risk Assessment (FRA) produced (or the existing Fire Risk Assessment reviewed) by the Responsible Person (the Manager of the premises for its use). On stations, this FRA comprises the Customer and Workplace Risk Assessments, the Congestion Control and Emergency Plan and station drawings (Compliance Fire Plans). On LU staff-occupied and managed premises it comprises the work place risk assessment and emergency plan. On all other premises a site or activity-based Fire Risk Assessment is produced for the use of the premises. All complex premises will have fire plans that identify the fire safety provisions required for the use of the building.
Proposed Structural Alterations / Room Use Changes

These will be detailed in the Fire Strategy or impact assessment. For Stations, notification of works and applications for approval to proceed with installation, the production of approval plans and the amendment to compliance plans will be made in accordance with an agreed process of change control, prior to the start of work. Design changes identified during the build will also be agreed using the same process. Fire precautions in the Bond Street tunnels were selected based upon the outcomes of fire and emergency risk assessments done on the specific construction phases by tunnelling specialists from the joint venture company.

The London Fire Brigade (LFB) was included in the development of the emergency plans and desk top exercises have involved LFB. Joint table-top exercises with the LFB elaborated reasonably plausible scenarios & these were collaboratively worked through to develop reasonable well-balanced, measured responses. Regular site visit familiarisation takes place for the nearest and second nearest fire station personnel and LFB information folders are updated on site by LFB personnel in addition to the LU Fire Safety Unit keeping records made of the changes in risk profile and site drawings. Emergency drills are conducted on site, including fire and personal injury scenarios. Station phased fire strategies have been carefully co-ordinated to allow emergency exits from the tunnel sections to the station. These are over and above the facilities and procedures already in place to ensure all workers and visitors are safe in the tunnels.

Control of Works

To ensure that the Fire Strategy for any premises remains effective, all works undertaken in any premises must be controlled. Controls ensure that hazardous processes are minimised, or if essential, undertaken in a safe manner. Steps are taken to ensure installed fire detection and / or suppression systems are not adversely affected by works, as they may be prone to false alarm or accidental system activation. The latter can lead to reduced confidence in, and effectiveness of the fire protection systems. During works involving the dismantling of active or passive fire protection measures for a given period, alternative arrangements must be made to cover for the reduced protection – this could include providing temporary fire stopping or increased frequency of inspections. Hoardings are provided to separate the work site in public and staff occupied areas to avoid accidents. If the work is being done during times when the train timetable is operation with members of the public in nearby stations, these hoardings may need to be fire separating.

Risk assessments & method statements govern all works. Risk assessments were undertaken on the work planned in the stations (behind hoarding lines) and the impacts assessed on the Over Site Development (OSD) buildings. A primary Risk Assessed Method Statement (RAMS) was produced for the overall works, with smaller activity-specific RAMS detailing each phase of the advance. Each RAMS covers project and programme methodology and includes the capability levels for operatives. All workers and visitors have self-rescue re-breather sets which provide breathable air for at least 30 minutes (at walking pace). Maximum numbers in the tunnels is limited by the 30 minute breathing capacity of the respiratory protection and how many “man-rider” lifts to be taken. (The slowest way out of each shaft is via the man-rider). If the man-rider is used, it can make one trip in approximately 3 minutes. Therefore, with 40 people who can escape, the number of operatives in a tunnel is never allowed to exceed 40. Visitors have their own area and there are limited respiratory protection re-breather sets for visitors to minimise the amount of visitors in the tunnels. A standard tally board system is, therefore, used to ensure the maximum number of workers and visitors is not exceeded.

Safe Systems of Work are developed and ‘signed-off’ by competent, accountable persons before processes and procedures are allowed on site. One example is in the use of specific Lifting Plans. These were brought about as a result of lessons learned in 2014.

In addition to the standard hot works procedures required on all sites, a tally system has been implemented to control and manage the provision of gas cylinders within the tunnels. This not only
clearly shows the location of gas cylinders are but limits their number. Ventilation systems are configured to shut down and reduce the supply of oxygen to any fire.

Minimising Ignition Sources and Fire Loading

Smoking is banned everywhere on the LU network. A hazardous operation such as the use of heat producing equipment by contractors is subject to risk assessment, limitations and control. ‘Hot Work Permit’ processes should be initiated where the use of heat producing equipment is necessary. The use is made of equipment and materials (e.g. electrical equipment) within specified limits and fitted with protective devices, where appropriate.

Oxford Street (near Bond Street station) has now achieved the dubious distinction as having the world’s highest known concentration of the toxic pollutant nitrogen dioxide (NO₂), exceeding the European Union maximum level of 40mcg/m³ by a factor of 3. Ways were examined that could contribute to a lessening of the impact of tunnelling works. By making the most use of electric plant, the project minimally contributes to localised atmospheric pollution levels.

The outcome is a welcome reduction in emitted diesel particulates and an associated safety benefit is that bulk fuel storage and usage has coincidently reduced.

Waste materials generated from works are kept to a minimum during progress of the project and disposed of at the end of every shift. Materials not disposed of are regarded as stored items and appropriate controls will need to be introduced. LU contract-management conditions and Rule Books deal with storage arrangements including arrangements for hazardous substances and non-compliant plant and materials. Escape routes must not be used for the temporary or permanent storage of materials or equipment, unless agreed with relevant parties including the landlord manager and the Fire Authority through a process of change control. Redundant services, fixtures and fittings, signage and posters should be removed as part of the works and made good.

Measures to remove rubbish and undergrowth from beneath platforms are incorporated into LU’s waste management policy; all materials used for LU premises and stations have been chosen in ways to minimise fire load. Furnishings, linings and equipment meet relevant criteria regarding ignitability, flammability, combustibility and the emissions of smoke and toxic fume. For stations and tunnels (including all sub-surface stations listed in LU Standard S1086) only materials compliant with the reaction-to-fire-properties of materials can be used.

EVACUATION

Means of escape

The provision and maintenance of safe escape routes is paramount to the evacuation strategy. The work must ensure the protection of the existing routes and, as far as reasonably practicable, improve the current situation. This will depend on the extent and location of the work. It will be reviewed during Design Reviews and ultimately tested when the Fire Strategy is presented at the Qualitative Design Review. Tunnel emergency training has involved rendering first aid, casualty extraction and fire fighting training. This has included a simulation of what to do in cases of anaphylactic shock when it was discovered that the tunnel ‘king’ would have a life-threatening reaction to bee stings.

Emergency Lighting

Sufficient emergency lighting must always be provided for escape routes for staff and members of the public in accordance with the strategy contained in LU Category 1 Standard, 1-066. This is to enable the station to be safely and effectively used for evacuation of passengers during a power failure and to permit the continuing function or use of critical areas or facilities such as machine and plant rooms. Emergency lighting will comprise either self-contained battery units and / or centralised off-line
battery inverter systems. Installations will be in accordance with BS 5266 Part 1. In addition, LU has its own power generating facilities.

Emergency lighting is provided by 110v lights with a battery back up, each luminaire being identified on site by red grommets. Portable fire fighting equipment is provided according to the aggregate number of the overall tunnel workings. This is additional to any specifically required by the method statements for particular works. A first aid kit, stretcher & automatic defibrillator are available in each shaft, station & OSD, with each tunnelling gang having its own trained first-aiders, additionally “tunnel-rescue” trained.

Signage

Topography - tunnel areas are confusing places and clear boards using the principle of ‘tourist maps’ bearing “You are Here” legends aids the identification of safe exits for any unfamiliar or complacent personnel. The strategy is to ensure that all exits and exit routes are indicated by symbol-based signs, and that all other signage is provided to a common standard. This is dealt with by the TfL Signs Unit. Illumination of signs is dealt with under Electrical Engineering systems (1-066).

Additional Fire Engineering Provisions

The requirement for fire suppression on trains within the UK railway safety principles relates to trains that could create a high fire load. London Underground has taken considerable steps in the design of its rolling stock to ensure this is not the case. Fire suppression systems are, therefore, not normally provided on passenger rolling stock. However if it is recognised through the design process for engineering works that such installations would be of benefit to plant used in construction, this will be considered and mention will be made of it in the a specific supplement to the Generic Fire Strategy. This has been the case with regard to construction plant used in the tunnels. All machinery used within the tunnel sections has automatic fire suppression fixed. A proprietary system made up of a small diameter plastic pipe which is positioned throughout the engine compartment is used to protect valuable machinery. The pipe melts when heated and extinguishing agent is sprayed directly at the source of the heat. The fire alarm system is linked to Tunnels, Over Site Development (OSD) & Station hand workings (behind the hoarding lines). The over-arching principle is that when the alarm sounds: evacuate all areas. Manually operated water mist curtains are installed along each tunnel and at major intersections, providing a facility to prevent the spread of smoke and toxic fumes along the tunnels, given improved visibility to allow operatives to evacuate. (These water curtains have not been designed to extinguish a fire but to aid evacuation).

ACCESS & FACILITIES FOR FIRE FIGHTING

Hydrant systems currently exist on the majority of sub surface stations. Where it is identified that the hydrants require replacement as part of a major improvement or specific asset renewal they should be replaced with dry falling mains. Dry falling mains will only be provided following consultation with the Fire Authority with regard to the location and number of inlets. The legal responsibility for ensuring adequate water supplies for fire fighting in the UK rests with the fire authorities. This includes, in particular, the provision of any street hydrants. These are installed by the local Water Undertaker, upon the request of the Fire Authority who pays the cost of the installation.

The Fire Strategy shall identify the location of the nearest street hydrants to each station and premise in order to identify where any shortfall may exist. The local fire authority should be notified if a shortfall in the public supply is identified. Hydrant provisions for extensive sites are provided and maintained as part of those sites and any shortfalls for any new development should be addressed in the Fire Strategy.

Due to the constrained nature of the tunnels under construction and the potential difficulty in accessing water supplies for fire fighting, fire hydrants were placed at 50 metre intervals along the
tunnel length. This equates to 2 or 3 standard hose lengths (hoses can vary in length from 19m to 25m). Tunnelling operatives have been trained in branch and hose handling and use. Management take personal accountability for checks on equipment, which ensures responsibilities are not overlooked or have been malapportioned or reapportioned.

As previously described, fire protection systems are incorporated into LU premises in compliance with statutory requirements and with any further conditions imposed by other parties (such as Insurers, the Fire Authority and the Office of Rail and Road (ORR)). Constructional fire safety features and materials used will comply with the intent of the Building Regulations Approved Document B, BS 9999 or any more onerous requirements specified in an LU Category 1 standard. Where there is the opportunity to improve the fire safety of the premises, this should be identified for discussion with the relevant regulator(s). Where works are being carried out consecutively or concurrently by a number of projects, it may be necessary for a ‘holistic’ view to be taken of the impact of all the projects combined when deciding what is reasonably practicable as regards fire precautions. Where the works are planned to retain existing non compliances, with relevant fire codes and standards, either during construction or once complete, a Fire Engineering approach may be used, as set out in BS 7974 – “The application of fire safety engineering principles to the design of buildings”.

**MANAGEMENT CONTROLS**

**Minimising Ignition Sources and Fire Loading**

Smoking is banned everywhere on the LU network. As previously written, any hazardous operation such as the use of heat producing equipment by contractors is subject to risk assessment, limitations and control.

Waste materials generated from works are kept to a minimum during progress of the project and measures to remove rubbish and undergrowth from beneath platforms are incorporated into LU’s waste management policy.

**SECURITY**

Once built, station forecourts often require vehicular access to service equipment and machinery, the permanent way, tenancies and retail outlets. In lengthy tunnels, intervention points will be inevitable to permit expeditious evacuation and aid fire services access. Intervention points on third party land bring with them all kinds of encumbrances. Negotiations entered into many years beforehand must continue to be respected and responsibilities that the many parties have towards each other must be made easy to enforce. An appropriate level of external lighting is used to deter trespass and discourage loitering and to ensure that, where external CCTV is deployed, the best quality of pictures is obtained.

When changes are made to the layout and use of any premises, the Fire Safety management shall be reviewed and the risk assessment(s) updated to address the impact of these changes. The responsibility to notify the responsible person of his responsibilities lies with the instigator of the change who should identify this in the Impact assessment or Fire Strategy.

**EMERGENCY PROCEDURES**

“Normal operation” means the operation of that part of the railway in the way in which it was designed to operate (e.g. includes the rush hour peaks and troughs in demand experienced during the day); “Degraded operation” means the state of part of the railway system when it continues to operate in a restricted manner (e.g. after the failure of one or more components, such as an escalator out of use or one track of a railway line out of use); and “Emergency Operation” means current unforeseen or unplanned events that have life threatening or extreme loss implications and require immediate
attention.

CHEMICAL AND BIOLOGICAL THREATS

There has only ever been one confirmed incident of Chemical, Biological or Radiological (CBR) attack on a transport system. That took place in Tokyo in 1995, with the release of a chemical nerve agent called “Sarin”. This demonstrates that such attacks are difficult to deploy effectively in a civilian environment. Although this sort of attack is considered less likely than conventional means, it cannot be completely ruled out. The experience of London Underground has only been with hoaxes and false alarms.

LESSONS LEARNED

Like many disasters of our time (1985 having been a very bad year for fire safety disasters), the Kings’ Cross fire of 1987 had a remarkable affect on London Underground. After the Herald of Free Enterprise ferry sank in 1987 the company went out of business. When the British Airtours aircraft caught fire on the runway at Manchester Airport in 1985 the company name was soon changed. Rail had its share of disasters like the King’s Cross fire of 1987 and the Oxford Circus fire in 1984, but rail still remains far safer than many other forms of public transport, excepting only air travel and LU has kept its name and improved its reputation. Constant research, development and testing are vital to maintaining a good track record. LU has been pleased to have been a partner in a European Project entitled “Getaway”, which examined the ability of tunnel and station occupants to discern prompts from traditional signs and to evaluate the potential of active, or dynamic, signage. LU pioneered this approach with configurable enamel signs on its premises in the 1950’s and still uses some very simple reconfigurable signs today. The next generation of signs will be controlled by the fire detection and alarm installation or by other detection technologies.

Modelling techniques can be very subjective and, sometimes, there is little science behind them, so full scale exercises and tests are very important. For these reasons, LU embarks on partnership working with others, such as SP and the London Fire Brigade to undertake evacuation trials and tests. It is equally important to not forget the hard truths that emerge from incidents of fire, such as the King’s Cross fire of 1987, nearly 30 years ago.

CONCLUSION

There have been many changes in station design, fire prevention technology and rolling stock design over the years and the rail industry has responded well in coping with those changes. The key has been to use readily available materials that meet passengers’ needs in terms of ambience, comfort and safety and build effective relationships with suppliers, who work very closely with fire scientists and stakeholder, such as the regulatory bodies.

Only when equal priority is given to every aspect of fire safety and security in the construction of tunnels and trains, the design of stations, the training of staff and the properties of new materials can interoperable safety and security be assured.
Ventilation Strategies – an Integral Part of Fire Protection Systems in Modern Tunnels

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ABSTRACT
Fires within confines of underground systems pose major safety issues and challenges to designers. In fact these fires are considered to be among the most difficult to extinguish due to restricted space of operation and limited access points for fire fighters; limited emergency exit locations; restricted availability of water supply; and ventilation capabilities. Nowadays these challenges are further deepened with the increase in the number of tunnels, their length and number of people using them. Incidents in tunnels can threaten life in a number of ways; e.g. the inhalation of combustion products such as carbon monoxide and carbon dioxide and the exposure to high temperatures and heat fluxes. Tunnel design should address all relevant fire safety issues such as: safeguard of tunnel users, safe rescue operations, minimal effects on the environment due to the release of combustion gases, and a minimal loss of property. Post-fire studies of major road tunnel incidents indicate that there are numerous opportunities for improving tunnel safety aspect following a fire incident. The article sheds the light on the inevitability of pursuing a holistic approach that integrates all elements of safety in the tunnel as well as tunnel operation procedures in order to ensure the overall tunnel safety during all phases of an incident.

KEYWORD: Emergency ventilation, roadway tunnels, fire incidents, visibility, backlayering, detection systems, fixed fire fighting systems, life safety.

INTRODUCTION
In general, fires in tunnels are rare events and, therefore, the statistical data on the rates of fires is limited. Nonetheless, the rates can change considerably by only one fire event. Tunnel fires are mainly generated by the traffic (95%) passing through the tunnel (collisions, electrical defects, brakes overheating, or other defects leading to the self-ignition of a vehicle) and to a much less degree by tunnel equipment and maintenance work [1]. As such, the likelihood of tunnel fires is mainly related to items like tunnel length, traffic density, type of traffic and combustible load, speed control and slope of the road.

The post-event analyses [2] of major road tunnel incidents, including the Mont Blanc, Tauern, St. Gotthard and Fréjus Tunnel fires, revealed that the fire size could rapidly grow and spread inducing high temperatures and a large volume of smoke over great distances within the tunnel. Furthermore, the analyses indicated unexpected behaviour of tunnel users in which they could not recognize the amount of danger they were in, and therefore opted to stay in their vehicles during the early stages of a fire incident over egressing and using the self-rescue safety systems. This resulted in loss of life in circumstances, which otherwise were not considered to be high risk scenarios.

In the event of an incident or accident, the first 10 to 15 mins are crucial when it comes to people saving themselves and limiting damage of tunnel structure and facilities. If the fire attains high levels of energy release rates, 50 to 100 MW, it becomes difficult to deal with it let alone to approach it. Past major fire events showed the difficulty of extinguishing the fire at this stage either due to the density of smoke in the tunnel or the intensity of radiation (Temperatures up to 1350°C) [1,3] and heat fluxes...
in excess of 300 kW/m², preventing the fire service approaching the fire source. The prevention of critical events or the early intervention are, therefore, the number-one priority, which means that the most important measures to be taken may have to be of a preventive nature.

The Standard for Road Tunnels, Bridges, and Other Limited Access Highways - NFPA 502 [4] requires that a tenable environment be maintained in the tunnel and dictates that motorist should not be exposed to maximum air temperatures that exceed 60°C during emergencies and maximum radiant heat of 2.5 kW/m² for more than 30 min. Furthermore, it states that smoke obscuration levels should be continuously kept below the point at which a sign internally illuminated at 80 lx is discernible at 30 m and doors and walls are discernible at 10 m. The World Road Association [5] recommends a tenable tunnel environment during the self-rescue phase in which: air temperature should not be higher than 80°C for longer than 15 min; radiation does not exceed a level of 2-2.5 kW/m² for users and 5 kW/m² for fire fighters; and, a minimum visibility of 7 to 15 m is maintained. Guidelines dictate that people must, in any case, be able to reach a safe place in a reasonably short time while travelling a reasonably short distance. Therefore, facilities such as emergency exits or fireproof shelters should be provided whenever necessary.

Fire Development in Tunnels

In the event of a fire incident, tunnel airflow becomes highly transient and is considerably modified due to the fire itself, the emergency ventilation operation, and the change in the traffic pattern. The combined effects of convective heat exchange with the tunnel walls and the mixing between the smoke and the fresh air layer causes the smoke to cool down and lose its stratification. The smoke progress speed along the tunnel and its degree of stratification depends on airflow, heat release rate (HRR), ambient conditions, tunnel geometry and slope and traffic. The tunnel slope could induce an acceleration of the smoke towards the ascending direction due to stack effect. Burning rates, and hence HRR, may range from slow burning of 3-8 min, in case of a low combustibility materials, to a near explosion in the event of ignition of large loads of highly flammable hydrocarbons. The rapid changes in the traffic flow during the initial stages greatly modify the piston effect induced by the circulation of the vehicles in the tunnel. Thus, the first few minutes of a fire (between 5 to 15 min) are crucial to the safety of tunnel users.

A fire incident involves a sequence of events or phases occurring, including: ignition, fire growth and development, self-evacuation, and assisted-evacuation after the arrival of the emergency services. The activation of emergency equipment depends on the fire being detected and the detection be confirmed.

Design Fire

A design fire is an idealization of a real fire that might occur in a tunnel and is generally defined in terms of HRR and combustion gases production (smoke, CO, CO₂, etc.) as functions of time. As such, design fires provide, quantitatively, the fire characteristics (e.g. ignition sources, qualities and configuration of the fuel, fire growth, peak heat release rate (PHRR), duration and decay) that are used in sizing tunnel equipment, developing emergency response plans and in determining impact of fires on the tunnel structure. As such, design fires form the base input for emergency ventilation, evacuation, and structural design analyses [6].

A prescriptive approach has traditionally been adopted in which a specific fire size, usually the PHRR depending on the type of vehicle (passenger cars, buses, heavy goods vehicles, pool fires, etc.), is chosen as a basis for the tunnel fire-life safety design (Table 1 and Table 2).

Performance-based approach, on the other hand, is usually based upon explicitly stated objectives that allow the freedom to develop innovative designs satisfying these objectives. Such innovative designs make possible the evaluation of the tunnel fire safety as a whole. A key step in this design approach is the establishment of possible fire scenarios. Different fire scenarios are created to instigate the design analyses of emergency ventilation, egress, structural, and fire safety tunnel equipment (e.g. detection
and fixed firefighting systems). The design fires are the cornerstone in developing such fire scenarios and, therefore, the basis for conducting a performance-based design.

Table 1. Fire data for typical vehicles [4].

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>PHRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger car</td>
<td>5–10</td>
</tr>
<tr>
<td>Multiple passenger cars (2–4 vehicles)</td>
<td>10–20</td>
</tr>
<tr>
<td>Bus</td>
<td>20–30</td>
</tr>
<tr>
<td>Heavy goods truck</td>
<td>70–200</td>
</tr>
<tr>
<td>Tanker</td>
<td>200–300</td>
</tr>
</tbody>
</table>

Table 2. Fire sizes adopted in different countries [7].

<table>
<thead>
<tr>
<th>Country</th>
<th>PHRR (MW)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>50</td>
<td>With FFFS (deluge system), for ventilation only</td>
</tr>
<tr>
<td>Austria</td>
<td>30</td>
<td>High risk category: 50 MW</td>
</tr>
<tr>
<td>France</td>
<td>30 – 200</td>
<td>200 MW when transport of dangerous goods allowed but only applied for longitudinal ventilation</td>
</tr>
<tr>
<td>Germany</td>
<td>30 – 100</td>
<td>Depending on length and HGV in tunnel</td>
</tr>
<tr>
<td>Greece</td>
<td>100</td>
<td>Longitudinal ventilation</td>
</tr>
<tr>
<td>Italy</td>
<td>20 – 200</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Netherlands</td>
<td>100-200</td>
<td>100 MW if tankers are not allowed, otherwise 200 MW for ventilation system</td>
</tr>
<tr>
<td>Norway</td>
<td>20 – 100</td>
<td>Depending on risk class, always longitudinal ventilation</td>
</tr>
<tr>
<td>Portugal</td>
<td>10-100</td>
<td>Based on traffic type</td>
</tr>
<tr>
<td>Russia</td>
<td>50-100</td>
<td></td>
</tr>
<tr>
<td>Singapore</td>
<td>30-200</td>
<td>Depends on vehicle types allowed</td>
</tr>
<tr>
<td>Spain</td>
<td>&gt;Or =30</td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td>100</td>
<td>Longitudinal ventilation</td>
</tr>
<tr>
<td>Switzerland</td>
<td>30</td>
<td>Smoke extraction equals 3.3-4 m/s times cross section</td>
</tr>
<tr>
<td>UK</td>
<td>30 – 100</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>30 – 300</td>
<td>300 MW if dangerous goods allowed</td>
</tr>
</tbody>
</table>

Different aspects of a design fire are more important to certain types of analysis than others. For example, the PHRR and burning duration are important in evaluating the impact of a fire on the tunnel structural. The HRR at the end of evacuation and the PHRR are considerations in evaluating tunnel ventilation equipment and is of concern for the life-safety of the fire service during the firefighting phase. The objective during this phase is to provide tenable conditions for safe firefighting activities.

Methods to manage combustion effluents

In a tunnel environment, various combustion effluent management strategies can be employed to achieve the goals of offsetting buoyancy of hot gases and smoke and to prevent the backlayering phenomenon. These strategies include extraction, transport, control direction of smoke movement, and smoke dilution. The dilution process, most suitable for tunnel normal operation, attempts to reduce concentrations of toxic gases and, therefore, maintain air quality and visibility. During emergency operations, hot gases and smoke management is ideally achieved by extraction, transport, or both of the vitiated air. Extraction can be performed through single or several extraction points on the ceiling or walls of the tunnel. The transport of combustion effluents can be achieved by creating a longitudinal airflow along the length of the tunnel by introducing into or removing air from the tunnel.
at a limited number of points.

**Smoke layer speed and depth**

Fire-induced smoke movement is principally manipulated by the stack effect, wind-induced action, and smoke buoyancy. These driving forces can produce significant pressure differences between different locations inside tunnel facilities preventing smoke movement from places with lower pressure to places with higher pressure.

The speed of the smoke layer dictates to a great degree the minimum distance for the smoke to be extracted through the ceiling vents. The smoke layer initial velocity, \( u_{so} \), and initial thickness, \( d_{so} \), for the situation where no longitudinal ventilation is provided, can be estimated from [8]:

\[
\begin{align*}
    u_{so} &= C \left[ \frac{gT_r Q}{T_F^2 \rho_s C_p W} \right]^{1/2} \\
    d_{so} &= \frac{m_s}{\rho_s u_{so} W}
\end{align*}
\]

where:
- \( u_{so} \) initial smoke layer moving velocity, m/s
- \( d_{so} \) initial smoke layer thickness, m
- \( g \) acceleration due to gravity, m/s\(^2\)
- \( W \) tunnel width, m
- \( Q \) fire heat release rate, kW
- \( C_p \) specific heat of air, kJ/kg·K
- \( \rho_{∞} \) density of ambient air, kg/m\(^3\)
- \( \rho_s \) density of smoke, kg/m\(^3\)
- \( T_{∞} \) temperature of ambient air, °K
- \( T_F \) average temperature of fire site gases and smoke, °K
- \( m_s \) smoke production rate, kg/s
- \( C_s \) 0.80

Table shows some information on the smoke layer speed and thickness calculated by Heselden [8] for a hypothetical tunnel for different fire sizes.

<table>
<thead>
<tr>
<th>Fire Size (MW)</th>
<th>3</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_s ) (kg/s)</td>
<td>17</td>
<td>24</td>
<td>35</td>
<td>48</td>
<td>95</td>
</tr>
<tr>
<td>( u_{so} ) (m/s)</td>
<td>1.3</td>
<td>2.2</td>
<td>3.0</td>
<td>5.3</td>
<td>6.7</td>
</tr>
<tr>
<td>( d_{so} ) (m)</td>
<td>0.7</td>
<td>0.9</td>
<td>1.2</td>
<td>1.7</td>
<td>2.7</td>
</tr>
</tbody>
</table>

**Visibility**

In a tunnel environment, visibility tends to be the most restrictive criterion for tenability. Evacuation can be significantly hindered by poor visibility. For acceptable visibility and, therefore, safe evacuation, reliable and robust control of airflow velocity is essential at all times. The visibility, \( S \), may be calculated as follows:

\[
S = \frac{K \Delta H V_s}{K_f C_{∞} \alpha_y \rho Q t}
\]
where:

$S$ visibility, m

$\alpha_m$ specific extinction coefficient, m$^2$/g

$K$ proportionality constant, dimensionless (e.g. 8 for illuminated signs, 3 for reflected signs)

$y_p$ particulate yield, (dimensionless)

$Q$ fire heat release rate, kW

$t$ time from ignition, s

$V_s$ volume of smoke in the space, m$^3$

$\Delta H_c$ heat of combustion, kJ/kg

$K_f$ 1000

**FIRE PROTECTION MATRIX**

Minimizing the negative impact of a fire to users and tunnels has long been a central focus of tunnel design and operation. A range of technologies and techniques have been developed and refined to address the risk of fire. These advancements have become an integral part of the fire prevention and protection matrix (FPPM) of modern tunnels (Figure 1) that resulted in tunnels often becoming the safest part of modern transportation networks, with lower rates of accidents, injury and death than any other network component. The type of technology or technique adopted is usually based on tunnel type and length, traffic pattern, etc. The range of technologies may include one, few or all of the following systems: detection, lighting, ventilation, and fixed firefighting systems (FFFS), emergency telephones, fire extinguishers, traffic control equipment, radio transmissions, loudspeakers, variable text signs, and emergency exits. Many countries use a tunnel classification scheme that categorizes tunnels into groups, and specifies the necessary emergency equipment for each group [4, 5].

It should be emphasized that evaluating tunnel safety requires a thorough review of all components including the tunnel’s infrastructure, systems, operation, users and vehicles. Assessment of any system performance, such as FFFS, should include the effect on/from other FPPM systems, existing or under consideration. Further, the assessment should be done on basis of all possible fire scenarios.

![Figure 1. Fire prevention and protection matrix in a tunnel.](image)

**DETECTION**

The dynamics of smoke movement in tunnels is such that evacuation or rescue operations should start within 5 to 15 min from the start of a fire incident. As such, a fire detection system is a critical element of FPPM in tunnels. Quick and reliable fire detection allows for timely activation of other elements of the fire protection matrix. Indeed, detection can make the difference between a manageable fire and one that gets out-of-control. On the other hand, false or nuisance alarms are not only costly but can also promote a lack of confidence in the reliability of detection systems.
Many factors affect the performance of detection systems in the harsh environment of tunnels. Pollution, ambient conditions, airflow speed, tunnel geometry, fire type, size and location, traffic congestion are a few examples of these factors. The different types of detection systems are affected to various degrees by these factors. Performance of fire detection systems is usually evaluated based on certain criteria, such as [9]: response time, locating the fire, monitoring, and reliability.

There is a range of methods available to detect fire and smoke within tunnels. Each method is designed to detect a certain fire-related signature. Detection is triggered by exceeding threshold values for a prescribed duration [9]. In this context, it is important to divide the tunnel into well-defined sections to enable accurate determination of an incident location. Particularly when using smoke extraction, the location of the fire needs to be identified in order to incorporate the correct response with respect to ventilation control.

There are five types of currently available technologies (Table 4): linear heat detection, video image detectors (VID), flame detectors, smoke and heat detectors, and spot heat detectors. Fire detection systems should be selected to support the fire safety goals and objectives as well as the overall fire safety program, which can include notifying occupants to allow for safe evacuation, modifying tunnel ventilation or operations, activating FFFS and notifying emergency responders.

**Table 1. Status of fire detection technologies [9].**

<table>
<thead>
<tr>
<th>Linear heat detection systems</th>
<th>Flame detectors</th>
<th>VID detectors</th>
<th>Smoke detection systems</th>
<th>Spot detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detecting principle</td>
<td>Heat</td>
<td>Radiation</td>
<td>Image/smoke</td>
<td>Heat, smoke, gas</td>
</tr>
<tr>
<td>Reliability</td>
<td>High</td>
<td>Moderate to high</td>
<td>Moderate to high</td>
<td>Low</td>
</tr>
<tr>
<td>Availability</td>
<td>High</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate to high</td>
</tr>
<tr>
<td>Applications</td>
<td>Europe</td>
<td>Japan</td>
<td>Unknown</td>
<td>Sprinkler head</td>
</tr>
</tbody>
</table>

**FIXED FIRE FIGHTING SYSTEMS**

FFFS [2] is a “family” of techniques and technologies that have actively been promoted for fire management in tunnels in the last few decades. FFFS, e.g. sprinkler, deluge and mist systems, are permanently attached piping systems in the tunnel with a fixed supply of extinguishing agent, e.g. water. The main objective of FFFS is to improve user safety and infrastructure protection by reducing heat release and fire growth rates.

FFFS can affect the fundamental aspects of a fire and its consequences, including fire growth rate, HRR, humidity, smoke stratification, visibility, air temperature and the likelihood of flashover. As such, FFFS must be considered only as one part of a totally integrated tunnel safety system.

When considering the use of FFFS in a tunnel, one should take into consideration the optimum time to
operate the FFFS. If a FFFS is activated very early, it has a better chance of limiting fire size, but at
the risk of hindering evacuation processes and trapping people in the activated zone. On the other
hand, if a FFFS is activated after completion of the two rescue phases, it will not be useful in terms of
life safety. In this regard, effective methods for detecting and precisely locating the fire must be
established in order for the FFFS to achieve its objectives.

VENTILATION SYSTEM

The ultimate goals of tunnel emergency ventilation systems are to provide an environment sufficiently
clear of smoke and hot gases to permit safe evacuation and to allow relatively safe access for rescue
services as a function of actual fire scenario. The emergency ventilation system must be available and
capable of handling combinations of worst-case fire conditions: fire size, location, traffic pattern, etc.
Establishing airflow requirements in the tunnel, and consequently the capacity of the ventilation
system, are challenging due to the difficulty of controlling many variables [10]. Among those
variables are the possibility of occurrence of many vehicle combinations, combustible loads and
traffic situations during the lifetime of the facility.

Smoke management in tunnels can be achieved using either natural or mechanical systems. The
consideration of natural smoke venting in the design of new tunnels is gaining more importance with
the continued drive toward environmentally sustainable infrastructures to reduce energy consumption
and save costs. Natural systems count on the pressure differential created by the piston-effect of
moving vehicles, the meteorological conditions (external wind, temperature differentials between the
portals) and differences in elevation to produce airflow through the tunnel. The pressure created must
be large enough to overcome tunnel resistance and is therefore a function of tunnel length, cross-
sectional geometry, wall roughness, number of vehicles in the tunnel, and air density. Any change in
meteorological and operating conditions significantly influence the performance of natural ventilation
systems. Natural and traffic-induced ventilation is adequate for relatively short tunnels and tunnels
with low traffic volume (or density). The use of natural ventilation for long and heavily travelled
tunnels should be carefully investigated to assure its reliability. Otherwise, mechanical ventilation
systems should be used.

Mechanical ventilation systems use a series of fans to produce airflow and ducts and dampers to
distribute this airflow. Regardless of mechanical ventilation equipment, the natural effects mentioned
above are present in all tunnels to a varying extent. A mechanical ventilation system is, generally,
classified based on the direction of airflow it creates in the tunnel. There are two basic types of
ventilation airflow systems applied in transport tunnels: longitudinal and transverse. Longitudinal
ventilation systems produce longitudinal airflow in the direction of the tunnel axis. Transverse
ventilation systems, on the other hand, produce airflow that is perpendicular to the tunnel axis and in
the plane of the tunnel cross-section. The choice of what ventilation system to use depends on several
parameters that include: tunnel length, cross-section and grade; meteorological conditions (prevailing
wind and temperature); traffic type, direction and volume; design fire size; and construction cost.

Longitudinal ventilation

The longitudinal ventilation system (Figure 2) creates a longitudinal flow along the roadway tunnel by
introducing or removing air from the tunnel at a limited number of points [11]. The ventilation is
provided either by injection, by jet fans, or by a combination of injection or extraction at intermediate
points in the tunnel. The longitudinal form of ventilation is the most effective method of smoke
control in a transport tunnel with unidirectional traffic. In a number of situations, if a longitudinal
ventilation strategy is adopted, it is necessary to provide massive extractions points of smoke.

In the event of a fire in a unidirectional tunnel, it is usually assumed that the traffic downstream of the
fire will proceed to the exit portal and the traffic upstream of the fire will come to a stop. The
ventilation system should therefore be operated to force the smoke and hot gases in the direction of
the empty tunnel to provide a clear and safe environment behind the fire for evacuees and fire
fighters. In this case, the main measure of the adequacy of the system for smoke management is its ability to prevent backlayering via generating sufficient longitudinal air velocity that is equal to or greater than the critical velocity [11]. The backlayering phenomenon is defined as the situation in which the smoke moves against the airflow provided by the ventilation system upstream of the fire, creating an environment that poses a danger to both tunnel users and emergency responders. Many parameters influence the smoke flow and its stratification. These include: HRR, tunnel length, cross-section and grade, traffic flow, meteorological conditions and fire protection systems.

The challenges occur in a tunnel that is congested, in which case users may be on either side of the fire, limiting the ability of a longitudinal system to properly manage the smoke. In this case, it is crucial to initially limit the longitudinal air flow in order to promote smoke stratification and allow users to evacuate underneath the smoke layer in the self-evacuation phase. Subsequently, the strategy of pushing the smoke in one direction can be applied to allow for the intervention of rescue and firefighting services.

As the length of the tunnel increases, excessive air velocities could be expected in one or a few locations across the tunnel. Moreover, in the event of a fire, smoke could be drawn throughout the entire length of the tunnel downstream of the fire.

**Critical velocity**

The ventilation system must generate sufficient longitudinal air velocity to prevent backlayering of smoke. The air velocity necessary to prevent backlayering is the minimum velocity needed for smoke control in a longitudinal ventilation system and is known as the critical velocity. The critical velocity depends on the HRR, the slope, and the tunnel section geometry. The critical velocity, minimum steady-state velocity, is used to define the fan requirements for smoke control from possible fires and can be determined by the simultaneous solution of Equations (3) and (4) [12]:

\[
V_c = K_1K_2 \left[ \frac{gHQ}{\rho AT_F} \right]^{1/2}
\]

\[
T_F = \left( \frac{Q}{\rho CAV_c} \right) + T_p
\]
where:

- $V_c$ = the critical velocity, m/s (ft/s)
- $g$ = acceleration due to gravity, m/s² (ft/s²)
- $H$ = tunnel height, m (ft)
- $Q$ = fire heat release rate, kW (Btu/s)
- $A$ = tunnel cross-sectional area, m² (ft²)
- $C_p$ = specific heat of air, kJ/kg·K (Btu/lb K)
- $\rho_\infty$ = density of ambient air, kg/m³ (lb/ft³)
- $T_\infty$ = temperature of ambient air (°K)
- $T_F$ = average temperature of fire site gases (°K)
- $K_1 = \text{constant} = F_r^{-1/3}$
- $F_r = \text{The Froude Number for a Flow ventilating a fire} = 4.5$
- $K_2 = \text{grade factor} = 1 + 0.0374(\text{grade})^{0.80}$

If the longitudinal air velocity is much greater than the critical velocity, the high flow rates may have the advantage of reducing temperature and decreasing toxicity in the tunnel. However, they will completely destroy the smoke stratification and may cause the fire to grow faster to higher heat release rates. Furthermore, excessive longitudinal air velocity can lead to a faster fire spread to other vehicles trapped in the tunnel.

As shown in Figure 3, the critical velocity increases rapidly with the fire size up to about 30 MW and then only increases slightly with increased heat-release rate. The same trend is true for different tunnel grades with higher values of the critical velocity corresponding to higher grades for the same fire size (e.g. for a 100 MW fire and grade of 3%, $V_c = 2.64$ m/s versus 2.38 m/s at 0% grade).

![Figure 3. Effect of fire size on critical velocity.](image)

The value of the critical velocity is influenced by the tunnel cross-section dimensions. Reducing the width of the tunnel or increasing its height will increase the value of the critical velocity (Figure ). While evaluating the required longitudinal ventilation system capacity in case of a fire, it must be assumed that a certain number of vehicles can be trapped in the tunnel and their presence reduces the performance of the ventilation system. The number of vehicles trapped can be assessed according to the design mix of traffic (% of passenger cars and heavy vehicles) for the specific tunnels. PIARC guidelines [5] recommended a design airflow velocity of 3 m/s for all fires which do not involve a heavy goods vehicle carrying very flammable dangerous goods.
Smoke stratification versus longitudinal airflow

If the airflow has a lower velocity, $V_{vent}$, than the critical velocity, $V_c$, the smoke layer will progress to the upstream side of the fire causing the backlayering phenomenon to occur. The length of the backlayering distance, $B_L$, can be estimated from [13]:

$$B_L = K_B \left[ \frac{gH^2Q}{\rho_c C_v V_{vent} T_a} \right]^{1/3}$$

where $K_B$ is the proportionality constant (0.60-2.2, [13]) and $V_{vent}$ is the airflow velocity in tunnel, m/s. Equation 6 does not consider other geometrical dimensions (e.g. cross-section shape, tunnel width, or tunnel slope) than the height of the tunnel.

Transverse ventilation

Full transverse ventilation systems (Figure 5) are usually used in extremely long tunnels (more than 2000 m long) and in tunnels with heavy traffic volume. This type of ventilation system comprises, both supply and exhaust ducts, to uniformly supply fresh air and collect vitiated air throughout the tunnel length. For shorter tunnels or tunnels with less traffic densities, the designer may opt to use a semi-transverse system, in which the system induces or collects air uniformly throughout the length of a road tunnel in a duct fitted with supply/exhaust outlets spaced at predetermined distances. In general, this type of ventilation has the advantage of being less affected by atmospheric conditions since the tunnel airflow is fan-generated.
In the event of a fire, the exhaust fan in the fire zone should attain its maximum available capacity, while the supply should be maintained at a relatively low capacity. This scheme limits the smoke spread within the extraction zone and maintains the stratification of smoke. Using this approach, a tenable environment could be maintained in the tunnel for firefighting and emergency egress. The extraction rate is usually estimated at 150% of the smoke-production rate of the design fire at a distance of 100 m from the fire. Traditionally, the extraction rate is about of 2½ to 4 times the tunnel cross section [14]. It should be noted that the construction and maintenance costs for these systems are higher than for longitudinal systems. Moreover, a larger design fire requires larger duct sizes impacting the resulting investment costs. Careful consideration should be given for the maintenance of dampers in areas of extreme weather (e.g. cold climates).

**PROTECTION SYSTEMS INTERACTION**

The primary objective of the ventilation system and other safety equipment is to facilitate the two rescue phases; self- and assisted-rescue, by maintaining tenable conditions along evacuation paths. It is paramount during the design stage to follow a holistic approach that integrates all elements of safety in the tunnel and to take into account operational procedures. This will ensure that all components of the FPPM are functioning in harmony and in such a way that will not compromise the overall tunnel safety during all phases of an incident. Moreover, the holistic approach should include verification and validation of actual effectiveness, reliability and performance of all FPPM constituents to ensure that appropriate and informed decisions are made.

Preforming a holistic approach would usually involve studying a set of fire scenarios. These scenarios should include tunnel information (geometry and cross sectional area), traffic pattern (unidirectional or bi-directional), traffic management equipment, egress routes, ventilation and detection systems, and surveillance of the tunnel (SCADA). Moreover, the scenarios should address severe conditions and different design fires to assess the performance of the FPPM as a whole and the level of safety in tunnel. A direct outcome of studying these scenarios is the establishment of spatial and temporal changes associated with each scenario. Understanding these spatial and temporal changes is vital in analyzing the interaction between the FPPM components, e.g. between FFFS and tunnel ventilation system.
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Fire Development and Spread in Rail Tunnels

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ABSTRACT

This paper deals with fire development in a traincar and the impact of tunnel ventilation on fire development and the conditions in the tunnel. Simulations of the traincar fire were done using the Fire Dynamics Simulator (FDS) model. The model is first used to model a full-scale experiment conducted at Carleton University’s Fire Research Laboratory on an intercity traincar. Comparisons are made between the experimental and numerical heat release rate as well as the tunnel ceiling temperatures. The model was then used to investigate the effect of a the size of the fire ignition source and a number of important fire related material properties, such as ignition temperature and peak heat release rate on fire development, the fire peak heat release and the time to peak heat release rate. The model was also used to study the effect of airflow velocity in the tunnel on tunnel ceiling temperatures and the fire heat release rate. The comparisons between the full scale tests and the model predictions show that FDS is capable of modelling the fire development in the event of traincar fire in a tunnel, provided appropriate fire properties of materials are used. Both the fire growth rate and the peak heat release rate sensitive to the material properties and the size of the ignition source.

KEYWORD: Fire development, traincar fires, tunnel fires, CFD modelling

INTRODUCTION

Railway transportation is one of the most common methods of transportation in many countries around the word. The railway transportation provides faster and more comfortable trips for passengers. Growing tendency towards using railway transportation in recent years caused many codes and standards to provide specific regulations for the safe design of this type of transportation system. NFPA 130 [1] is a standard that focusses on fire safety design of railway systems. NFPA 130 [1] states that the initial fire development inside a vehicle is dependent of the performance of the interior finish materials, location of the combustible materials, the location and size of the initiating fire, the size of the enclosure where the fire occurs and the ventilation conditions. It also states that the material's ignitibility, heat release rate and the severity of the initiating fire are the main essential factors that impact the fire development in a vehicle.

The mechanism of fire development in traincars and subway cars might be different, as the seat materials and seat arrangements, which play important roles in the fire development inside the traincar, are different. Addition, material properties are usually different in different types of traincars. Seats constructed using a metal structure and base with a light textile lining are more common in subway cars, as the passengers are using the subway cars for shorter trips. On the contrary, traincars carry on more fire load, as the seats normally contain a thick cushion and the walls, floor and ceiling are covered by combustible materials.

Several researchers studied the mechanism of fire development in traincars. Flashover in a compartment fire is mainly caused by radiation from the hot layer to the combustible surfaces in the early stage of the fire [2]. The mechanism of fire development in the traincar, however, is different due to the long length of the train. Li et al. [3] stated that fire development inside the traincars follows the concept of a travelling fire. When the first seat gets involved in fire, the fire spreads to the entire...
chair. The fire then spreads to the next chair and other combustible materials around the initiating fire. This causes a local flashover around the ignition source. The local flashover increases the temperature and speed up the heat transfer to the next chairs. This causes the next series of chairs to get caught in the fire quickly and eventually full flashover occurs. The full flashover causes the fire to engulf the entire train car.

Milford et al. [4] evaluated the effect of the characteristics of the ignition source on fire development in a traincar fire by simulating a traincar fire under different conditions of initiating fire size, location of initiating fire and ventilation conditions using FDS. They modeled four initiation fire sizes including 25 kW, 50 kW, 150 kW and 350 kW fires. These fire sizes represented the possible ignition sources in traincar fires. They considered three locations of the ignition source; at the top of the seat, at the end of the train car and adjacent to the seat at the floor of the train and the open-gangway. They have also evaluated the effect of the ventilation system velocities on fire development. They have considered velocity values ranging from 0 to 3 m/s. Their results have shown that when the ignition source was placed on top of a seat at the end of the tunnel the fire did not grow. The fire development in the case of ignition source adjacent to a seat and the gangway with no forced air velocity was limited to the area around the fire origin. They have found that increasing the air velocity causes a higher heat release rate (HRR), as the air velocity enhances the fire spread through the interconnected cars. The maximum HRR in the case of high air velocity was relatively independent of the strength of the initiating fire size. However, a faster fire growth and full flashover was observed by increasing the size of the ignition source. They have concluded that only in the case of a large ignition source there is a significant risk of fire to occur for the material properties and train configuration used in their study. They have also concluded that full flashover is unlikely to occur in the case of a small ignition source unless a second source of fuel gets involved in the fire to sustain and prolong the burning. Also, in the case of no forced air ventilation, the fire development is likely to remain localized even if the size of the ignition source is large.

Chiam [5] numerically investigated the fire growth and flame spread in the event of train car fire in a tunnel. He used FDS to simulate the train car fire. He considered thirteen fire scenarios including three ignition sources, (arson fire on top of a seat; arson fire in a corner; and an undercarriage fire), and different conditions for the ventilation velocity. He used two methods including the cone calorimeter heat release rate per unit area and the heat of vaporization for modeling the train fire. He stated that the materials used in his research were tested in the cone calorimeter and they were difficult to ignite and burn. He found that using fire retardant materials delay ignition and reduce the heat release rate. He also found that FDS predictions are not able to estimate the thermo-physical properties of the fire retardant materials. Therefore ignition and fire growth might not be accurately predicted by the CFD model. In the final simulations, these two modeling approaches yield the same results for the fire severity of different fire scenarios. He realized that fire growth was slowed down in the case of the corner fire scenario due to the effect of the high airflow which reduced the flame temperature; however the low ventilation air flow enhanced fire growth. On the contrary, a high ventilation airflow velocity helps the fire to spread to the adjacent car in the case of the undercarriage fire scenario where the initiating fire size was considerably larger than the corner fire. He observed that direct air flow through the tunnel supports flame spread and fire growth and that fire spread to the adjacent train car is very quick in the case of a full flashover fire under the condition of high ventilation velocity. He proposed two peak heat release rates for the design of the ventilation system for a subway car fire. A 10 MW fire is proposed for the subway car fire in a tunnel and a 5 MW heat release rate is proposed for a subway car fire in a station. He concluded that the airflow would not support the fire spread in the case of a large ignition source if the detainment door is closed during the fire because it prevents direct air flow through the train compartment.

Lonnermark et al [6] conducted three full-scale experiments of train carriage fire. Test 1 was designed to investigate the effect of a fire underneath a railcar, for instance, in the case of a break initiates the fire. In the Test 2 and 3 the initiating fire was located inside the traincar. The Test 2 used the original seats and linings and the peak heat release rate reached 76.7 MW at 12.7 min after ignition. In this case, flames spread to the lining of the ceiling and radiated to the seats and luggage in the lower layer.
They stated that flames were observed at the ceiling, when the growth rate of fire was increasing. In the Test 3 modern seats and aluminium linings were used in the train, and the peak heat release rate reached 77.4 MW at 118 min after ignition. The difference between the rate of fire development in Test 2 and 3 is due to the involvement of the combustible materials including seats; wall and ceiling linings used in the old style X1 carriage. The slower fire development rate in the Test 3 provides longer time for passengers to evacuate. The peak heat release rate of these is significantly higher than the heat release rate reported in literature. They attributed the higher heat release rate to high fire load due to the presence of luggage in the train car, under or between the seats. They recommended that designers must consider the effect of this live load in risk assessments and fire safety designs of tunnels.

Hadjisophocleous et al. [7] studied traincar fires in a tunnel by conducting two full-scale experiments at Carleton University’s Fire Research Laboratory. The first test used an intercity railcar and the second a subway car. They observed that fire development in the traincar follows the concept of a travelling fire as reported in [3]. Fire spread during the first 500 sec and before the initial flashover is slow, however, a faster seat to seat fire spread occurs after the initial flashover. The entire train got involved in the fire at about 1000 sec when full flashover occurred. The peak heat release rate reached 32 MW at 1200 sec. Although the ventilation system was effective in preventing backlayering of smoke, the visibility in the tunnel was very bad due to the heavy smoke that reached to the floor of the tunnel. Also, they stated that video cameras inside the train were not able to record the smoke propagation after 200 sec due to poor visibility inside the train.

Hadjisophocleous et al. [8] also measured the heat release rate of a subway car fire and compared the results with the results of train car fire. The subway fire took more time to start spreading after ignition; however once it started to spread, it grew fast and flashover occurred very quickly. Although the peak heat release rate reached 52.5 MW in about 540 secs after ignition, the fire developed from 1 MW to 52.5 MW in only 140 sec. They concluded that the presence of four open doors provide adequate ventilation and resulted in a fast fire growth. In addition, the higher heat release rate and lower fuel load caused a shorter duration in the subway car fire.

Li et al. [9] reviewed research on fire development in train and subway cars. The maximum heat release rate of fires in these cars was found to vary from 7 MW to 77.4 MW and the time to reach the peak heat release rate was in the range of 5 to 118 min. The different values for the peak heat release rate and the time of peak heat release rate is a strong indication that several parameters have a major impact on fire development. These parameters include the type and amount of combustible materials inside the train car, the body type (aluminum, steel etc.), the opening area and arrangement, the window breakage temperature, the initial moisture content, the construction of bellows, the tunnel cross section and the air velocity in the tunnel. The fire develops slowly as long as the windows have not reached the breakage temperature. As soon as the windows break and more air enters the traincar, the fire develops significantly faster. As the openings in the metro carriages are usually larger than the traincars, the fire grows faster and reaches to a higher heat release rate in the subway cars. This was observed in the Carleton University’s fire tests on the train and subway cars. Due to the aluminum coverage in the METRO refurbished X1 test, the fire development was delayed for 107 min and reached the maximum heat release rate at 118 min. This shows that the wall and ceiling lining materials play an important role in the fire development process.

Li et al. [9] proposed a correlation to estimate the peak heat release rate of a subway car fire. They stated that this correlation has been verified to be able to correlate the experimental results in different scales. They also stated that the peak heat release rate in a subway car fire is related to the effective heat of combustion, heat of pyrolysis and configuration of the combustible materials in the car. The peak heat release rate of the carriage fire can be calculated using:
Emergency ventilation systems in tunnels are designed to exhaust smoke and hot gases from the tunnel in the event of a fire. Standards such as NFPA 130 [1] require that the tunnel ventilation system should be capable of providing a velocity greater or equal to the critical air velocity to prevent backlayering of smoke. Backlayering is smoke movement against the intended air flow in the tunnel which is caused by the ventilation system. Critical velocity is the velocity that the smoke starts to move opposite to the intended air flow and causes backlayering [10].

Several researchers [11, 12, 13] have studied the effect of different parameters on the critical velocity, that resulted in different correlations for calculating the critical velocity. However, all of the recommended correlations agree that the heat release rate is one of the main parameters in calculating the critical velocity. The effect of the air velocity on fire development depends on the material properties and the arrangement of the materials inside the train car. A low air velocity might cause fire spread only around the fire origin area resulting in lower heat release rate.

Milford et al. [14] investigated the effect of ventilation velocity on the critical velocity in the event of train car fire in the tunnel. They realized that the fire does not develop to the entire train when the ventilation velocity is below 1 m/s. In this case, fire is limited to the seats and combustible materials around the initiating fire. Also, it was observed that any velocity higher than 1 m/s causes the whole train to get involved in the fire with a shorter burning duration. Also, they simulated the same fire scenarios in 0% and 6% grade and observed that the maximum heat release rate and the rate of fire development in the train car is more sensitive in the case of downhill ventilation scenarios. They also found that the CFD modelling predictions for critical velocity is close to the value which is estimated by the following semi-empirical correlation [15].

\[
V_c = K_g \left( \frac{g \cdot H \cdot E_c}{Frc \cdot \rho \cdot C_p \cdot A \cdot V_f} \right)^{\frac{1}{3}}
\]  

(4)

\[
T_f = \frac{E_c}{\rho \cdot C_p \cdot A \cdot V_c} + T_s
\]

(5)

Where, \(A\) is the net annular tunnel area, \(E_c\) is the convective HRR (assumed to be 70% of the total HRR), \(Fr_c\) is the critical Froude Number for a flow ventilating a fire (taken to be 4.5), \(H\) is the tunnel height, , and \(Kg\) is an empirical grade correction factor, given by:
They concluded that the peak heat release rate must be carefully selected for the design of ventilation system, as full train car involvement in the event of localized ignition in the train car fire with low ventilation velocity may not occur.

Although there are several studies that have been carried out in recent years to investigate the effect of the different parameters on fire development in the event of train fire in a tunnel, very few studies have attempted to compare results from full-scale tests to the predictions of CFD models. In this study the CFD model FDS was used to simulate the intercity train car tests conducted at Carleton University to determine how well the model can reproduce the real fire test. In addition, the model was used to evaluate the effect of material’s ignition temperature, size of ignition source and ventilation system velocity on fire development in the event of a traincar fire.

**DESCRIPTION OF CFD MODEL**

For this study the CFD model FDS [16] was used to model the intercity traincar fire tests conducted in the Fire Research laboratory of Carleton University [7]. Figure 1 shows the model of the traincar in FDS and Figure 2 shows the full computational domain. As the figure shows the computational domain includes not only the traincar, but also the tunnel in which the test was conducted. A mesh size of 0.12 m x 0.12 m x 0.12 m was applied to the entire computational domain [17]. One end of the tunnel is defined as passive opening in order to let the air entrain into the tunnel. An exhaust fan is located at the ceiling level at the other end of the tunnel to exhaust the smoke and hot gasses from the tunnel. The air flow through the exhaust fans was varied to achieve the required air flow velocity in the tunnel. The location, size and duration of the ignition source were defined to match the location and values used in the test. In the model, the ignition source was defined using the heat release rate per unite area (HRRPUA). A core i7 computer equipped with eight 3.40 GHz processors was used to run the FDS model. In order to use the maximum performance of the system, parallel processing was used by equally-dividing the whole computational domain into eight meshes along the length of the tunnel.

\[
K_g = 1 + 0.0374 (\text{grade})^{0.8}
\]  

(6)
SIMULATION OF FULL-SCALE TEST

To model the full-scale test on the intercity traincar, the ignition source and tunnel velocity were defined in the model to match the characteristics of the test. The ignition source is defined based on the heat release rate per unite area (HRRPUA) with values as shown in Figure 3. The location of the ignition source is shown in Figure 1 (a). During the test the ventilation system was exhausting 120 m$^3$/s from the tunnel, which results in a tunnel velocity of 2 m/s. The exhaust rate of the model was defined to match the experimental tunnel velocity.

![Figure 2 Computational domain.](image)

**Figure 2  Computational domain.**

The interior materials used in the model and their fire properties are shown in Table 1. Figure 4 indicates the heat release rate per unit area of the materials used in the model. All materials except glass were defined by using of the HRRPUA feature. The windows were set to break at 400°C by defining the glass as a burn away material. The default values for soot and species yield concentrations were used.

![Figure 3 Ignition source heat release rate.](image)

**Figure 3  Ignition source heat release rate.**

The interior materials used in the model and their fire properties are shown in Table 1. Figure 4 indicates the heat release rate per unit area of the materials used in the model. All materials except glass were defined by using of the HRRPUA feature. The windows were set to break at 400°C by defining the glass as a burn away material. The default values for soot and species yield concentrations were used.

### Table 1 Material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Peak HRRPUA (kW/m²)</th>
<th>Ignition Temperature (°C)</th>
<th>Density (kg/m³)</th>
<th>Conductivity (W/mK)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat Cashion</td>
<td>320</td>
<td>400</td>
<td>300</td>
<td>0.117</td>
<td>15.0</td>
</tr>
<tr>
<td>Floor Cover</td>
<td>110</td>
<td>513</td>
<td>1550</td>
<td>0.130</td>
<td>4.0</td>
</tr>
<tr>
<td>Glass</td>
<td>-</td>
<td>400 (burn away)</td>
<td>2700</td>
<td>0.840</td>
<td>3.0</td>
</tr>
<tr>
<td>Side and ceiling panels</td>
<td>110</td>
<td>513</td>
<td>1550</td>
<td>0.130</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Figure 4 Material's heat release rate per unit area (HRRPUA) [18].

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Fire Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>![Image]</td>
</tr>
<tr>
<td>300</td>
<td>![Image]</td>
</tr>
<tr>
<td>600</td>
<td>![Image]</td>
</tr>
<tr>
<td>900</td>
<td>![Image]</td>
</tr>
<tr>
<td>1200</td>
<td>![Image]</td>
</tr>
<tr>
<td>1500</td>
<td>![Image]</td>
</tr>
<tr>
<td>1800</td>
<td>![Image]</td>
</tr>
<tr>
<td>2400</td>
<td>![Image]</td>
</tr>
<tr>
<td>3000</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

Figure 5 shows Smokeview [19] screenshots at different times during the simulation. The figure shows that the fire grows slowly in the vicinity of ignition and then it travels to the front of the train engulfing the entire train at 1200 sec. A comparison of the experimental and numerical heat release is shown in Figure 6. The model was able to predict the peak heat release rate and time of the peak heat release rate however it failed to predict the HRR plateau observed in the test between 400 to 800 secs. The model predicted a slower growth but then the heat release rate increased quickly to the peak value. This may be due to the fact that all windows broke at about the same time in the model as opposed in the experiment when windows towards the front of the train remained in place until the peak heat release rate was reached.
During the test, thermocouples located near the ceiling of the tunnel along the centerline were used to record temperatures. The experimental temperatures are shown in Figure 7 (a). From this figure it is clear that the location of the peak values of the ceiling temperatures started at the back of the tunnel and move towards the front with time, following the fire as it travelled from the back to the front of the traincar. The maximum peak ceiling temperature was reached at 1200 sec at which time the peak heat release rate was recorded. Figure 7 (b) shows the numerical tunnel ceiling temperatures. Overall the predicted temperatures follow a similar trend as the experimental, however the predicted maximum peak value is about 150°C lower than the experimental. Another difference is that the temperatures at the early stages of the simulation at the back of the tunnel remain at ambient conditions, as a result of the airflow velocity, while in the tests they started to increase early on.

**EFFECT OF THE PEAK HRR OF THE MATERIALS**

The (HRRPUA) is a very popular method to model the materials inside the traincar, as it simplifies the burning process. Several studies showed that by properly defining the HRRPUA and the ignition temperature provides a good estimation of the fire development in the traincar [4]. The seats play an important role in spreading the fire, as they contain the main fire load in the traincars. The ignition
temperature of the seat cushions is usually lower than the ignition temperature of the other combustible materials in the traincar and the maximum heat release rate is higher. The longer burning times of the seats causes the other materials to ignite and spread the fire.

In this study, the effect of the material peak HRR on fire development and especially on the heat release rate is investigated by selecting four different peak values for the seat cushion. The ramp-up time to the peak HRR and the ignition temperature was assumed to be the same. All other model parameters were the same as the ones described above.

Figure 8 shows the results of these simulations. It is clear from the figure that this parameter has a major impact on fire development and the peak heat release rate. Materials with a lower peak HRR slow down the fire development and also decreases the peak heat release of the fire. With a peak HRR of 250 kW the peak heat release rate of the fire is reduced to 23 MW and the time to peak increased to 2400 secs. For all cases, once the fire reaches 5 MW its growth rate increases significantly and continues until the peak value is reached.

![Figure 8 Comparison of total HRR for different peak HRRPUA.](image)

**EFFECT OF THE IGNITION TEMPERATURE OF THE MATERIALS**

A number of simulations were conducted to determine the effect of different material properties and ignition temperature on the fire development and the heat release rate. The different material properties used are shown in Table 2 [14]. Figure 9 shows the results of these simulations. The figure shows that decreasing the ignition temperature causes the fire to develop faster inside the traincar. The peak heat release rate does not change significantly by changing the ignition temperature. As it was discussed earlier the peak value depends on the HRRPUA. Figure 9 also shows that the initial fire self-extinguishes when the ignition source is removed in the case with seat cushion 2 and floor cover 1 for any ignition temperature of the seat cushion. In the case with seat cushion 2 and floor cover 2, fire engulfs the entire train when the ignition temperature of the seat cushion decreases to 400°C. The ignition temperature of 533°C for seat cushion 2 is too high for the initial fire to spread into the train. The comparison between the case of seat cushion 1 (400°C), floor cover 1 and seat cushion 2 (400°C), floor cover 2 indicates the change in the total HRR by changing the HRRPUA of the material properties.
Table 2  Material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Peak HRRPUA (kW/m²)</th>
<th>Ignition Temperature (°C)</th>
<th>Density (kg/m³)</th>
<th>Conductivity (W/mK)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat Cushion 1</td>
<td>320</td>
<td>300/350/400</td>
<td>300</td>
<td>0.117</td>
<td>15.0</td>
</tr>
<tr>
<td>Seat Cushion 2</td>
<td>208</td>
<td>300/350/400/533</td>
<td>506</td>
<td>0.030</td>
<td>19.7</td>
</tr>
<tr>
<td>Floor Cover 1</td>
<td>110</td>
<td>513</td>
<td>1550</td>
<td>0.130</td>
<td>4.0</td>
</tr>
<tr>
<td>Floor Cover 2</td>
<td>342</td>
<td>419</td>
<td>1637</td>
<td>0.190</td>
<td>3.1</td>
</tr>
<tr>
<td>Glass</td>
<td>-</td>
<td>400 (burn away)</td>
<td>2700</td>
<td>0.840</td>
<td>3.0</td>
</tr>
<tr>
<td>Side and ceiling panels</td>
<td>110</td>
<td>513</td>
<td>1550</td>
<td>0.130</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Figure 9  Comparison of total HRR for different material properties and ignition temperatures.

EFFECT OF THE SIZE OF THE INITIATING FIRE

The effect of the size of the ignition source on fire development is investigated by defining an ignition source with a constant heat release rate and a 600 sec duration. Figure 10 shows a plot of the time to ignition versus size of ignition source. Ignition for this tests is defined as the time when the seat ignites causing the fire to spread to the entire seat. From the figure it can be seen that smaller ignition sources cause a longer ignition time. The 35 kW ignition source was the smallest source that could cause ignition the fire to spread to the seat in this model. When the fire spreads to the seat, the mechanism of fire development are the same for all the different sizes of ignition source, as the heat release of the seat is larger than the ignition source and causes the fire to spread to the other seats. The effect of the ignition source on the heat release rate is shown in Figure 11 which shows the fire heat release rate for the cases with a 100 kW and a 35 kW ignition source.
EFFECT OF THE AIR VELOCITY

Because of growing tendency towards using the fire retardant materials inside the trains, the full flashover may unlikely to occur in the case of low design fire. The higher air velocity might enhance the fire spread and increase the fire development rate which might results in higher HRR [14].

The effect of the air velocity on the fire development in the traincar is also studied by considering 0.25 m/s, 1.5 m/s, 2 m/s and 3 m/s air velocity in the tunnel. The results of the total HRR is shown in Figure 12. The maximum HRR increases from 30 MW to 35 MW by increasing the air velocity from 0.25 m/s to 3 m/s. Moreover, the time to reach the peak HRR decreases from 1300 sec to 1150 sec. The effect of the air velocity on the fire development depends on the air entrainment condition. In this model, the effect of the ventilation system on the total HRR is relatively small, as the detrainment door is close and the air does not entrain the traincar directly.

Also, the effect of the air velocity on the fire development may depend on the materials properties inside the traincar. Therefore it is very difficult to find a trend between the change in the heat release rate and increasing the air velocity.
The effect of the air velocity on the ceiling temperature in the tunnel is studied numerically by considering different air velocities in the tunnel. The traincar conditions and ignition source used for these simulations were the same as those of the full-scale test. Given the heat release rate of the traincar fire, the critical velocity for the experimental tunnel, computed using equations (4) and (5) is 2.3 m/s.

Figure 13 shows the smoke conditions and temperature slices in the tunnel for different air velocities at the time when the peak heat release rate is reached. As the figure shows with an air velocity of 0.25 m/s there is smoke backlayering and temperatures in the tunnel are high along the whole tunnel length. Also with 1.5 m/s air velocity there is evidence of backlayering. With 2 m/s air velocity the flames issuing from the train windows and the hot gases are forced towards the back of the tunnel, improving upstream visibility in the tunnel.

The tunnel ceiling temperatures are shown in Figure 14. The maximum temperature in the case of 1.5 m/s and 2 m/s at the time of peak heat release rate is around 700°C. The results show that there is some smoke backlayering in the tunnel as temperatures near the entrance to the tunnel are higher than ambient. Smoke backlayering disappears in the case of 3 m/s air velocity and the maximum temperature decreases to 600 sec due to the increased flow of cold air into the tunnel that cools the hot gases. This demonstrates the validity of the critical air velocity computed earlier.
<table>
<thead>
<tr>
<th>Ventilation Velocity</th>
<th>Smoke and Temperature Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 m/s at 1300 sec</td>
<td>![Image of smoke and temperature conditions]</td>
</tr>
<tr>
<td>1.5 m/s at 1200 sec</td>
<td>![Image of smoke and temperature conditions]</td>
</tr>
<tr>
<td>2.0 m/s at 1180 sec</td>
<td>![Image of smoke and temperature conditions]</td>
</tr>
<tr>
<td>3.0 m/s at 1150 sec</td>
<td>![Image of smoke and temperature conditions]</td>
</tr>
</tbody>
</table>

*Figure 13  Comparison of smoke and temperature conditions in the tunnel.*
CONCLUSIONS

Traincar fires in tunnel environment are usually modelled using computational fluid dynamics models such as the Fire Dynamics Simulator (FDS). The results of these models have seldom been compared to experimental data due to the unavailability of such data. In this study the data from a full-scale fire test on an intercity traincar conducted at the Fire Research Laboratory of Carleton University was used as a benchmark for comparison with the predictions of FDS. The experimental data used include the fire heat release rate, and the tunnel ceiling temperatures.

FDS was used to model as close as possible the experimental set-up including the tunnel geometry and ventilation conditions, the interior of the traincar including the seats and windows as well as the location and size of the fire ignition source. The traincar interior combustible materials included the floor, the seats and the wall and ceiling lining materials. These materials were modelled in FDS using the heat release per unit area (HRRPUA) concept and the ignition temperature. Modeling the materials by defining the HRRPUA and ignition temperature is a very common method used in FDS.

The comparisons of the FDS predictions with the experimental data showed that with appropriate material properties, FDS provides good predictions of the peak fire heat release rate and the time to peak. The model however predicted a slower initial fire growth rate and also failed to predict a heat
release rate plateau observed in the experiments, which was most likely due to the availability of fresh air into the traincar. The front windows during the fire tests remained intact until the fire spread to the front of the traincar, however in the model the windows broke in a short time. This demonstrated that modelling window breaking plays an important role in modelling fire growth. The FDS predicted tunnel ceiling temperatures had similar trends as the experimental, but the predicted values were lower than the experimental.

A number of simulations were done to investigate the effect of material fire properties on fire growth, peak heat release rate and time to peak. The results of these simulations showed that reducing the peak heat release rate of the material results in a lower fire peak heat release rate and an increase in the time to peak. The material ignition temperature has even a larger effect. A higher ignition temperature reduces the peak heat release rate and the time to peak. In some cases it causes the fire to self-extinguish one the ignition source is removed.

The size of the ignition source has also a significant impact on the time of seat ignition. Once the heat is ignited the fire heat release rate profile was found not to be affected by the ignition source size, hence the peak heat release rate was the same but the time to peak increased with a reduction of the heat source. It was found that, for the material properties traincar characteristics used for the study, an ignition source less than 35 kW resulted in no ignition of the seat.

The simulations done with different air velocities in the tunnel confirmed that when the air velocity is higher than the critical velocity there is no smoke backlayering. The results also showed that an increase in the tunnel air velocity causes a slight increase of the peak heat release rate and a slight reduction of the time to peak.

REFERENCES


NFPA 130 - Keeping up with Rail Safety

Harold L. Levitt,
The Port Authority of New York & New Jersey/Port Authority Trans-Hudson Corporation (PANYNJ/PATH)
2014 & 2017 Technical Committee Chairperson for NFPA 130

NFPA Mandatory Disclaimer - NFPA’s Regulations Governing Committee Projects, allows me, as a member of the Technical Committee (TC) to provide you with my personal opinion; it should also be known that my opinion does not necessarily represent the position of the TC or the Association (NFPA) and may not be considered to be or relied upon as such.

ABSTRACT:
The National Fire Protection Association (NFPA) Standard 130, entitled “Standard for Fixed Guideway Transit & Passenger Rail Systems” provides criteria to the transit and rail industry for the design of underground, at-grade and above ground (elevated) transit systems and their elements. The Technical Committee (TC) of NFPA 130 for the 2017 edition is taking on a number of significant issues, all of which have evolved since the previous edition published. First is the need for new and possibly expanded systems to locate stations and their respective tunnels deeper in order to go beneath existing infrastructure. A constant inquiry received over the years is that we must develop a uniform methodology for determining the Fire Heat Release Rates (FHRR) of fixed guideway and passenger rail vehicles. On-Board Fire Suppression technologies for new and existing rail vehicles to fight the fire at its main source will be introduced. All of these improvements, plus others are under consideration.

The National Fire Protection Association (NFPA) Standard 130, entitled “Standard for Fixed Guideway Transit & Passenger Rail Systems” provides criteria to the transit and rail industry for the design of underground, at-grade and above ground (elevated) transit systems and their components where the scope of the committee is:

Committee Scope Copied from NFPA 130: “This Committee shall have primary responsibility for documents pertaining to fire safety requirements for underground, surface, and elevated fixed guideway transit and passenger rail systems including stations, trainways, emergency ventilation systems, vehicles, emergency procedures, communications and control systems and for life safety from fire and fire protection in stations, trainways, and vehicles. Stations shall pertain to stations accommodating occupants of the fixed guideway transit and passenger rail systems and incidental occupancies in the stations.”

INTRODUCTION
In 2012, the late William D. (Bill) Kennedy and I presented a paper at the fifth Symposium of International Symposium of Tunnel Safety & Security entitled “SOME OF THE NFPA 130 IMPROVEMENTS PROPOSED FOR THE 2014 EDITION”. At that time, the NFPA-130’s Technical Committee proposed changes it felt would strengthen the 2014 Edition of the standard as it had done with all prior Editions; the changes were to the Technical and Annex Chapters:

- The Technical Committee proposed the a standard methodology of how to development Fire Heat Release Rates (FHRR) for Fixed Guideway or Passenger Rail Vehicles, we also planned that later editions would progress a methodology even further;
- The Technical Committee decided to extract all Wire and Cable requirements from the multiple chapters of the standard and address them in one location a new Chapter 12;
• The Technical Committee reorganized existing Chapters 5 (Stations) and 6 (Trainways) and put them in a normal construction sequence to make it easier to follow and build from;
• The Technical Committee introduced “Vehicular On-Board Fire Suppression Systems”. This became a new Annex Chapter G.
• An item that requires further consideration, as a carryover from the 2014 Edition, is how to incorporate an NFPA 130 quality, life-safety philosophy, for a “deep-station”. The Technical Committee must first define a deep station distance wise in feet and/or meters below ground. This may cause designers and their system operators to understand the need for new and expanded systems that go above-and-beyond what we understand today as that which falls into the basic principle of the standards’ criteria for a passenger stations, as we know it. Designers and operators must understand as they are obligated to locate stations and their respective tunnels deeper into the earth in order to go under existing infrastructure that already exists or to be within a geologically stable sub-grade.

The “Standard for Fixed Guideway Transit and Passenger Rail Systems,” NFPA 130 as it is known, is updated every three (3) to five (5) years or sooner if necessary to keep up with the ever-changing national and international transportation industry. The standard is the only all-encompassing rail transit and passenger fire-life safety standard in the world that incorporates all of the components of a fixed guideway transit and passenger rail system within its covers. For NFPA 130, as well as all other NFPA standards and codes, as well as other local codes and ordinances, it provides minimum requirements. It is incumbent upon designers, operators and AHJ’s involved the planning and development phases of any undertaking to meet or beat what has been covered in the standard or codes. The standard is for new construction and it provides guidance for the rehabilitation of older tunnels and stations should the operator adopt it in that manner. The Technical Committee’s unyielding mission is to provide ridership with a safe, reliable and cost-effective transportation services.

Because NFPA 130 was written to provide for the movement of commuting passengers transit and rail transit vehicles, other categories do exist but are not covered within the standard, they are: conventional freight systems, trolley coaches, circus trains, tourist trains, scenic, historic or excursion operations. That is, unless they do so by sharing a transportation corridor common with a fixed guideway transit and/or passenger rail system where they could potentially pose a threat to its fire-life safety because those vehicles in consist form are not constructed to the same standard. The other categories listed above frequently used historically older and out of service vehicles that were formally in service before NFPA 130 existed. Simply said, they do not meet NFPA 130’s vehicle construction standards. For those vehicles that are running on a common transportation corridor with a fixed guideway transit and/or passenger rail system, the operator(s) requests from the operator of the not covered within this standard, a Fire Heat Release Rate Analysis (FHRR) of the vehicle or consist if more than one vehicle. The Analysis shall be submitted to the operator of the fixed guideway transit and/or passenger rail system where if it has been found to create a detrimental condition that the fixed guideway transit and/or passenger rail system property owner/operator would then have the option of implementing additional fire-safety measures of which there are at least three available:

1) Increasing emergency ventilation capacities when it is determined through a fire analysis that the fire heat load of the non-included vehicle that it will be significantly higher than the design fire heat load of the “fixed guideway transit or passenger rail system” thus creating an untenable situation;
2) Holding back passengers in safe areas until the hazardous condition passes, and;
3) The introduction of tunnel and/or station sprinklers also potentially introducing on-board misting systems to vehicles, and;
4) Request that the non-fixed guideway transit and/or passenger rail systems operator, incorporate on-board fire-suppression system into their vehicles.
Chapters and Annex’s of the Standard

In the matter of creating a clearer and concise document, the 2014 edition and 2017 editions of NFPA 130 added 2 more Chapters updated the 2010 edition to twelve (12) technical chapters and seven (8) annexes.

Technical Chapters Contained in the Standard

- **Chapter 1  **Administration: Provides the scope of the Standard and defines the applications under which this standard will relate.
- **Chapter 2  **Referenced Publications: Lists all applicable publications referenced within NFPA 130 from the NFPA and other organizations such as the Air Movement and Control Association (AMCA), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the American Society of Testing Materials (ASTM) and the Underwriters Laboratories (UL), etc.
- **Chapter 3  **Definitions: Lists all the terms as they apply to this standard and provides a listing of all relevant standard NFPA terms along with their definitions.
- **Chapter 4  **General: Provides the characteristics of fire safety and defines the goals and objectives of NFPA 130.
- **Chapter 5  **Stations: Provides requirements for below-grade, at-grade and elevated stations including civil works and construction materials, wiring and power, emergency egress, lighting, and fire protection including sprinklers and standpipes, etc. (where required).
- **Chapter 6  **Trainways: Provides requirements for below-grade (tunnels), at-grade and elevated trainways including civil works and construction materials, wiring and power, emergency egress, traction power, and fire protection requirements for underground fuel storage tanks adjacent to or above subsurface trainways.
- **Chapter 7  **Emergency Ventilation Systems: Provides requirements for the design of emergency ventilation systems, including but not limited to emergency fans, dampers, power and wiring, inflatable barriers and their operation and control (local and/or remote).
- **Chapter 8  **Vehicles: provides requirements for vehicle construction, material and component testing, fire propagation resistance, ventilation, emergency egress, fire protection, testing and maintenance, and electrical elements including insulation, motors and their control, wiring, overload protection. (Note – Wiring and cables to remain in this chapter in the 2014 Edition as they pertain to Vehicles)
- **Chapter 9  **Emergency Procedures: This chapter, one of the most important chapters in the standard, it was developed by first responders and property owners/operators to give guidance on proper and prompt response to an emergency event. Over the years, more lives have been lost due to slow response than to insufficient equipment to handle the event. Having the proper emergency response precautions in place influences the day-to-day operations of any transit system. This chapter includes requirements for emergency planning and responses, planning of initial responses, roles of participating agencies (Authorities Having Jurisdiction (AHJs)), the role of the Central Supervising Station (also known as Operations Central Control), and requirements for training, drills and critiques. The components covered in this chapter apply to ALL types of systems, old and new.
- **Chapter 10  **Communications: This chapter was added to the 2010 edition. It covers communications of all kinds that would exist in fixed guideway passenger and rail transit systems. The chapter includes requirements for radios, telephones and public address systems in stations during normal, day-to-day operations as well as in the event of an emergency. The standard also defines the relationship between the Central Supervising Station and the at-the-scene Command Post throughout an emergency.
Chapter 11  Control and Communication System Functionality, Reliability, and Availability: This chapter defines requirements for the functionality, reliability and availability of control systems and communication systems when exposed to the effects of smoke and fire. It includes but is not limited to the following topics: train controls (signaling systems); emergency communication systems; traction power systems and Supervisory control and data acquisition (SCADA) systems as they apply to fire emergencies.

Chapter 12  Wire and Cable Requirements: This chapter, brought together in one chapter all of the requirements for wire and cable that is with the exception of wire and cables in vehicles. Chapter 8–Vehicles - Wire and cable information was not removed from this chapter because the wire and cable information contained within was too specific to a vehicle that it should not be re-located.

Annexes
The Annexes are included in NFPA 130 to provide clarification and supporting information to that which is included in the technical chapters of the standard. An Annex does not contain enforceable requirements unless an owner/operator or AHJ adopts it for use.

Annex A  Explanatory Material: Provides supporting information for elements contained in Chapter 1 entitled Administration.

Annex B  Ventilation: Provides supporting information for design of emergency ventilation systems. This annex also identifies factors for consideration in maintaining a tenable environment.

Annex C  Emergency Egress: Provides examples of emergency egress calculations to allow the designer to properly plan egress routes to areas of safety with the proper number and locations of stairways, escalators and elevators;

Annex D  Rail Vehicle Fires: Provides information the hazards associated with burning vehicles and the impact on passengers evacuating from them;

Annex E  Fire Hazard Analysis Process: Provides an expanded description understanding of the process required to conduct a fire hazard analysis for fixed guideway and passenger rail vehicles;

Annex F  Creepage Distance: Provides the minimum creepage distance for transit vehicles;

Annex G  On-board Fire Suppression System: While a relatively new concept in the Passenger Rail and Fixed Guideway industry; the installation of the type of system has been have been successfully used on a number of passenger rail and diesel powered light rail systems outside of the United States, and:

Annex H  Informational References: The documents or portions thereof referenced in this Annex are contained within the informational sections of the standard and are not part of the requirements of this document unless also listed in Chapter 2.

BACKGROUND OF THE STANDARD, WHERE AND WHEN IT ALL BEGAN
In 1975, the National Fire Protection Association established a Technical Committee to develop a standard for the rail industry because there were not any codes or standards in the industry that specifically dealt with Rail. Existing codes and standards revolved around building codes and standards for buildings and structures but none of which dealt with the fire and life-safety needs of Fixed Guideway Transit and Passenger Rail Systems. Members of the transportation industry quickly realized that rail was unlike buildings and structures. Once the NFPA 130 Technical Committee was established, transit properties in Atlanta, Baltimore, Los Angeles, Pittsburgh and Washington had
systems on the drawing board and recognized the need to for the industry to develop a rail fire and life safety standard; NFPA 130 became that standard.

Plans for systems under consideration for expansion or major modifications had progressed to where they were at the time ready for the drawing board did not have any rail guidelines to follow through the planning process; that is, other than what designers had knowledge of from their many years in the industry. Furthermore, it was determined that design methodologies that had were employed prior to World War II were no longer suitable in an evolving transit market. Older transit systems in Boston, Chicago and New York were all reaching their saturation levels and expansions became necessary but they no guidelines to follow.

Because there was not a standard in existence, the responsibility for design within the older rail systems fell to the “Authority Having Jurisdiction, the enforcers (“AHJ” as it is more commonly known, building departments, 1st responders, etc.) to make decisions in concert with this transit property owner/operators. AHJ’s were obligated to make engineering judgments that they felt were appropriate to resolve an apparent need. An AHJ has the responsibility for enforcing local rules and regulations in which a facility was located or one where a new system is being planned. However, while adhering to these existing rules and regulations (building codes), most AHJ’s, rightfully so, are profoundly experienced in high-rise buildings and structures where fire-life safety applications are needed rail on the other hand presented different revelations than to which they were not accustomed and thus treated rail as a high rise building. Also each owner/operator wanted their systems designed and constructed at as low a cost as possible, as expeditiously as possible and they did not want to incur any delays caused by the statutory approval process especially when they followed non-obligatory standards. There was no consistency of safety in design of rail systems available and thus each property owner/operator along with their respective designers, were designing to what they individually thought and knew as being appropriate.

The standard and code development process within the NFPA, under which NFPA 130 falls, is comprised of volunteer representatives from every facet of the industry both national and international regardless of which document. Each member of the committee is impart its knowledge and experience to others; all members are volunteers that are from a wide range of property owners/operators, special experts (i.e. engineers/architects), enforcers (often AHJ’s, first responders, code enforcement organizations, etc.) to product manufacturers. NFPA 130’s Technical Committee consists of 30 Principal voting members plus their Alternates. The NFPA proportions Technical Committees so that one group does not have the ability to control an outcome of a recommended change; all changes are agreed to by consensus voting.

The composition of the NFPA 130 Technical Committee is:

Users (U) (Operators)
- National Railroad Passengers Corporation (Amtrak)
- Bay Area Rapid Transit (BART)
- Metropolitan Transportation Authority (MTA) organized amongst three individual rail services:
  1. New York City Transit (NYCT)
  2. Long Island Rail Road (LIRR)
  3. Metro-North Railroad (MNR)
- Washington Metropolitan Transit Area Authority (WMATA/Metro)
- Chicago Transit Authority (CTA)
- Port Authority Trans-Hudson (PATH)
- Toronto Transit Commission (TTC)
- Societe de Transport de Montreal (STM)
- Land Transit Authority of Singapore (STA)

Special Experts (SEs)
- Parsons Brinckerhoff, Inc.
- Hughes Associates
- AECOM
- ARUP
- LTK
December 1971 Montreal Fire was a big turning point in the realization that guidance was necessary when designing and building new rail systems and for when expansions or major modifications to existing systems were necessary. The defining moment came when a large fire occurred on Montreal’s Metro System at the Henri-Bourassa Station. At the station, a train operator lost his life and, the large fire burned a number of locally stored train-sets. The fire also was so intense that it consumed automobiles parked in an above parking structure. For the firefighters to put out the fire they had to flood the entire terminal with almost 10 feet (3.5m) of water that covered everything and waited until the fire extinguished.

After the investigation concluded, the results pointed towards a faulty brake system on the incident train. During the investigation of the incident, the reviewers found that the incident train kept drawing power, and with power still on it continued to supply the fire and, once power was removed, the fire soon went out. However, with power now off, the terminals life safety systems and emergency ventilation fans could not be used. With the absence of power to operate meant that the smoke management ventilation fans became inoperable. With power-off, the fans smoke that controlled smoke was not present and the needed critical velocity afforded by those fans to keep the smoke from moving back to the incident location through backlayering was not present. (“Backlayering” as defined by NFPA 130 is “The reversal of movement of smoke and hot gases counters to the direction of the [required] ventilation airflow” or to take it a little further, tunnel smoke diffusing in both directions at any time in the absence of adequate ventilation.) To make a bad situation bad, the train’s tires were nitrogen filled and began exploding from the heat generated by the fire.

Montreal Metro provided their findings to the transit industry from which corrective recommendations that lead to solutions were stated. The solutions, as part of this review, led designers to develop methodologies to protect life and property. The concept of two sources of power to critical life-safety elements was set into motion such as two independent, separated protected power feeds to the emergency fans was developed. Additionally, introduced was a dependable fire standpipe system, rather than going to the extreme of flooding an entire station/terminal to extinguish a fire, it should be fed by two independent water supply sources; also, as we have found was that multiple fire districts could and would to respond to a fire. These fire districts in some cases used different hose fitting threads; the concept of having various fittings at each tie in point became an important factor.
At least one of the lessons learned as an outcome of the Montreal investigation encouraged NFPA 130 to adopt the concept of dual feed/redundancies for various fire-life safety systems such as fire standpipe system, fan power systems, etc. Critical systems should cross-connected or fed from two separate sources as well as power that is to be fed from two separate and independent feeds. For standpipes, each feed should have appropriate fire department fittings available for each tie-in point. That power to critical life safety mechanical systems, such as emergency ventilation must have two protected and available sources. The incident in Montreal triggered the thought process for which NFPA 130 was developed.

A Summary of NFPA 130 Updates from the 1st 1983 Edition to the Present Issued Edition:

In 1983, the National Fire Protection Association issued the first Edition of NFPA 130 after which it became evident that good practice said with the ever changing rail transportation industry that there was a need to update the standard on a regular basis, at intervals of approximately every three (3) to five (5) years or sooner if necessary.


I have included a summary of what the Technical Committee has proposed for the 2017 Edition, it will however, not be official until August 2016 when the NFPA Standards Council meets to approve these proposed revisions, with a date of the next Edition of 2017.

1988 In 1988, the Technical Committee added the Automated Guideway Transit (AGT) component to the standard. This caused modifications to former Appendixes C (Emergency Egress) and D (Suggested Fire Test Procedures for Fire Risk Assessment).

1990, 1993, 1995 The Technical Committee introduced some minor revisions during these three updates.

1997 The 1997 edition included a new chapter on emergency ventilation systems for transit stations and trainways. A new Appendix B addressing ventilation replaced the previous Appendix B, “Air Quality Criteria in Emergencies.” Also, the first three sections of Chapter 6 (renumbered as Chapter 7 in the 1997 edition), “Emergency Procedures,” were revised, and several new definitions were added.

2000 The 2000 edition addressed passenger rail systems in addition to fixed guideway transit systems. The 2000 Edition was re-titled to reflect that the combination accordingly. Additions and changes were introduced throughout the document to incorporate the combining passenger rail requirements with fixed guideway transit systems.

Much of Chapter 2 was rewritten to incorporate changes that were made to the egress calculations in NFPA 101®, Life Safety Code®; examples contained in Appendix C were revised using the new egress calculation methodologies; protection requirements for Chapter 3 were modified addressing emergency lighting and standpipes and lastly, Chapter 4 was modified to clarify and expand emergency ventilation requirements.

1990 The 1990 edition included minor changes to integrate provisions and special requirements for AGT systems into the standard. Table 1 from Appendix D was merged into Chapter 4, “Vehicles,” and new vehicle risk assessment material was added to Appendix D.

1993 Definitions for “enclosed and open station” were added to the standard in 1993 along with minor changes to Chapters 2 and 3.

1995 The 1995 edition made minor changes to Chapters 1, 2, and 3.

2003 For the 2003 edition, the Technical Committee incorporated a number of technical revisions to the egress requirements and respective calculation methodologies for stations. Chapter 8 (Vehicles) was modified to incorporate a performance-based design approach to vehicle design. This
changed the industry’s thinking on the traditional prescriptive (specified-based) vehicle design requirements. The 2003 version also incorporated conversions to SI (new metric) units throughout the document.

**2007** The 2007 edition of NFPA 130 saw revisions affecting station egress calculations, including incorporation of escalators into the calculation methodology; allowance for vehicle interior fire resistance; and power supply to tunnel ventilation systems. All guidelines associated with maintenance facilities were removed as those guidelines were contained in other codes and standards. Finally, the Technical Committee revised the vehicle performance-based design criteria to address the uniqueness of the rail vehicle as opposed to other transportation type vehicles.

**2010** Changes to the 2010 edition included provisions allowing elevators to be counted as means of egress elements, and revisions to escalators, doors, gates and turnstile-type fare equipment allowing them to be more appropriately used in egress calculations. Further, the Technical Committee modified Annex “A” by adding several fire scenarios to provide guidance on how to calculate other types of fires not originally included in the annex such as certain vehicle and station fire types.

**2014** The 2014 edition of NFPA 130 includes substantial re-organization of Chapters 5 and 6 for consistency and consolidation of wire and cable requirements into a new Chapter 12. Other changes include reconciliation of terminology related to enclosed trainways and engineering versus fire hazard analysis; revisions to interior finish requirements; revisions to requirements for prevention of flammable and combustible liquids intrusion in Chapters 5 and 6; and improvements to Annex C.

**2017** As with previous updates of the NFPA 130 standard, for the 2017 edition we have focused on Emergency Response and Emergency Communications, acoustical concerns and better defined insulation (not for wires and cables) but for all other infrastructure (walls, etc) elements and also furthered discussions, but were not ready to include, for On-Board-Fire-Protective-Systems.

**Application of NFPA 130 in National and International Transit Venues**

A number of National (USA) and International venues have adopted NFPA-130 as their railroad standard guideline mostly because the standard incorporates all of the known components of what an operating rail (fixed guideway or passenger rail system) system should contain. The adoption of NFPA 130 characteristically occurs when the transit system in a city such as was the case in Boston, Camden, Chicago, Los Angeles, New York City, Newark, and San Francisco requires a significant modification and/or a major expansion.

NFPA 130 has evolved into a well-recognized standard for fire-life safety of rail systems for the rehabilitation of older transit systems and development of new transit systems particularly internationally.

- National locations include the following: Atlanta; Baltimore; Dallas; Detroit; Los Angeles; New York City; Pittsburgh; Portland; Oregon; San Francisco; Seattle; St. Louis and Washington DC (certain pieces).
- Internationally, countries that have adopted NFPA 130 include the following: Argentina, Brazil, Canada (Montreal, Toronto and Vancouver), China, Copenhagen, Denmark, Guangzhou, Hong Kong, Istanbul, Izmir, London, San Juan, Shanghai, Singapore, Taipei, Taiwan, Turkey, Middle-East Countries and the United Kingdom.

The NFPA 130 Technical Committee has members from the international community as well as the USA: Australia, Canada and Singapore.
For the 2017 EDITION, the Technical Committee will continue to investigate:
The Beginnings of a Development for a Fire Profile Methodology for Rail Vehicles with a simplified Flow chart of how to get to that point.

![Flow Chart](image)

**Figure 1 Concept Flow Chart for Material(s) Material Testing to develop the Fire Heat Release Rate of a Vehicle**

Fire modeling has provided insight on a spill (e.g. gasoline) fire size required that causes a vehicle (railcar) to reach flashover, there are at least three standard techniques employed: 1) doors closed, 2) doors open on one side and 3) doors open on both sides. Fires with less initial ventilation, that is, with fewer doors open require less of gasoline to cause flashover inside the car. The amount of gasoline required to facilitate a flashover or even a burn can range anywhere from ½ gallon or less if the conditions are right and materials chosen are wrong to 1¼ gallons and up, again if conditions are right. However, of course, the more need for gasoline that is required for burn the less likely the opportunity for flashover will become. You can say the materials selected for the vehicle are appropriate.

Descriptions of what the above flow chart means:
- Obtaining drawings of a vehicle;
- An experienced testing laboratory will determine which materials are critical for testing usually associated with major surface areas;

<table>
<thead>
<tr>
<th>Element Name</th>
<th>Material of Selection</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seating</td>
<td>Glass Reinforced Plastic (FRP)</td>
<td>Seat</td>
</tr>
<tr>
<td>Flooring</td>
<td>Rubber</td>
<td>Floor</td>
</tr>
<tr>
<td>Windows</td>
<td>Polycarbonate</td>
<td>Windows</td>
</tr>
<tr>
<td>Rubber Gasket</td>
<td>Chloroprene Rubber</td>
<td>Window Gasket</td>
</tr>
<tr>
<td>Ceiling/Wall Panel</td>
<td>Melamine Coated Alum.</td>
<td>Ceiling and Walls</td>
</tr>
<tr>
<td>Window Pan</td>
<td>Glass Reinforced Plastic</td>
<td>Wall Panel Around Windows</td>
</tr>
<tr>
<td>Light Diffusers</td>
<td>Polycarbonate</td>
<td>Covering Light Fixtures</td>
</tr>
<tr>
<td>Windscreen</td>
<td>Melamine on Aluminum (MOA)</td>
<td>On Ends of Seats Around Doors</td>
</tr>
</tbody>
</table>
• Conduct fire testing of each component to determine its values. Testing lab’s usually obtain multiple samples of each of the critical components so that test of components can be repeated multiple times in order to gain an average value;

<table>
<thead>
<tr>
<th>Description</th>
<th>Material</th>
<th>Total Fuel Load (kg)</th>
<th>Combustion Mass (kg)</th>
<th>Total Heat Released (MJ/m²)</th>
<th>Heat of Combustion (MJ/kg)</th>
<th>Heat of Gasification (MJ/kg)</th>
<th>Surface Area (m²)</th>
<th>Energy Load (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seating</td>
<td>FRP</td>
<td>146.47</td>
<td>58.74</td>
<td>68.20</td>
<td>18.20</td>
<td>2.51</td>
<td>15.67</td>
<td>1069</td>
</tr>
<tr>
<td>Flooring</td>
<td>RBR</td>
<td>236.97</td>
<td>50.00</td>
<td>73.20</td>
<td>25.80</td>
<td>2.30</td>
<td>17.62</td>
<td>1290</td>
</tr>
<tr>
<td>Windows</td>
<td>POLYC</td>
<td>87.07</td>
<td>71.40</td>
<td>123.50</td>
<td>20.40</td>
<td>2.40</td>
<td>11.79</td>
<td>1457</td>
</tr>
<tr>
<td>Rubber Gasket</td>
<td>NEOP</td>
<td>38.29</td>
<td>13.40</td>
<td>185.50</td>
<td>14.70</td>
<td>1.90</td>
<td>1.06</td>
<td>197</td>
</tr>
<tr>
<td>Ceiling/Wall Panels</td>
<td>MELM</td>
<td>173.13</td>
<td>27.70</td>
<td>8.100</td>
<td>10.60</td>
<td>1.50</td>
<td>36.25</td>
<td>293.62</td>
</tr>
<tr>
<td>Window Panel</td>
<td>FRP</td>
<td>68.33</td>
<td>50.49</td>
<td>50.80</td>
<td>20.30</td>
<td>0.75</td>
<td>20.18</td>
<td>1025</td>
</tr>
<tr>
<td>Light Diffusers</td>
<td>POLYC</td>
<td>16.64</td>
<td>14.11</td>
<td>73.40</td>
<td>20.20</td>
<td>1.10</td>
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<tr>
<td>Windscreen</td>
<td>MOA</td>
<td>183.21</td>
<td>29.31</td>
<td>5.10</td>
<td>13.1</td>
<td>1.50</td>
<td>75.29</td>
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<td>Totals</td>
<td></td>
<td>1075.52</td>
<td>766.89</td>
<td>285.84</td>
<td></td>
<td></td>
<td>106.46</td>
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</tr>
</tbody>
</table>

Abbreviations: FRP-Fiber Reinforced Plastic, MOA-Melamine on Aluminum, POLYC-Polycarbonate, NEOP-Neoprene, MELM-Melamine, RBR-Rubber

• Initial steps in this process focus on understanding and documenting the important features of the railcar for the fire modeling and selecting materials that needed to test in order to determine the appropriate fire properties for modeling.

• Two separate models are normally used, the “Fire Growth Model” and the “Compartment Fire Model”. Both Modeling methodologies serve different importance’s, one is used, the “Fire Growth Model”, to predict an initial fire development and to determine whether a spill fire could cause the railcar to reach flashover;

• If a flashover does occur, then use the “Compartment Fire Model” to determine the history of the fire using the heat release rate of the interior materials from the fire growth model. If a flashover does not occur, a design fire is found. Better definitions of both the Fire Growth Model and the Compartment Fire Model Method are below.

**Fire Growth Model Logic**

Fire growth modeling is performed using an improved version of the fire growth model described in the literature (Lattimer and Sorathia, 2003a, Lattimer et al. 2003) this modeling method predicts ignition and flame spread along a combustible lining when exposed to a user specified fire. When the fire is located inside an enclosure, the model predicts the gas flows in and out of the enclosure as well as the depth and gas temperature in the hot upper-layer that accumulates inside the enclosure. This gas layer pre-heats un-ignited materials in the upper-part of the enclosure that accelerates the flame spread across the material. The current version of the model includes a one-dimensional finite difference routine for more accurate calculation of surface temperature up to ignition, improved methods for predicting the heat release rate of the burning material, and a more robust, fully validated two-layer compartment fire model for predicting upper-layer and lower-layer gas temperatures.
Compartment Fire Model Logic

The compartment fire model used in this analysis to determine the heat release rate history was a quasi-steady, single layer compartment fire model. This model is capable of predicting fire conditions during pre-flashover, post-flashover, and decay stages of the fire. Model features include flow in and out of the compartment through one or more vertical openings that may have different sill heights (i.e., doors and windows), predicting plastic window failure time, multiple materials burning with different properties burning in the compartment, effects of compartment thermal environment on material burning, and heat losses through multiple boundaries with different construction. The output from the model includes time varying total heat release rate, gas temperatures, flow rates in and out of the compartment, window failure time, remaining mass of combustible materials, mass loss rates of combustible materials, heat release rate contribution of individual materials, heat release rate inside the compartment, and equivalence ratio.

Introduction of Acoustical Needs

Acoustic control concepts, with this new standard, are being presented in Annex B so that noise level establish criteria’s can be under those situations specific to the various components/elements set-forth in the standard. The Criteria that has been added will allow passengers, crews and first responders with the ability to maintain at least a minimal level of speech intelligibility along emergency evacuation routes. This might require additional noise control measures and acoustical treatments to achieve an acceptable level commiserate with an incident. Considering exceptions to the recommended noise levels for reasons of cost and feasibility should be as few as reasonably possible. For example, local area exceptions to the recommended acoustic criteria could be required, and applied, for defined limited distances along an evacuation path that are near active noise sources, near a fan shaft in a tunnel. The designers should consider other means of providing emergency evacuation guidance using acoustic (sound), non-acoustic (visual) or combined methods as an alternative to reasonable yet functional intelligibility to all.

Continuing Investigation into On-board Vehicle Fire Suppression Systems (i.e. Misting)

At the Technical Committee’s recent meeting in October 2015, FOGTEC presented the latest in technologies for a vehicle on-board fire suppression system. As with most USA regulations, the increased vehicular weight factor due to this methodology it will become necessary to obtain waivers from the various regulatory agencies (FRA, FTA, etc). However, ultimately this on board suppression system can be of great benefit when it comes to capital cost savings. For example, when it comes to the design/construction and even finding properties for LARGE Tunnel Emergency Ventilation (TEV) Facilities that needed to remove and/or pull smoke away from a fire. Property issues and their associated costs, plus the physical and environmental constraints of construction play an important role on where a TEV facility can be located. If in residential areas, the considerations become demanding and restrictive and that equates to COSTLY not saying that TEV facilities can be eliminated in their entirety but it is feasible that their fan sizes can be reduced and as such so will the building sizes that house the fans. With On-Board Systems, space becomes an issue especially for a vehicle especially where retrofitting a vehicle is necessary. Most operators want little to do with losing space, because loosing space means less occupants and less occupant mean less revenue; every operator wants to crush load each vehicle to get the best return on investment.

In the last edition The Technical Committee came to the reality that since its inaugural publication in 1983 that it must look more closely into whether or not to require sprinklers and/or misting systems in stations and on rail vehicles. The Technical Committee’s Vehicle Task Group proposed that vehicles should contain on-board fire suppression (misting) systems. We added language was to a new “Annex G”; it was the committee’s intent of developing it further in the following editions and with that in mind migrating it into Chapter 8-Vehicles where, it could become enforceable. We would introduce on-board fire suppression systems only when introduced when vehicle fire modelling demonstrated the benefits of it in order to reduce a vehicle’s FHRR.
Addressing the Deep Station Egress Issue

Stations are there to move passengers back and forth between the street and trains/platforms, however, in today’s environment where transit stakeholders are contemplating new stations, trackage, etc., because of existing subsurface infrastructure to go much deeper under that existing infrastructure. ‘Deep’ stations introduce factors that require consideration beyond the provisions that have been developed for more typical station designs, largely associated with the potential for delayed egress on stairs due to fatigue. Thus, becomes the need for improved ingress/egress techniques to get passengers and first responders to/from the deeper station locations.

By allowing protected high-speed elevators, escalators and protected stairs as a means of egress from deep station would help but a few jurisdictions are not in favor of using elevators and escalators. Providing additional and protected areas of safe refuge on platforms and/or in other areas of the station/facility would also help immensely. The more and more commonplace deep station has made it necessary for the NFPA 130 Technical Committee to step back and look more aggressively into these components as viable means of egress. Other methods employed could be a more robust emergency and station ventilation system, supplemental sprinkler protection, operational procedures, etc. A sample of what could be an acceptable design, it happens to be for a center platform station is below, it is by no means to be considered the only way, it is a single potential solution.

Deep stations already in service:

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Depth (m/f)</th>
<th>System</th>
<th>Built</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Admiralteyskaya</td>
<td>105m/344f</td>
<td>Saint Petersburg Metro</td>
<td>2011</td>
<td>Russia</td>
</tr>
<tr>
<td>Arsenalna Station</td>
<td>105m/344f</td>
<td>Kiev Metro</td>
<td>1960</td>
<td>Ukraine</td>
</tr>
<tr>
<td>Washington Park Station</td>
<td>97m/318f</td>
<td>MAX System-(Tri-Met)</td>
<td>1998</td>
<td>USA</td>
</tr>
<tr>
<td>Park Poebey Station</td>
<td>97m/318f</td>
<td>Moscow Metro</td>
<td>2003</td>
<td>Russia</td>
</tr>
<tr>
<td>191 Street Station</td>
<td>55m/180f</td>
<td>New York</td>
<td>1911</td>
<td>USA</td>
</tr>
<tr>
<td>Beacon Hill Station</td>
<td>49m/160f</td>
<td>Sound Transit</td>
<td>2009</td>
<td>USA</td>
</tr>
</tbody>
</table>

Depth’s - m = meters, f = feet
NFPA Codes and Standards are updated at least every three, but not more than every five years in order to meet the needs of the industry for which they are being prepared for. This is a National Fire Protection Association requirement.

For the Next Edition, the Technical Committee include but not be limited to the following and will also entertain other issues as they are presented to the Technical Committee for advancement:

- High Speed elevators from platform to surface
- Rated Sliding/Accordion Fire Doors That Hide Away in a Wall Pocket (same other side)
- Storage Closets for Emergency Gear
- Scissor Stairs for both FD use and Passenger Use to surface Rated Fire Doors.
- Tracks
- Platform
- Lobby
- Tracks

Figure 4 An Example of a Deep Station’s Platform Layout for Egress Capabilities For a Center Platform Station
• To Further the development of a standardized methodology for formulating the FHRR for vehicles; and
• To Further develop methods for including on-board fire suppression systems into vehicle; and
• To investigate and incorporate issues associated with the growing high-speed rail industry; and
• Exploring additional methods for safe egress from deep station’s; owners and operators of new rail and transit systems are confronted with the long-term issue of having to go deeper into the earth to by-pass existing subsurface infrastructure. Passengers must consistently be reassured that they are safe and secure while down there. For the next issuance of the standard, the Technical Committee will be developing modeling methodologies that will allow designers to correlate modeling results with real real-life situations and put them into place; and
• To further study and develop and include into the standard – ACOUSTICS

INTERNATIONAL ACCEPTANCE

NFPA 130 will continue to be a major force in the world, as it is the only comprehensive document that provides AHJs, owners/operators and designers with a basis for the safe and efficient design and construction of passenger rail and transit systems, whether new or old.

The ventilation guidelines provided in NFPA 130 are internationally accepted. Although not the target topic of this paper, there exist many differences between the emergency egress requirements of NFPA 130 and those used on projects outside the USA. These differences have sometimes resulted in the adoption of NFPA 130 by other countries in part, rather than in its entirety. The Technical Committee will continue to improve it to meet the growing needs of the industry, and keep it up-to-date and in line with the global market. The TC will incorporate criteria and recommendations as they are generated especially information as obtained from the international marketplace that can improve NFPA 130 and make it more widely accepted.

ACKNOWLEDGEMENT

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Self Evacuation from Fires in Long Subsea Road Tunnels: The Case of the Oslofjord Tunnel Fire in 2011

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ABSTRACT:
This article presents results from a case study of the crisis management of the Oslofjord-tunnel fire 23 June 2011. The Oslofjord-tunnel is 7.3 km long and the fire occurred in a heavy goods vehicle (HGV) approximately 1.7 km from the tunnel mouth at the eastern side (Drobaek). Our study was based on interviews with the involved parties in order to reveal their narratives about the event. We focused on decision making in the accident, based on the theory of Naturalistic Decision Making. Our conclusion is that the current tunnel design does not comply with principles of self-evacuation. The road-users had very little knowledge about tunnel fires and how to react in the emerging situation. We think that the tunnel fire safety competence issue is still unresolved and that more effort should be given to increase knowledge amongst all cooperating actors. This implies that authorities, voluntary, private and official actors are individually responsible for establishing appropriate interactions with relevant parties regarding the fire and rescue situations. The contents of the self evacuation principle must be understood by all parties if it shall premise the design of existing and future road tunnels.

KEYWORDS: Major tunnel fire, self evacuation, crisis management, performance of safety measures

INTRODUCTION
The Oslofjord-tunnel is a 7.3 km long sub-sea tunnel and the fire occurred in a heavy goods vehicle (HGV). The gradient at the location was 7 %, which is 2% more than what is accepted in the current EU regulations. A description from the investigation report provides an introduction to the case (AIBN, 2013, p. 5):

“On Thursday, 23 June 2011, at 1436 hours, a lorry truck registered in Poland started burning in the Oslofjord tunnel as a result of engine breakdown. The lorry truck was climbing the incline towards Drobaek approximately 5.5 km from the tunnel exit on the Hurum side and 1.7 km from the tunnel exit on the Drobaek side. The driver tried to extinguish the fire as best he could before being forced to evacuate the tunnel due to increasing heat and smoke. The fire ventilation system was activated about 4 minutes after the Road Traffic Centre (VTS) registered the fire in the lorry truck. The ventilation direction was predefined on the basis of the fire department's extinguishing effort, resulting in 5.5 km of the tunnel being filled with thick, black smoke at a speed of 2-3 m/s. The danger to road users was exasperated by the tunnel's safety equipment and emergency preparedness solution not being sufficiently designed for self-rescue. There was only one escape tunnel (3480 metres away from the location of the fire) in addition to the tunnel exits and no smokeproof evacuation rooms. In addition, many road users did not receive information from the VTS via radio on time to turn/evacuate before being trapped in the smoke. The fire extinguishing from the Drobaek side functioned in a satisfactory manner and as expected. The rescue effort from the Hurum side encountered major problems due to the smoke development, risk of collisions and the distance to the fire location. 25 of 34 road-users exited the tunnel under own power. Nine road-users were later evacuated from the tunnel by rescue crews. The overview VTS had through CCTV monitoring of the tunnel and direct contact with road users in the SOS boxes, in addition to the emergency services' fire and rescue efforts, saved lives that day. The fire escalated quickly and road-users downstream of the tunnel ventilation (from east towards west) were suddenly trapped in smoke. No-one were killed in the event, but 34 persons were trapped and some of them seriously injured due to inhalation of toxic gases”.

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The description of the fire shows that individuals from the emergency services as well as individuals who were trapped in the tunnel were forced to make critical decisions during the fire. These were decisions related to their own survival, either because they considered rescuing individuals who were trapped in the smoke, or because they themselves were in the tunnel and were surrounded by smoke. The Oslofjord tunnel fire is therefore an interesting case regarding how the decision makers, trained or not trained, assess situations and mentally simulate the crisis in order to carry out their tasks.

**STUDY APPROACH**

When studying the fire in the Oslofjord tunnel, the major issue of examination was; how was the tunnel designed to maintain self-evacuation in major fires? By *tunnel design* is understood the physical layout of the tunnel, the safety systems, the traffic regulation, the crisis response system, the road-users abilities and prerequisites in major fires, such as HGV fires. The regulation regime in Norway entails that the road-users’ expected emergency response behaviours in tunnel fires is based on the *self evacuation principle*. This means that the road-users are supposed to evacuate from the tunnel by own means, either by car or by foot. We organized the data gathering as semi structured, rather informal interviews with involved persons in the crisis. These were:

- Road-users trapped in smoke, where urgent evacuation was necessary (7)
- Emergency services (ambulance, fire and rescue, and the Police - 6)
- Road traffic centre employees who were responsible for remote management of emergency response measures and communications (3)

The Police was in charge of the rescue operations and had access in the aftermath to identities of the people involved in the accident. We let the Police identify and invite potential interview respondents. Thus, we have not been in contact with any of the victims that were asked by the Police to participate but who declined. We do not posess any overview of persons approached by the Police, and the portion who rejected to participate. 7 of 341 potential road-users is not a large portion. It would have been desirable to interview the persons who decided to remain in their cars recirculating the air. Neither of the road-users we interviewed had experienced a tunnel fire before, no one knew about the self evacuation principle and how escape from the tunnel should be accomplished. There were four women and three men between the ages of 35 and 61 years. Four of them were on leisure travels while the other road-users travelled in work related activities. All of them had experience travelling through the Oslofjord tunnel.

The emergency response personnel interviewed were all working on the Drøbak (eastern) side of the tunnel, from which the major search and rescue work was carried out. The personnel we interviewed in the Road Traffic Centre (VTS) were also involved in the event and were directly in contact with the emergency response personnel and/or the road-users.

The outline of the interviews were influenced by the Critical Decision Method - CDM (Crandall, Klein, & Hoffman, 2006), which is a technique that encourage the respondent to think, rethink and thoroughly reflect upon his or her reasoning in the situation when he or she made the choices. In this way we could relate the respondent’s knowledge about tunnel fires and the specific factors and cues that were deemed important for the respondent at that time. The Critical Decision Method has been scrutinized for the reliability of decision point identification and the coding (Taynor, Crandall, & Wiggins, 1987; Tissington, 2001), and hence internal validity related to the causal explanation of the data. In the study performed by Taynor, Crandall & Wiggins two researchers reviewed selections of the interview data and found a high degree of correspondence. For example, from a wildfire study eight respondents were interviewed a second time after 3 and 5 months after the interview. The correspondence between critical decision points identified in the first and second interview varied from 56-100%. The CDM approach has been widely adopted in NDM studies since the 1990s. The technique is highly relevant for interviewing the search and rescue personnel, but we also thought that for the road-users it was interesting to observe the effect of this interview technique. The analysis of

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1 Data is gathered from the AIBN (2013), but information received from the respondents questions the numbers.
the material also included a comparison of the information given and observations from the investigation reports and other documents provided.

We interpreted the data from the perspective of the Naturalistic Decision Making process (Klein, 1993; Klein, Orasanu, Calderwood, & Zsambok, 1993). The two major elements in naturalistic decision-making (NDM) are situation assessment and mental simulation, which is context specific and experience based. The main model often referred to as contributions from NDM is the Recognition-Primed Decision (RPD) model (Klein, 1989, 1993). The RPD model is based on research from a variety of tasks and domains, such as fireground command, wildland fire incident command teams, battle planning, critical care nursing and chess tournaments (Klein, 1993). The RPD model is a process model where decision making is a sequence of activities. The process consists of three typical phases: Situation recognition; Serial option evaluation; and Mental Simulation. Klein’s conclusion is that proficient or expert decision makers rarely compare among alternatives. Instead they assess the essence of the situation, e.g. types of building fires and their demands. Then they select an action which they know will cope with the urgent situation, e.g. use a ladder and smoke divers to rescue people trapped on third floor of the burning house.

The RPD model describes emergency situations, minor as major, offshore and onshore, earthquake and landslides, and that is its forte. In addition it is easy to understand and it is holistic. The decision maker identifies critical cues (e.g. is the driver breathing after a car crash?), then one assesses the situation (the driver is not breathing), and implements action (CPR, cardiopulmonary resuscitation). Plausible goals are set (the non-breathing driver should be able to breathe on his own). The action is evaluated (is he breathing?). If the patient does not breathe the decision maker has to start the process over again. The RPD model includes feedback loops (e.g. the effect of the actions that have been carried out) and mental simulations promote feedback loops, which is a way of being proactive.

We wanted to identify the critical cues mentioned by the various decision makers, and we more or less regarded all respondents decision makers in their own context and as part of the larger emergency response system. Could we say that most of the operational decisions were made by intuitions, or the “knee jerk reaction” to each of the individuals involved? The context matters, but also the basic knowledge possessed by the persons involved. Some relevant questions were:

- What was the course of events?
- What kind of expectations did the actors express regarding the event development?
- Was considered a rapid and skillful response?
- What was the basic knowledge of the actors with command responsibilities and tasks?
- How did experiences from the event, and the actors’ perceptions vary between different personnel groups?
- Which factors might be part of the tunnel owner’s management system, and the first responders’ systems in such crisis situations?
- How well does the NDM explain the actors’ decision making and implemented actions in the crisis?

The interviews gave us information about the road-users behaviors. As a group we found that the respondents’ answers were characterized by great uncertainty about the situation in the early phase of the incident, which delayed their decision to escape. Based on our analysis of the data material we present the identified critical decisions that influenced the outcome of the fire event and how injured people were treated.

RESULTS
When the road-users realized they needed to the self evacuate from the tunnel many of the road-users grouped together in order to evacuate. Also when driving was impossible these persons remained together in order to find their way out of the tunnel until they found shelter behind the tunnel arch. Some people (4-5) decided to sit in their vehicles using the recirculated air. These persons have not been part of this study. The other road-users tried to turn their vehicles around in order to drive out
downstream the fire to the western mouth of the tunnel. Most of them succeeded, but a number of persons (9-12 – we do not know exactly) did not make it and were forced to find shelter in the tunnel. They ended up behind hatches leading to the space between the tunnel arch and the mountain profile, which were not supposed to serve as a shelter. When the fire and rescue personnel gained control over the fire the search and rescue work started. All victims were found and brought to safety and hospitalized within two hours after the fire broke out.

The current tunnel design did not comply with principles of self-evacuation. The road-users had very little knowledge about tunnel fires and how to react in the situation. Their situational awareness was not aided by others than the threatening cues (heat, noise, smoke, smell, etc) and fellow road-users at the site. Their behavior was socially conditioned, and for example principles of the recognition-primed decision-making was not seen amongst the respondents. The critical decisions that contributed to the difficult but positive outcome (no fatalities) were:

**Event detection on CCTV and tunnel closure.**
At the VTS the initiating fire was detected by two operators simultaneously. Both of them saw that the event had the potential to develop into a major accident. Their internalized procedural behaviour of closing the tunnel immediately and switch to emergency lights were put into action. The emergency services were notified (the fire department first). According to an operator at the VTS, preparations for taping a radio message were taken. The CCTVs ensured a reasonably good overview of who and how many persons were in the tunnel at the time of initial fire situation, even though there was some uncertainty. The operators also registered several road-users entering the tunnel after the tunnel was closed and physical measures were in place to prevent cars from entering the tunnel, by driving around the hinderances. For the road-users outside the tunnel on their way in, the decisions and implementations of measures from the VTS operators were extremely important. These measures were in place in very short time. No one has estimated the effect of these actions. Amongst the VTS operators these actions were automatically carried out without any reflections of alternatives.

**Triplet alarm and resource allocation**
The triplet alarm on both sides of the fjord was initiated immediately as a routine act (cf. the “Summary after the fire in the Oslofjord tunnel Thursday 23 June 2011”, Søndre Follo Fire Department). The first emergency vehicle was at the scene 13 minutes after the event had been detected by the VTS. The resource allocation on both sides was comprehensive, both based on previous experiences from especially an event in April the same year and the fact that fire in the Oslofjord tunnel was a scenario internalized by the emergency services in their plans and exercises. They were prepared for fires in HGVs. The fire commander acted immediately to organize water and human, technical and back-up resources to the scene.

The medical emergency services were also considerate about their potential needs in the crisis response. Use of Helseekspressen² (“Health Express”) became an opportunity highly regarded amongst the emergency services for its role as operations centre and location for health services and triage. The leader of the Helseekspressen applied mental simulation in his approach to the crisis management, and from the early call he was never in doubt that use of the Helseekspressen would be important. From the interview: “Yes, I imagined situations where there would be dangerous goods and toxins included in the fire. It could have become a disaster then. I also considered chain collision near the fire location in which people would be trapped in their own cars”. The emergency services prepared for worst case scenarios and allocated resources accordingly, which included provision of their own fire water supply.

**Fire ventilation**
The most difficult decision, regarded from a hindsight perspective, was the switch to fire ventilation. VTS had their overview, information from CCTV which indicated numerous humans downstream the fire. The fire ventilation was from the Drøbak side towards the Hurum side in accordance with the procedure, which prioritized the most sufficient equipped fire department (Søndre Follo fire

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² “Helseekspressen” is a modified bus with medical equipment able to treat and transport patients of various conditions.
department) for fighting HGV-fires. Thus, when the decision was made the only question was when to turn on the fire ventilation, and that was the operator’s dilemma. The fact that no one used the SOS telephones and informed the VTS of the situation within the tunnel complicated the response.

The criterion for switching to fire ventilation was that the fire units had arrived at the tunnel portal from the Drøbak side, and the underlying arguments were that the fire department needed full access to the fire in order to combat the situation. One of the respondents from the emergency services claimed that delaying maximum ventilation was perhaps the most important decision with respect to the road-users’ self evacuation efforts. There exist major uncertainties about how various ventilation strategies affects smoke production, toxic gases and in general the conditions for the victims. The road-users described their experiences being trapped in the smoke as a dramatic experience. Many of them found that they were in a hopeless situation, both with respect to understanding the situation and providing correct responses in order to evacuate in time. One of the road-users expressed serious criticisms regarding the time and reasoning for putting on the fire ventilation. None of the road-users described that they registered changes in the smoke concentration, for example after maximum ventilation was initiated. The first decision (fire ventilation) was made upon clearly defined procedures, on the contrary the decision to switch to maximum ventilation was knowledge based. However, the assumptions and models considered by the incident commander in this situation has never been pursued in the investigations. Other solutions to the ventilation issue were never considered. There was a request to reverse the ventilation at the scene, but the suggestion was rejected promptly.

**Information to road-users (radio information, light, smoke dispersion)**

AIBN (2013) criticized the emergency response activities with respect to how information about the fire was presented to the road-users. According to the AIBN the radio message was launched too late. The interviews with the road-users showed that only one thought that something was said on the radio, but it had no effect on how the self evacuation was carried out. It needs to be considered that our interview data is restricted to 7 of 30-50 involved road-users, and the individuals we interviewed were trapped in the smoke. We do not know if the road-users who successfully evacuated before the smoke caught them, received vital information regarding leaving the tunnel from the radio message. However there has not been information in the aftermath that support the role of the radio message, for example in the media. Thus, we claim that information to help road-users to adopt correct evacuation behavior before they met the smoke projectile was not disseminated in the early phases of the event. The road-users who evacuated based their decisions on other road-users or they saw the fire themselves.

The road-users received information of varied quality during the crisis. In one of the cars that succeeded in evacuating out of the smoke through the Western portal, the passengers received a recommendation to lay down at the tunnel floor from the contact with the dispatch centre. The road-user perceived a lack of knowledge and understanding from the emergency service. Another person that after a while found the area behind the tunnel arch, was told that the rescuers was on their way to rescue them: “I had contact with them up there. Yes, the emergency service is getting control now they said. It was an operator that tried to calm us down, but it only became worse because what was said was nonsense. We thought then that something very bad was happening, and we became sceptical to all information presented to us.” Another road-user said that it was the contact with the VTS that gave them the idea to enter the tunnel arch behind the SOS-telephone box. This became very important for their (6 persons) survival. After the smoke filled the tunnel volume there was no view, that is the emergency lights did not fulfill their function at all.

**Road-user solidarity**

The road-users described a situation perceived as hopeless and an opinion that they were “doomed to die”. One of them searched for other road-users in order to hold a hand while dying. Other road-users described a situation of resignation, hysterical or panic filled fellow road-users. Nevertheless there was only one road-user who said she had been rejected when she asked to join a fellow road-user in his vehicle. People gathered and the driver of the car became the leader of the evacuation team. The
groups that were formed in general remained together also after they had to leave their car walking towards the west entrance of the tunnel. The group that found shelter closest to the fire described the air behind the tunnel arch as much better to breathe than outside the hatch that separated the tunnel room from the back of the tunnel arch. However, one person did not enter the area behind the arch, but sat in front of the hatch. This road-user did neither not comply about a worsened situation while she sat there. All the respondents said they were conscious throughout the entire scenario. Even though the road-users claimed to be in a resigned mood they did not act that way. They tried to increase the conditions for their own survivability and our analysis shows that the group solidarity strengthened their want to survive.

**Fearless firefighting behavior**

We encountered very confident emergency responders, when discussing their own procedures, especially the fire fighters’ approach. Their own equipment, resources and experiences and competence were regarded as being sufficient to combat crises in the Oslofjord tunnel. The first vehicle that arrived at the scene had been notified that the HGV did not contain dangerous goods and the fire operation leader therefore when entering the tunnel neglected to stop by the driver of the HGV, who was on his way out of the tunnel. The operations leader fully trusted the reliability of the information from the dispatch centre. To us this was quite odd, based on our earlier research on dangerous goods in Norway. We know that there are comprehensive rule bending behavior and lack of information regarding commercial heavy goods transport, for example related to HGVs on ferry transport or when it comes to coloading (Njå & Vatn, 2010).

The fire extinguishing started immediately and the breathing air conditions were so good upstream the fire that the respondent from the emergency service worked close to the fire without self-contained breathing apparatus. When an 11 kg propane bottle within the HGV exploded, the fire fighters did not reconsider their strategy, but continued to fight the fire with foam and water. Probably they thought the explosion was due to the HGV-tires exploding. Keeping the responders back and not entering the smoke filled tunnel room was perceived a major problem for the operations leader. He had to wait until they gained control over the fire, and that presented him with a dilemma because he knew that there were several persons downstream the fire. It is not clear when the maximum ventilation was started, but according to the fire department’s log it happened approximately at 15:25, which was half an hour after the road-users became enveloped by smoke. The fire extinguishing activities were carried out in accordance with procedures. The operations leader assumed that he required 4-5 minutes more time from the first search and rescue responder asked for permission to enter the area filled with smoke until he gave the permission.

**Rapid rescue with ATV (all-terrain vehicle) and the paramedics available close to the scene in the tunnel**

The real time assessment by the on scene commander and the professional leaders at scene regarding the smoke injured victims concluded that one ambulance should be sent down in the tunnel to retrieve patients. This was controversial to the health workers, because it represented a threat to their own safety. Subsequently it turned out to be a good solution, which some of the respondents said could serve as a learnt lesson from the event. Who decided on this solution is a bit unclear, because several respondents claimed to have been involved in making the decision. We saw this as an indication of cooperation and ownership of the decision.

Infraread camera and use of ATV (all-terrain vehicle) were efficient tools to search and evacuate patients from the tunnel. The initial search was restricted to people sitting in their vehicles (respondents said that there were people sitting as close as 50 m downstream the HGV on fire) and bring them to medical treatment. We have not interviewed these victims, thus we do not know the reasoning behind their behavior. However the respondents from the emergency services did not recognized critical conditions for these road-users, hence we assume that the situation for them (heat and smoke) seems to have been no worse than for the road-users that walked and found shelter behind the tunnel arch. In general all respondents emphasized the professional treatment they received when the emergency services found them.
Debrief and the road users own initiatives to gather and cope with the psychological stress reactions

Based on the interviews with the road-users we found that they were very different with different needs to cope with psychological injuries. They have all experienced a traumatic crisis, and some of them sustained severe damages. Three of seven road-users that were interviewed said that they had respiratory injuries even three years after the event, information they gave unasked. The professional services (Public Road Administration and the emergency services) organized debriefings the day after the fire, which was considered very helpful by the individuals that experienced the fire. They were given the opportunity to enter the tunnel to look at the scene of the fire. Some of the road-users complained about the tunnel owner’s evasive answers to questions raised regarding the safety management of the tunnel, for example related to the ventilation strategy and the regulatory requirements to safety. Some of the respondents (road-users) talked very positively about private ad hoc gatherings in the aftermath where the fire was the subject of discussion. These informal meetings became opportunities to speak about their own experiences. These meetings seemed to be important for the individual’s crisis management processes and psychologic well-being.

DISCUSSION

The above presentation of critical decisions is an overview of individual and collective response activities that prevailed for the specific fire situation. To what extent was the behaviours in accordance with the NDM theory and the RPD-model? The basic assumption related to NDM theory is knowledge based behavior, which would be a reasoning beyond established procedures, which will entail situation awareness at a mature level. Based on our analyses of the interview data there were few examples of such a behavior, but some initial precautions were creative, such as use of the Helseekspressen, and the operational and professional leaders of the fire fighting activities requesting ambulances in the tunnel and the provision of resources in the early phase. There were some kind of mental simulations that based their decisions. However, we do not think that NDM had a general explanatory power for the response activities performed, neither amongst road-user nor responders (VTS and emergency services).

Based on our analysis of this event we think that safety should be improved based on various characteristics with the tunnel design that emerged:

- It takes too long time before road-users realise dangerous situations in tunnels and prepare for self evacuation.
- The organizing of self evacuation is arbitrary and to a very little extent adapted for the road-users’ needs.
- The road-users do not posess knowledge of tunnel fires.
- The buyer of transport services, transport salesmen, forwarding agents, transport companies and drivers of HGVs containing large amount of energy has been very little considered and scrutinized with respect to their roles and responsibilities regarding major fires in tunnels.
- Knowledge of fire dynamics, heat development and smoke dispersion in tunnels is weak.
- Procedure driven or knowledge based fire and rescue work must be balanced. No one seems to define what is a good balance.
- Easy accessed information about Norwegian road tunnels and fire protection strategies is lacking.
- The individual victims’ post traumas and stresses is underrated.

Knowledge about the contents of goods travelling through Norwegian tunnels is scarce, especially with regard to the potential for exposure to toxic substances in serious releases and combustions. The tunnels are sociotechnical systems not very easily predicted in case of future accidental events. For the tunnel owners and the emergency services the level of complexity is challenging for their safety management work. To a certain extent risk analysis approaches address simplified systems, which for tunnels similar to the Oslofjord tunnel might not be sufficient to optimize safety and provide useful
decision support. Instead a more systems engineering approach (Leveson, 2011), providing insights into safety constraints should also be part of the design basis. This solution would bring the general understanding of traffic dynamics, and accident and risk images a step further than the recommendations presented by the Accident Investigation Board Norway in their investigation of the fire (AIBN, 2013). Based on our preliminary investigation into the experiences of the Oslofjord tunnel fire we think that important risk reducing effects could be obtained by for example (Njå & Kuran, 2015):

- Develop the regulation regime for the commercial heavy goods transport (large amount of energy and dangerous goods) to place larger responsibilities upon the transport companies and their drivers to cope with emergent crises, more in line with the IAMSAR (International Aeronautical and Maritime Search and Rescue) Manual. This includes the ADR regulation, but is not restricted to that regulation, because there are a vast number of transports with large energy amounts for example related to food (carbohydrates and fat).

- Situation awareness as governing principle for the safety management systems in road tunnels, in which personnel safety is prioritized. This will influence design of the ventilation strategies, traffic flow systems, surveillance etc. The ban on emergency rooms which is found in existing regulations should be reconsidered.

- Maximum ventilation strategy combined with fresh air facilities available for road-users enveloped in smoke.

CONCLUSIONS

How was the Oslofjord tunnel designed for self evacuation? The fire event clearly showed a lack of measures to carry out evacuation in a controlled manner. When the emergency ventilation was switched on the self evacuation principle was abandoned. The victims, who were occasional road-users were presented with smoke exposures no one controlled. The outcome of this fire was fortunate, there were no deaths, but the number of seriously injured people remains unknown. Our study showed that three out of seven respondents complained about their health situation and believed it to be a result of their experiences with the fire. The Norwegian government adhere to the Zero Vision philosophy (Larsson, Dekker, & Tingvall, 2010) in their traffic safety management and in accordance with the Zero Vision philosophy events as the Oslofjord tunnel event are very critical for the Norwegian Public Roads Authorities.

The NPRA has carried out many arrangements to improve the safety of the Oslofjord-tunnel. The risk reducing measures span from reduced speed when entering the tunnel, better signs and road marking, dynamic emergency lights and emergency rooms, to automatic voice input in emergencies. The efforts done are assumed to have improved the self-evacuation conditions.

However, these measures assume a certain level of knowledge about tunnel fires. We think that the need for knowledge is still unresolved and that more effort should be given to increase knowledge amongst all cooperating actors. It implies that authorities, voluntary, private and official actors are individually responsible for establishing appropriate interactions with relevant parties regarding the fire and rescue situations. Establishing effective emergency response cooperation requires coordinated response plans, procedures and routines as well as regular exercises and training involving all relevant parties.

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Implementation of a Priority Based Emergency Management System in the “Antigoon” Rail Freight Tunnel in the Port of Antwerp

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ABSTRACT

On December 15th 2014, after a 6 year period of drilling, building and commissioning, Infrabel started the exploitation of its new “Antigoon” train tunnel in the port of Antwerp. Since then, this more than 6 km long twin-bore tunnel is the longest tunnel in Belgium. It forms a major link between the left and right bank of the river Scheldt, has specifically been designed as a rail freight tunnel, and is meant to accommodate the rise of freight traffic in the years to come.

The main threats to the construction are severe freight train fires (up to 300 MW if not suppressed in early stage), explosive and toxic gases, and intrusion by unwanted “guests”. To deal with these different kinds of threats, the project team within Infrabel established a clear hierarchy for these threats. Furthermore, we devised a unique priority based emergency management system that provides an automatic and incremental incident response when one or more incidents occur, based on the hierarchical classification of these safety & security threats.

In this paper we present the rationale behind our system design and we present our experiences of implementing the system. We show how we aligned our automatic emergency management system with fire department intervention and with tunnel operations from our remote control room. In this paper we also include our experiences of the 1st year of tunnel operation, and share it with the symposium audience.

KEYWORDS: Emergency management, scenario management, rail freight tunnel, case study, incremental incident response in function of severity, automated firefighting with light foam, ventilation control of nocuous gases, intrusion, fire department intervention

THE LIEFKENSHOEK RAILWAY LINE

With its 6 km in length, and situated up to 40 m beneath the river Scheldt, the twin tube Antigoon tunnel is the most impressive part of the so-called Liefkenshoek railway line. But in fact, the Liefkenshoek railway line is more than just the Antigoon tunnel. It’s the common denominator for a newly built 16 km long railway route that also consists of open air tracks, access ramps and a second (but shorter) rail freight tunnel, the “Beveren” tunnel, which is 1.2 km long (see Figure 1 and Figure 2).

The Liefkenshoek railway line forms an extra link between the left and right bank of the river Scheldt, and fits within Infrabel’s strategy of gradually expanding rail capacity in and around the Port of Antwerp in order to support the growth of freight traffic in the years to come and to ensure optimal intermodality of freight traffic between rail and water.
Figure 1: location of the Liefkenshoek rail link in the Port of Antwerp

Figure 2: longitudinal section of the Liefkenshoek rail link
The construction of the Liefkenshoek rail freight line took place from 2008 till 2014, and was a joint effort of several project partners:

- railway infrastructure manager *Infrabel* (acting as founder of the project), its engineering subsidiary *Tuc Rail*, its ICT department,…
- private investment group *LocoRail NV*, responsible for the financing, building and maintenance of the civil infrastructure,
- the Flemish government,

in cooperation with several stakeholders such as the Port of Antwerp, and the fire departments of the city of Antwerp and the town of Beveren.

**OBJECTIVES & PRINCIPLES OF THE SCENARIO MANAGEMENT**

As indicated in annex D of the relevant TSI [1], we need tunnel safety measures in four lines of defence: prevention, mitigation, evacuation and rescue. As the Antigoon tunnel is a rail freight tunnel, with transports of hazardous goods taking place but also with a limited amount of people present in the complex (mainly train drivers and maintenance staff), our automatic scenario management system has mainly been devised to offer assistance in the defence lines prevention, mitigation and rescue: the safeguard of the tunnel infrastructure and a thoughtful automatic assistance to the fire fighters and rescue services were main design criteria for the development of the system.

![Figure 3: annotated TSI 2008/163/EC – figure (chapter 2.1)](image)

A scenario is an automatic and logical response of all tunnel equipment to a first or confirmed detection, in order to manage a safety or security related incident. Scenarios simplify and accelerate equipment management in case of an incident and simplify communication between the control room and the emergency services, as each ‘technical’ scenario has been complemented and aligned with ‘operational’ schematic intervention plans that structure the emergency services’ intervention on a per-scenario basis. These plans depict a clear view on the type of incident that occurred at a certain tunnel location and also depict the most useful points of intervention (e.g. stairwells in the evacuation shafts). A similar example from a previous project can be found in reference [2]. At a selected number of main intervention shafts, dynamic screens also show these plans together with real time information about the environmental conditions in the tunnel and the operating status of the tunnel’s safety systems (see Figure 7 for an example).
PRIORITISATION OF SCENARIOS

In our project we’ve got the following kinds of detection that serve as inputs to our scenario management system: fire detection in the tunnel and its ancillary buildings, gas detection, intrusion detection, camera surveillance and train detection (i.e. rail section occupation). Depending on the type of trigger, our system responds to the trigger by activating the automatic scenario best suited to handle the threat or incident. After a thorough RAMS-analysis [3], we classified our 127 different scenarios according to the hierarchy mentioned below:

1. **fire in tunnel scenarios** activate (amongst others) the foam based extinguishing system once the fire has been localised at a steady location [video: https://youtu.be/2CGGzEAScY];
2. **explosive gas scenarios** try to alleviate the conditions that may eventually lead to a gas explosion (% LEL), by activating a.o. the longitudinal tunnel ventilation;
3. **high intoxication gas scenarios** prevent CO- and NOx-gases from intoxicating people in the tunnel when their higher detection alarm threshold has been reached;
4. **fire in building scenarios** trigger the evacuation of people present in evacuation shafts, cross passages and technical rooms;
5. **fire in tunnel pre-scenarios** trigger actions that can already be performed when a train on fire is still riding and the foam extinguishing location cannot be determined yet;
6. **low intoxication gas scenarios** prevent CO- and NOx-gases from intoxicating people in the tunnel when their lower detection alarm threshold has been reached;
7. **cold scenarios** are started manually from the control room for ‘cold’ incidents like derailment;
8. **intrusion scenarios** trigger both security and safety actions upon unauthorised tunnel access;
9. **train stop scenarios** start preventive ventilation in order to avoid intoxication when a diesel train has a prolonged standstill in the tunnel.

Figure 4 shows the hierarchical classification of the different scenario types, together with their respective main objectives, triggers, and possible transition phases.
The concept of scenario escalation

An important notion in our emergency management system is the concept of “escalation”. In the event that a more serious incident happens while a scenario is running for a lesser incident, this scenario will stop automatically and all emergency equipment will react towards the newly triggered ‘heavier’ scenario. Of course, in this situation of sudden changeover, some equipment must first come to a stop before switching to its new status. The big ventilation fans are an example of this possibility. Otherwise all equipment that remains in the same status while escalating from the lower to the higher scenario, does not need any transition time.

Logic escalations are those from low to high gas alarm and from a ‘moving’ fire to a fire on a train that stopped in the tunnel. A special attention is needed when an explosive gas scenario turns into a tunnel fire: a proposed automatic escalation must then be confirmed by the responsible fire brigade officer in charge. When explosive gases have been detected in the tunnel, we only want to execute the transition after careful consideration, as the activation of the fire in tunnel output equipment (e.g. activating the tunnel lights) may ignite the explosive gases. Therefore we implemented a T1/T2 acceptation and verification cycle at the control room, to assess the location and severity of both scenario triggers and to constrain the automatic execution of this transition.

A reverse ‘deceleration’ is not possible. We’ve put the necessary prioritisation logic in place to guarantee that the ‘most important’ scenario is active at any given moment in time: it’s impossible to overrule a scenario of a higher priority by a scenario of lower priority, unless a total reset of the first scenario is executed or unless the programmed actions are individually adjusted from the control room, explicitly on demand of an authorised operator or intervening officer. See Figure 4 for the exact order of priorities and the possible escalations between scenarios.

The role of the control room operator in scenario activations and adjustments

The scenario activation and escalation principle, based on the priority classification of each scenario type, has been implemented as an automatic process that doesn’t require any specific operator.
intervention. Once a detection system has been triggered, all appointed emergency equipment will react accordingly based on their settings in our scenario configuration matrix (see below). Two scenarios however need an intervention from the operator for their activation:

- An intrusion detection (door opening or thermal camera) is always to be followed by a confirmation by the operator. This is done to eliminate the effect of false positives on tunnel operation;
- A ‘cold’ scenario is by definition a manual action after a responsible officer demanded for it.

Besides the aforementioned system interaction, the control room operator also has the possibility to intervene and adjust the scenario outputs on a per-equipment basis while a scenario is running, in function of the needs during the intervention. Examples are: adjust the ventilation settings, manipulate the tunnel lighting, start/stop the foam extinguishing, arrange access to the tunnel complex,… In a first instance, the operator will have to put the scenario in a so-called “freeze” condition. From that moment on, all equipment stays in the automatic modus unless it is individually changed by the operator. During the course of the intervention, the visualisation screens in the control room show the current status of the equipment in real time to allow remote supervision by the operator.

**Synoptic representation of tunnel scenarios**

During the design phase of the project we created a synoptical representation of the tunnel complex with a length to width factor of 20, which was useful to visualise all of these scenarios by zone and type.

![Synoptic representation of tunnel scenarios](image)

**Figure 5: representation of different scenario types on a synoptic layout**

**Scenario matrix allows flexible output configuration**

We fully documented each scenario by location in the tunnel complex and by type, and we listed the consequent actions of the emergency equipment in our scenario matrix. This was done in such a way that each individual item will be activated when asked for by a ‘steering-code’ in our matrix. See also reference [2] for a more visual representation of this matrix.

Figure 6 gives an example for the scenario type with highest priority: Fire detection in a tunnel tube AND the train has stopped (i.e. the point with the highest temperature has been located at a steady position).
The scenario with the lowest priority, a diesel train stopping in the tunnel, has only 1 of these actions, say the start-up of the necessary longitudinal ventilation, to prevent any built up of nocuous gases. There is however no overpressure in the shafts, no alarm in the control room and certainly no foam extinguishing or signals put to red. Therefore, these scenarios are also called ‘automatic actions’ and they run in the background, without any inconvenience for train conductor or security operators. Once the train departs again from the spot where it stopped, ventilation will automatically stop after 15 minutes.

While there is a possibility that 2 trains stop in the tunnel on different tracks, it is also possible that the ventilation runs in 2 directions, one in tube A and the other in tube B but NEVER against each other in the same tube. Important: these lowest ranked diesel train stop scenarios are the ONLY scenarios that allow 2 (or more) safety conditions of the emergency equipment (in casu the ventilation fans) at the same time, on condition that they are not counterproductive.

For the other scenarios there is a simple rule: if a detection system (e.g. fire) starts an automatic scenario with higher priority and a lower scenario (e.g. intrusion) was active at that moment, this lower priority scenario will stop immediately and all equipment will adopt a new status as demanded by the matrix codes for the new higher scenario. If however a higher scenario is active then all incoming detections, with the intention of eventually starting a lower ranked scenario, will be neglected by the system.

OVERVIEW OF INSTALLED SAFETY & SECURITY EQUIPMENT

Detection systems serving as input to the scenario management system

In order to give a quick response to an incident, following detection systems have been put in place:

- A performant linear heat detection system in the tunnels, comprising of 36 km of twin fibre glass cables and 7 control devices. Detection is done by scattering of a laser signal that is permanently emitted into the fibres;
- A total of 690 smoke or temperature point detectors in all utility buildings, evacuation shafts and
cross passages, completed with 220 manual call points;
- 18 control panels throughout the complex, according to the EN 54-2 standard, giving the link between a detector alarm and the redundant safety PLCs who control further output actions.

**Gas detection:**
- 10 detectors for nocuous gases as CO and NOx, located at different stop signals where a stationary freight train can produce these gases from the diesel engine exhaust;
- 7 detectors for explosive gases as CH₄, located at vulnerable locations in the tunnel;
- 5 control panels, located nearby the detectors, giving the link between the detector alarm and the redundant safety PLCs who control further output actions.

**Intrusion detection:**
- All doors between an evacuation shaft and a tunnel section are monitored for unwanted opening during normal train traffic. This monitoring can be lifted during maintenance works;
- At the tunnel entrances at both sides, thermal cameras are operational to spot intruders.

**The processing core of the scenario management system**

To automate all scenarios we designed and implemented a distributed system architecture with a PLC- and IT-based processing and communication layer that also interfaces with our control room in Antwerp that also guards other railway tunnels [2]. The core of our scenario management system has a SIL 2 functional safety level, according to NBN EN 61508 [4], and takes the above-mentioned detection systems as inputs, and the systems mentioned below as outputs. Our scenario management system also consists of visualization screens, installed in the control room and at the 3 main intervention shafts. They support control room operators and the intervention teams in assessing the severity of an incident, and allow the control room operators to adjust individual equipment settings during the course of an active scenario.

![Figure 7: visualisation screen at the main intervention shafts + control room](image)

**Actuated systems serving as output of the scenario management system**

After a detection has been registered in the system and confirmed, a set of safety equipment can become operational, depending on the type of scenario (Fire, Gas, Intrusion) and its location:

Automatic **Fire Fighting System** in the tunnel by light **foam extinguishing**:
- 5 water and foam supply stations at an interdistance of some 1.800 m, each including 2 diesel pumps of 11.350 l/min, a water reservoir of 864 m³ and 2 foam tanks of 5 m³ each;
- 243 water/foam mixing and flow devices, located every 60 m along the tunnel wall; in case of a confirmed fire detection in zone ‘n’, also the devices of zones ‘n-1’ and ‘n+1’ will activate to form an extinguishing zone of 180 m long within the tunnel section (see Figure 3);
- Some 5100 light foam generators with an expansion ratio of 600:1 have been installed at both sides of the tunnel walls – also in the center of the ceiling where 2 tracks are alongside each other in the same tunnel → a maximum of 90 generators will eject a foam flow of 55 m³/min each.
- Automatic fire suppression with nitrogen gas in 16 ICT-rooms, located on top of the evacuation shafts and at auxiliary buildings.

3 large tunnel ventilation stations, each with 2 huge fans, able to eject 720.000 m³/h into a tunnel section, creating an air speed of approximately 3 m/s. The main use is the automatic removal of noxious and explosive gases, after being detected at low level. The fans can also be used in a post-fire situation, for removing smoke and pushing the residual foam to the outside of the tunnel.

An overpressure, up to 60 Pa (± 10 Pa) is created in all evacuation shafts and cross passages between the tunnel tubes. For the shafts, with a stair inside, this means importing air from the outside. In the cross passages, the air is taken from the “non affected” tunnel tube.

32 blue flashlights indicate the places where the intervention team can find extra fire fighting material. Where this material is located in a cross passage, flashlights have been mounted above the access doors in both tunnel tubes.

The tunnel lighting system has been divided into 24 tunnel zones + 14 evacuation shafts. This system will automatically be activated depending on the incident zone under consideration. The emergency lighting is independent from the integrated system and will switch on as soon as the main electric supply is lost.

Revolving cameras (180°) have been installed every 200 m in the tunnels. The scenario management system will direct them towards the place of the incident, followed by a direct pop-up of 16 camera images on the visualisation screens in the control room and at the main intervention shafts. In addition, some 70 fixed cameras have been placed at doors and vulnerable places.

All doors are guarded by the acces control system. Unlocking of these doors in case of incident is in favour of an easy access to the infrastructure for the intervention teams, not having a badge.

Sirens are present throughout the complex. They give a warning signal to all workers that might be present in a distant location, relative to the place of the incident. This is important in case of an explosive gas detection.

Upcoming trains must be stopped before entering the tunnel when subjected to an incident. Therefore a selection of signals will keep their red light or will be put on red, depending on the type of incident and the incident’s exact location.
Besides this safety equipment, there are also installations for normal daily use. These must be halted and put in a secured position: air supply in transformer rooms, climate control in ICT-rooms, elevators in the evacuation shafts and the tunnel drainage pumps.

**MAIN EXPERIENCES FROM THE FIRST YEAR OF TUNNEL OPERATION**

**Calibration tradeoffs for the linear heat detection system**

The detection of a fire in the tunnel immediately starts a sequence that leads to the automatic activation of the foam extinguishing system, and fills – without intervention of a control room operator - a complete tunnel section of 180 m with foam. So any unnecessary activation of the extinguishing system should be avoided to the maximum extent possible, as it leads to a considerable downtime of tunnel operations and a non-negligible cost for cleaning up the tunnel.

For the calibration of the linear heat detection system, the project team had to make a tradeoff between two important choices:

- We should configure the detection thresholds of the system sensitive enough in order to enable the detection to occur in an early phase of the incident, when the fire is still small enough to be controlled by the foam extinguishing system;
- We should make the detection system as insensitive as possible in order to avoid that it will be triggered by – for example – the heat from an engine exhaust pipe of a diesel locomotive.

Linear heat detection systems can typically be configured with 3 types of detection criteria:

1. An absolute temperature;
2. A temperature gradient, i.e. a certain change of temperature over a certain period of time at a specific location;
3. A hotspot or temperature deviation at a certain point when compared to the detection zone it is part of.

We started the commissioning phase of the project with the following set of parameters:

- An absolute temperature of 58°C;
- A combination of temperature gradients of 17°C per minute, 19°C per 2 minutes or 22°C per 3 minutes;
- A hotspot or temperature deviation of 22°C.

In Infrabel’s other tunnels with a similar heat detection system (but without the diesel traffic that typically comes with freight transport), this set of parameters has been implemented with good results. In the Diabolo tunnel for example [2], which is a passengers-only railway tunnel, no single exceedance of these thresholds has been observed during the first 3 years of operation, apart from a single activation by direct sunlight at the tunnel entrance during the first “really sunny” day of operation.

During commissioning, the project team sent a number of trains with different diesel locomotives through the Antigoon tunnel with the purpose of trying to trigger the detection thresholds. We tried to create a worst case situation by using a large and heavy cargo train that has stopped at the lowest point in the tunnel, then trying to accelerate its way up to the exit of the tunnel, without any tunnel ventilation in operation. Only for the diesel locomotives that had their exhaust pipe positioned in such a way that the exhaust fumes immediately stimulated the linear heat detection cable (attached to the fire resistant cable trays at both sides of the track), led this approach to a situation where the configured temperature gradient parameter was exceeded.

Luckily, an experimental analysis that was conducted earlier in a test facility by the specialists of the foam extinguishing system, learned that its extinguishing potential would not be compromised by the
speed of fire detection when only the first criterium (absolute temperature) and the third criterium (hotspot) would be applied for the fire types under consideration. This led us - at least temporarily – to remove the second parameter (temperature gradient) from the activation parameters for a tunnel fire scenario, until we know to what extent diesel engine locomotives influence the temperature gradient parameter. The first 9 months of commercial tunnel operation proved that this was a good decision: by doing so, we avoided the activation of a tunnel fire scenario (and hence the foam extinguishing system) 3 times over that period of time. All 3 temperature gradient exceedances occurred at the steepest part of the tunnel on the right bank of the Scheldt, in the (bored, single track) tunnel tube where diesel locomotives are pulling their cargo upwards and need to use the maximum of their engine power in a very confined area. In Figure 8, we marked these 3 locations with small crosses, in tunnel section 5-6 beneath the Canal Dock B1/B2. At that location, the inclination is at its steepest with a rate of increase of 18‰. It’s not yet clear whether the exceedances occur for specific locomotive types, but we know that the percentage of diesel-propagated traffic is considerable and amounts to approximately 75% of the total traffic.

Figure 8: locations of exceeded temperature gradient threshold (marked by crosses)

Table 1: linear heat detection parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Absolute temperature $T_{max}$ [°C]</th>
<th>Temperature gradient $DT1$ [°C/60s]</th>
<th>$DT2$ [°C/120s]</th>
<th>$DT3$ [°C/180s]</th>
<th>Hotspot [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>initially configured</td>
<td>58</td>
<td>17</td>
<td>19</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>currently configured</td>
<td>58</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Together with the observation that the first and the third parameter didn’t lead to a tunnel fire scenario activation during the commissioning tests, it’s interesting to note that we observed in a similar earlier test at the Diabolo tunnel that these parameters were positively influenced by the application of preventive tunnel ventilation. The observed maximum temperature decreased to a level far below the absolute temperature threshold, and the ventilation led to a double positive effect on the hotspot criterium by decreasing the maximum temperature and increasing the average temperature in the zone under consideration. So this is also a useful side effect of the train stop scenario (see section “Prioritisation of scenarios”) that was originally only meant to prevent intoxication when a diesel train has a prolonged standstill in the tunnel.

Actual use of scenarios during the first months of operation

In the scenario hierarchy of our priority based scenario management system, train stop scenarios and
intrusion scenarios are among the scenarios with lowest priority. In practice, these two scenario types have also accounted for most of the scenario activations during the first months of operation. While the number of activations of train stop scenarios can easily be attributed to the mere fact of trains (although avoided if possible) temporarily stopping or slowing down in the tunnel, the cause of intrusion detection activations appears to be more varied.

Thermal imaging cameras are one of the techniques used for intrusion detection at the tunnel edges and entrances. They need quite some calibration in order to minimise the number of “false positive” intrusion alerts, but on the other side they’re effective in detecting real intrusions. It’s clear that we regard this system as an aid for the control room operators to ease the surveillance of the tunnel entrances. But contrary to the tunnel fire scenarios for example, the project team estimated that a second opinion by a control room operator is always necessary with this kind of systems. Therefore we implemented a T1/T2 acceptation and verification cycle by the control room operator before activating an intrusion scenario.

Another scenario type that has been activated rather frequently, is the low intoxication gas scenario, corresponding to the exceedance of the lower detection alarm threshold for CO- and NOx-gases. The main cause for the activation of this scenario type are the exhaust fumes emitted by diesel locomotives. So the initial idea of only using the natural tunnel ventilation during standard tunnel operation, will probably be complemented with a more permanent forced ventilation to provide a more proactive way to deal with the issue of exhaust fumes. No occurrences of high intoxication gas scenarios have been observed during the first 9 months of tunnel operation.

In general, the fire detection and explosive gas detection systems behaved well and according to our expectations during the first months of operations. Apart from a limited number of false positive activations due to a small amount of detectors that got polluted during the construction phase, these systems have shown to operate reliably.

CONCLUSION

As a conclusion we can say that the definition of different scenario types proves its worth, as they are all used to a certain degree. The classification of scenarios into priority classes enables the scenario management system of our rail freight tunnel to execute the most relevant scenario at any given moment in time. After a run-in period, with a calibration and finetuning based on the first usage of the system, we can conclude that the scenario management system contributes positively to the implementation of the safety and security policy of the rail freight tunnel, and assists control room operators in their daily management of the tunnel.

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Recommendations for Firefighting in Underground Facilities

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ABSTRACT

The need for a successful fire and rescue operation in an underground facility, e.g., a tunnel, introduces challenges both in the planning phase and during the incident. This is because these types of facilities can be very complex, and thus, specific tactics are needed compared to the more common incidents, e.g., in residential premises. When planning a fire and rescue operation and developing the tactics, many different aspects need to be considered: complexity of the facility, the expected number of people involved in the operation, information available about the incident, the purpose of operation, etc. This paper contains recommendations for firefighting in underground facilities. The recommendations are structured in accordance to the sequential time period during which some specific fire safety design measures are taken. These periods are the design phase, the construction phase and finally when the facility is in operation. The recommendations presented in this paper are based on the results of the Swedish TMU research project (Tactics and methodologies for firefighting in underground facilities), results from other research projects and experience from real fire and rescue operations.

KEYWORD: Tunnel, fire and rescue service, underground facility, rescue operation, recommendations

INTRODUCTION

The development of cities, environmental considerations and the desire to use city ground for new purposes lead to the construction of new and more complex underground facilities. At the same time, such underground facilities are usually parts of an infrastructure sensitive to long interruptions. Due to these aspects, fire and rescue services have to adjust their resources and methods originally based on operations in ordinary buildings above ground.

What kind of, and how large, problems that can arise in connection with operations in underground facilities will vary depending on the rescue force and on the complexity of facility in question. In addition, important factors such as what is burning, where the fire is located and the conditions for a rescue operation can vary considerably. This makes it evident that some kind of guideline for the fire and rescue services is necessary, which explicitly considers fire rescue operations in underground facilities. Furthermore, different facilities require different solutions, and thus recommendations, depending on geographical location and the capacity of the specific fire and rescue service.

One of the objectives of the Swedish TMU research project - Tactics and methodologies for
firefighting in underground facilities - has been to develop guidelines or recommendations for operations in different types of underground facilities. These recommendations are intended to provide authorities, fire and rescue services, and fire safety designers with guidance on how to perform rescue operations in an efficient way, while at the same time minimizing the risks for the rescue personnel. Others that may benefit from the recommendations are educators and researchers.

In this paper, the term underground facility primarily refers road tunnels, rail tunnels, mines and underground garages. Since the possibilities for a safe and efficient operation are affected by the properties and conditions of the facility, recommendations are given also for the design phase. In the paper the recommendations are given in different sections depending on what phase (design, construction or operational) that it primarily relates to. To some extent the recommendations take into account the different resources available depending on whether the operation will be performed by rural or urban fire and rescue services.

BASIS FOR THE RECOMMENDATIONS

The recommendations presented are based on the tests performed in the TMU project (further described below), tests performed in previous projects, the experiences of the partners from real operations in underground facilities and on discussions with the TMU project advisory group. This means that not all recommendations were actually evaluated in the TMU project, but the authors suggest that these are tested in future preparations for rescue operations. Some recommendations are also as mentioned based on tests performed in previous research projects, e.g. other projects financed by the Swedish Civil Contingencies Agency [1-3], the METRO project [4] and the BARBARA project [5]. Altogether, this means that the recommendations are based on many years of experience of a large number of involved persons. This includes not only specific tests with the fire and rescue services, but also several projects studying the fire development and the conditions in a tunnel during a fire.

One of the most important issues discussed in relation to different recommendations is the time to get an overview of the situation and the legal requirements in Sweden to have secured access to water during a BA (breathing apparatus) operation in a fire situation. For this reason, in this paper BA operation means an operation in thick smoke to save life or fight a fire. A team conducting such an operation is referred to as a BA team.

The recommendations also consider the availability of different organizational resources, the capacity of different types of equipment and how to improve the use of these. In addition to the division between design phase, construction phase and the phase when the facility is in operation, the recommendations cover areas such as preparation, management, evacuation, communication, ventilation and how to handle the long distances often characterizing underground facilities.

THE TMU PROJECT

This section summarizes the overall content of the research project leading to the recommendations presented in this paper. The TMU project started in 2012 as it was acknowledged that there was a great need for increasing the knowledge about rescue operations in underground facilities. The duration of the project was three years. The project was a cooperation between SP Fire Research, Mälardalen University, Lund University and the fire and rescue services in Borås (SÄRF), Stockholm (The Greater Stockholm Fire Brigade) and Sala-Heby. The purpose of the TMU project was to develop tactics and methodologies to improve rescue operations in underground facilities. The projects concerns fire and rescue services both in large cities and in small municipalities. The project has led to improved methodologies and training material (for fire and rescue services, rescue schools and universities), which will lead to more efficient rescue operations.

The project was performed in different work packages, largely following a chronological order: firefighting operation tests in a real underground facility → development of a planning tool →
organization and tactics → training material → recommendations. Below follows a brief description of these different steps (work packages; WP1 was project management):

**WP2 – Full-scale tests with firefighting operation in a real underground facility**
In this work package, tests were performed to study movement speed, the impact of different types of emergency response equipment and its possibilities and limitations. The tests focused on what is limiting in different situations; personnel resources or the equipment used. Consideration was given to the different conditions in urban areas and in small municipalities in rural areas. The focus was the combination of firefighting techniques, extinguishing equipment, ventilation and the use of infrared (IR) equipment. The tests were conducted in cooperation with the participating fire and rescue services and documented with IR technology. In the work package, new detailed knowledge of movement speed, radiation effects, extinguishing water throw distance, penetration distance into the tunnel with various types of firefighting techniques/extinguishing equipment were developed, which is presented in the test report [6].

**WP3 – Development of a planning tool**
To support the planning of response operations at different facilities, a simple planning tool in the form of a simulation model for evacuation and rescue operations was developed for decision makers. The simulation model was named TuFT (Tunnel Fire Tools), and is based on that the user provides input data in the form of, e.g., the type of tunnel, the number of possible entering points for the fire and rescue service and escape routes, number of staff, available equipment, fire size, the location of the fire inside the tunnel and number of users of the tunnel. The model, which can be used on any standard PC or Mac, can be used to make risk assessments for different scenarios. The basis for the development of the tool comes from the tests conducted in WP2 as well as from the results and experiences from earlier projects. The planning tool is intended primarily to be used to describe the possibilities for the fire and rescue services to reach fire under different conditions. The program also contains an evacuation module that can be used to give the user an idea of the possible consequences of a fire for the tunnel users. The key benefit of this type of tool is the planning of the operation, the training of response personnel and the design of large complex underground facilities. TuFT is described in more detail in a separate report [7] and in a conference paper [8]. The simulation tool can be downloaded from www.brand.lth.se/tuft/.

**WP4 – Organization and tactics**
In this work package the different parts developed in WP2 and WP3 was tied together. Management structures that takes into account the organization, tactical thinking and management was developed. Experience from the research that has been conducted in Sweden previously, see for example [11-13], was also studied and incorporated.

**WP5 - Training material**
In this work package, educational and training material for firefighters was developed. The material consists of reports and paper that was generated in the project, and a comprehensive training program that also builds on earlier experiences and knowledge from other research projects. For the efficient and correct use of thermal imaging in the underground environment, new training material documentations were developed, since such has been lacking in the past. The material includes instructions on how various practical exercises on the use of thermal imaging in the underground facilities can be designed. The training material will be used for courses at different levels; everything from basic training of firefighters to the training of engineers and other education at academic level. Also facility owners, tunnel operators, and traffic managers will be able to benefit from part of the training material.

**WP6 - Recommendation**
The results from this workpackage are given in the following sections.
More detailed information on each work package can be found in the summary report from the project [9], and in the reports from the different work packages [6, 7, 10-12]. However, all of these are in Swedish.

**GENERAL ISSUES IN CONNECTION WITH FIRE AND RESCUE OPERATIONS IN UNDERGROUND FACILITIES**

There are a number of factors of an incident site that can have a critical effect on the development and result of a rescue operation. Examples of such critical factors are: the design and construction features, the fire, the activities in the facility, available resources, number of people and their physical status, the situation and specific risks. These factors will be discussed in the paper in relation to rescue operations in underground facilities. Specific risks in relation to the different phases will also be presented and discussed.

The conclusions regarding rescue tactics in tunnel fires is that there is a need of an initial overview of the accident scene and that this overview is swiftly communicated with the incident commander above ground. Within the TMU project it was discussed that at an incident site there exists a number of critical parameters or factors: Position, Extent, Resources, Tactics, Analysis and Situation Awareness (PERTAS) [10]. These critical incident site factors are factors that can have a significant influence on how a rescue operation develops. Examples of some general incident site factors in relation to a fire are construction/building/facility, the fire, the activity, resources, people, situation awareness, and specific hazards. Based on analyses of real incidents and of the tests performed within the TMU project, the general incident site factors can be related to an operation during a fire in an underground facility [9]. How each factor can be defined in connection with a fire in an underground facility is discussed below:

- **Design and construction features** – For an underground facility this means the entire extension underground that could be involved in the incident. It can be more difficult to define this extension for an underground facility compared to a building above ground. Examples of other factors relating to the geometry of the object are slope, height differences, size, availability of access routes and installations.

- **The fire** – Some of the differences between fires above and underground are related to the ventilation conditions and the fire load. Other factors to take into account are the fire position and its effect on different structures of the facility.

- **The activity** – The significant difference between different underground facilities is whether there are people in the facility or if it, e.g., is a service tunnel with only technical installations. The possibility for access can vary, e.g., for rail tunnels, where external control for letting a rescue crew to gain access to the track area.

- **Resources** – Often a large amount of material and personnel resources is needed to fight a fire in an underground facility even though the fire itself not necessarily is very large. Furthermore, some special equipment might be needed, such as equipment that is not always available locally, but need to be ordered externally.

- **Occupants** – Depending on type of facility there can be significant difference in how well the people know the facility, e.g. the difference between a metro station and a mine. Irrespective of type of facility, it is important to get information on position and number of people in the facility as early as possible.

- **Situation awareness** – In an underground facility, it may be difficult to quickly get a clear picture of the situation since it is often not possible to observe the fire. Deployed resources are also difficult to move when put in place and therefore gathering information is to be prioritized.

- **Specific hazards** – A major risk in case of fire in an underground facility is the lack of strength in fire-exposed parts of the plant's construction, but there may be other specific risks: high voltage, flammable liquid / gas, shafts, ongoing traffic, etc.

These and other conditions, which are specific for underground facilities, are presented and discussed below.
RECOMMENDATIONS

This chapter provides recommendations based on the results of the project (including consultation with the reference group of the project) and from previous research and experience from real operations. The recommendations are divided both in different phases of an underground facility and in different areas in terms of tactics and methodology of the fire and rescue service.

Design phase

It is important to see the design from a holistic perspective and think about how different parts and systems work together in the event of, e.g., a fire, so that not different safety installations are added to each other, without making sure that they contribute to the overall safety level. Therefore, it is also important that the actors involved as early as possible discuss local conditions and constraints. It usually becomes much more expensive for a project, the later in the process various important planning decisions, e.g. regarding changes, must be made. Important issues are evacuation routes, distances of attack routes, availability of a parallel tube, smoke extraction and control, availability of firefighting equipment and extinguishing systems, etc. In connection with this it is also important that the builder, planned owner/operator and the local fire and rescue service discuss the ability of the fire and rescue service, including its available resources.

Construction phase

In the construction phase, the conditions concerning fire safety is often very different from those prevailing in a completed and operating facility. This has been studied in an earlier project [2] and the conclusions and recommendations below to a large extent come from that project. Some of the most important conditions in an underground facility during the construction phase and the differences to a completed facility are:

1. Physical and geometrical differences that affect the opportunities for evacuation and rescue operations.
2. Different type of fire load in terms of construction vehicles, trucks, drill rigs, etc.
3. Prerequisites and conditions change continuously during the construction period, which implies the need for temporary response plans and temporary safety solutions.
4. Different installations, where the planned fixed installations of the finished tunnel are missing during the construction phase.
5. The vehicle and equipment used in the construction stage are different from those when the facility is in operation.
6. The facility can before the breakthroughs have a tunnel section that ends in a dead end
7. The number of persons expected to be present in the facility and their knowledge of locality.
8. It is not unusual that there are groups of workers with different nationalities, which can lead to language issues. This may affect both the alarm chain and the information that reaches the fire and rescue services.

The single most important point that was identified in the mentioned project [2] was whether a fire occurs in the phase before or after the breakthrough of the tunnel. It was also concluded that the fire and rescue services cannot make an adequate operation if dense toxic smoke has spread over a long distance, i.e. from the fire site to the point of the start of the BA operation. If dense smoke has spread more than 200 m when the fire and rescue service starts their operation, the possibilities to reach the fire within a reasonable period of time is very limited, with the present methods, equipment and regulations that are available nationally today.

The recommendations for the construction phase can be summarized as:

- Operational response planning should be done in collaboration between the client, the contractor and the fire and rescue services. Site visits are important. In this context it is
important to highlight what the facility owner can offer, what is the ability and capacity of the fire and rescue service, and what is the distribution of responsibility of distribution between these. It is also important to actually determine what fire and rescue services can and cannot achieve.

- Changed conditions during construction require updated response plans.
- Someone (a named person) should be responsible for drawings and data are always kept up to date.
- Continuous collaboration and joint exercises between contractors are important to clarify and state the responsibilities of the individual parties. Joint exercises should also be performed with the fire and rescue services, ambulance and police. Response and evacuation exercises must be carefully coordinated.
- Scenario games are a great tool for practicing different functions of management, both within its own organization and for the fire and rescue services. Exercises should be performed for the organizations and individuals to gain necessary skills to handle the situation, and to detect any imperfection before an emergency situation arises.
- When the responsible officer is to make decisions on how the rescue operation shall be designed, the task of highest priority is to determine whether persons are still inside the tunnel or not and what resources are needed to rescue these people. It is essential that the number of persons in the facility is confirmed, independently of whether a manual or automatic logging system is used.
- Incident commander must gain an overview of the specific risks which may be present in the facility. Special risks may consist of vehicles, hazardous substances, high voltage and/or weakened structural components.
- The main strategy during a fire is often to reduce environmental ventilation to a minimum. The responsible officer on the scene will then perform a new assessment of the situation.
- When using a rescue chamber at a workplace, consideration should be taken to the tunnel cross-section, as it affects the fire dynamic environment.
- There must be a plan for other types of emergencies than fire, e.g., rescue of trapped persons or disposal of fallen boulders. There is also the risk of crushed and stuck persons.
- For tunnels under construction the regulation of four hours of breathable air in the rescue chamber is insufficient. Full-scale tests have shown that some of the vehicles used in the tunnels under construction could have a significantly longer fire process.

Operating phase
In this stage, the facility is completed. Rescue operations in underground facilities are significantly different from operations above ground primarily because the lack of an overview and the complexity that often is the case for underground fires and that a large number of rescue personnel is needed to fight such fires [10]. One of the major problems in emergency response in an underground facility is lack of information about what is burning, and whether there are people remaining in the system, their location and if they are threatened by a toxic environment. As with other operations it is important to determine the appropriate route of attack. The lack of information, however, can make this decision even more difficult during operations in underground facilities. It can also be very far to the next possible attack route and a change in route or tactics can be very complicated and time consuming, especially considering the extensive resources in terms of equipment and personnel required for this type of operations. Attacking where the smoke exits can often lead completely wrong. For these reasons it is very important for facility owners and fire and rescue services to communicate continuously during the operating phase to ensure an as effective rescue operation as possible with the most relevant information and minimized risks. It is essential to test the ability to carry out rescue operations. The principle of recognition is important for the firefighters in order to carry out rescue operations. The pre-planning of a rescue operation is vital so that one already in advance has knowledge about the capability and limitations.

The recommendations for the operating phase can be summarized as:
• According to the Tunnel Directive (2004/54/EC) and the Swedish law (SFS 2006:418), a tunnel manager and the fire and rescue service shall organize joint periodic exercises and regular inspections of a tunnel. The administrative authority shall make sure that inspections are made at least every sixth year and include all prescribed safety requirements. In addition to this, it is important that known or suspected deficiencies are remedied as quickly as possible when they can be an important part of a wider safety concept that can be crucial to the outcome of an operation. Even if the mentioned directive relates to road tunnels only, the same need for joint exercises and regular inspection of course exist also for other types of underground facilities.

• The fire and rescue service needs to be given the opportunity to continuously practice in the facility.

• Any changes in geometry or safety installations should be communicated with the fire and rescue services.

• The regular exercises should test communication, responsibilities, methodology and ability.

• Means of radio communication for the fire and rescue services must be ensured, even inside the underground facility. This needs to be resolved in coordination between facility owners and fire and rescue services.

• A specialist from the tunnel operator (and/or owner) should be able to meet up the incident manager within the same time interval as the municipal fire and rescue services is expected to be at the scene. This specialist should be able to provide information on the design, technical solutions, possible paths of attack, etc., and also have a mandate to make decisions that may be effected on site.

• The amount of available extinguishing water can be adapted to the design scenario of the current underground facility and the tactics and methodology of the local fire and rescue services.

• The possibility for attacks from a smoke free environment is an important starting point in the discussions between the facility owner/operator and fire and rescue services.

• If possible limit the length of the attack routes:
  o A rescue tunnel or a parallel tunnel tube can increase the possibilities for the fire and rescue services to attack from a smoke free environment.
  o The distance between the attack routes affect how long hose system is needed to be built up and thus how long it takes to reach the fire.

• Detection/monitoring capabilities speeds up the alarm and gathering of information and fire and rescue service capabilities to quickly being able to initiate the operation.

Tactics and methodology of fire and rescue services

Planning and preparation

For a fire and rescue service, a simple and well-trained concept is important for an efficient response, especially for an operation in an underground facility where the recognition factor is limited. This type of operation, therefore, requires simple procedures and standard operating routines. Since it rarely catches fire in an underground facility, the organization must get the chance to train together and have knowledge about the different types of facilities they might need to carry out rescue operations in. They should also have a well thought-out tactics and methodology, which can be trained.

The recommendations for the planning and preparation can be summarized as:

• For a fire and rescue service, a simple and well-trained concept is essential for an efficient response, especially in the case of an underground facility because the recognition factor is limited.
• Exercise should be performed at the place where an probable scenario might take place.
**Management**
For all major accidents, there is a need for designated functions that can analyze the safety regarding the risk of collapse, altered fire behavior and development, air flow, etc. This applies not only to underground facilities, but since operations in underground facilities are especially resource intensive there is a need to very early take height for a large resource need in terms of equipment and personnel to ensure a continuous effort. Some questions that should be continuously asked are:

- Are the correct resources in place?
- Has the risk situation changed?
- For how long is the operation expected to last?
- How does the supply of personnel resources vary over time?

The main recommendation for the management is:

- Operations in underground facilities are particularly resource intensive and there should be a special function (the officer in charge) who is responsible for the availability, both in the short and long perspective, of firefighters (BA teams), air, consumables, specialized equipment in the form of mobile fans, etc.

**Evacuation**
The conditions in underground facilities in terms of evacuation and the number of people can vary considerably between different facilities. Some are complex, with many people being in a for them relatively unknown environment, e.g., an underground metro system. In a simple and straight railway tunnel, on the other hand, usually no people are in the tunnel, but there can be cases when many people have to evacuate from a train and then walk a long distance in the tunnel during an accident. In a mine, the environment is known for the workers, but great distances, height differences, etc., make the evacuation and rescue operation complicated. A key objective is to ensure that evacuation in case of fire can take place in an as safe way as possible, regardless of the type of facility. Therefore, both the facility design and emergency tactics have to be planned in such a way that evacuation is facilitated. Typically, this is done by providing means for a so called self-evacuation, i.e., so that people in an underground facility can rescue themselves in case of a fire, without the assistance from fire and rescue services.

The recommendations for the fire and rescue service evacuation assistance can be summarized as:

- Facilitate possibilities for self-evacuation
  - Create smoke-free environments with good visibility
  - A lightline, installed in advance or brought in by the fire and rescue service, e.g. by a specific recognition unit (see below), can facilitate evacuation
- Regarding rescue tactics, one should distinguish between firefighting and lifesaving. Every rescue operation aims at primarily saving human lives. This means that from a tactical point of view, putting out the fire should be considered a secondary task. The obvious exception is when the life saving operations cannot be performed if the fire is not extinguished and no alternative attack route is available.
- For rural fire and rescue services, the focus should be solely on saving lives, due to the limited size of the rescue units.

**Communication**
At the beginning of an operation, there is almost always a lack of information, but for an underground facility the lack of information is usually greater than for example a residential fire. This is partly because it is not physically possible to see where the fire is located and how the situation is evolving and because of that the recognition factor from similar operations is less. There can also exist specific difficulties with communication, radio coverage may be lower further into the tunnel and a BA unit commander may lose contact with the BA unit at the scene of operation. Furthermore, lack of information about the event itself creates uncertainty on e.g. incident size, location, number of
vulnerable people and the conditions that the rescue personnel will meet.

The recommendations for the communication can be summarized as:

- The choice of route of attack is especially important in underground facilities. Information from CCTV:s, from facility owners and supplementary information from witnesses, etc., will therefore be especially important for an effective response.
- Designate a reconnaissance unit (rec.unit) that does not have the aim to put out fires, and thus can move faster than BA teams, who needs to build up a complete hose systems for secured water. The rec.unit has two main purposes:
  - Obtaining better and more reliable information about what has happened and what the situation looks like; this is to get as good basis for decisions as possible.
  - To help and guide evacuating people.
- During BA operations for extinguishing, evaluate the possibility of coordination inside the tunnel by using an inner BA operation commander, who sees the BA unit and the scene of operation and can control their work locally.

**Ventilation**

In a tunnel, the ventilation flow and direction have great influence on fire behavior and development. The airflow affects the risk of fire spread, depending on the fire location in relation to other objects. Direction mainly affects the direction that the fire will spread, since the fire mainly spreads in the ventilating direction. Since the visibility, toxic gases and temperature have great influence on both the evacuation and on the rescue operation, the control of the ventilation can be decisive for the outcome of an operation. However, it is important to understand how ventilation affects conditions downstream of the fire and the consequences this has for fire and smoke spread and for those who are in the facility.

The recommendations for the ventilation can be summarized as:

- Consider the use of ventilation to create smoke-free environment
  - To advance towards the fire with the wind in the back in relatively smoke free environment increases the possibilities for a quick and safe rescue operation.
  - The use of ventilation, particularly if it involves a change in the ventilation direction, must be used with caution if there is a risk that there are still people downstream of the fire, for example, in a vehicle queue situation.
- If mobile fans are to be used in long tunnels to control the smoke one must ensure that the fans have sufficient capacity.
- When using the mobile fans one must consider both its use and its physical location.
  - The sound of the fan can be very distracting and significantly complicate communication.
- The most common fans of the fire and rescue services are often too weak for large complex facilities. If such facilities are within the area of responsibility, other solutions should be found and prepared.
- When using fans during an operation in a parking garage, it is important to beforehand check the design of the facility to know where the smoke will be pushed out and what the risks are in relation to that.

**Long attack routes**

The risk for elevated body temperature of the rescue personnel is high during operations in the underground facility. This is due to often long attack routes in combination with hard physiological work, but closer to the fire the high surrounding temperatures may also contribute. Long attack routes also means long retreat routes, which in turn affects the risk of running out of air. Available air is many times the limiting factor of the operation. The recommendation in relation to handling long attack routes are:
• Investigate the feasibility of attacking as far as possible in the smoke-free environment
  o This will significantly extend the possible time of operation as the advancement of rescue personnel can be done without BA equipment.
  o This may be done through the parallel traffic tunnel or through special safety tunnel.
• Try as far as possible to reduce or simplify procedures of rolling out and connection of hoses, pressurisation of the hose system, etc. Examples of improvements can be pre-connected or partially connected hose system.
• Empty hose systems for the advancement in safe environment increase the movement speed, as well as the use of carrying harness. A harness for material facilitates both transport and installation of hoses.
• Thermal imaging cameras are important for an efficient rescue operation.
  o It is very difficult (virtually impossible) to orient oneself in the smoke-filled environment without IR camera.
  o It is an advantage if all members in the BA team have access to an thermal imaging camera.
  o It is important to be educated on the existing thermal imaging camera since different camera brands have different settings and different terminology.
  o Thermal imaging cameras need to be adapted to the underground environment.
• Investigate further development of good IR cameras sitting in the helmet or which can be carried by other means than with a hand, for example, fasteners.
• Tests with a trolley for the transport of air and other equipment showed that one needs to practice for it to become an effective tool. It is, however, recommended to continue investigating the trolley opportunities. Especially in rail tunnels where a rail trolley might make the operation more efficient.
• When planning to use other specialized equipment, e.g. CAFS (compressed air foam system), practice and coordination are very important for the efficiency and success.
• Examine the possibilities to use oxygen.
  o The advantage is an increased action time, which may lead to a more efficient and safer operation.
  o The downside is the risk of overheating of the BA staff because of the long reaction time combined with the physical work, the limited cooling of gas (compared to an open system) as well as the possibilities for using emergency air is limited.

APPLICATION

One must distinguish between the aim and text of the legislation on one side and the general interpretation of it on the other side. In the Swedish work environment legislation on BA operations and full suit rescue the paragraph on safe access to water reads: In a fire or when risk of fire, firefighters must have safe access to fire extinguishing water for their protection. This has generally been interpreted as whenever there is a BA unit operation in thick smoke, there has to be safe access to extinguishment water. After fires in Swedish mines there have been discussion on whether the firefighters have broken the law or not. One of the fire brigades took this a step further and sought an exemption from the regulation regarding safe access to extinguishment water in cases with BA operations in smoke, but not in the vicinity of a fire or with the aim of fighting a fire. The answer from the Swedish Work Environment Authority was that no such exemption could be given since the described case was not covered by the paragraph in question. The authority meant that if there is no fire or there is no risk for fire, safe access of extinguishment water for the firefighters is not required. This is a very important clarification of the regulation, even if of course means that the available information of a fire situation must be of such a quality that a situation with no fire and no risk for fire can be determined before a rescue operation without safe access to extinguishment water can be initiated. Even if the case above regards mines, the same situation can be found in, e.g., tunnels and metro systems.
CONCLUSIONS

The project has resulted in a large number of recommendations. These are primarily based on the operation tests in a tunnel performed within the project, but also on the results of previous research projects and experience from real operations. The project results have also been discussed with the reference group of the project. In all this means that recommendations are based on years of experience of a large number of people with different background. Some recommendations can be derived directly from the tests, while others describe methods which were proposed as a solution to various problems that occurred during the tests, but need to be further developed and tested in full scale.

The recommendations are divided both in different phases (design, construction and operating phase, respectively) of an underground facility and in different areas in terms of tactics and methodology of an fire and rescue service.

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A Review of Competencies in Tunnel Fire Response Seen From the First Responders’ Perspectives

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ABSTRACT:
Norway has an increasing number of long and complicated road tunnel designs, which can be defined as complex sociotechnical systems. To avoid major accidents and fire situations knowledge about the fire safety is demanded. This article focuses on how representatives from fire and rescue services express uncertainties and expectations regarding the knowledge dimension of the road tunnel fire and rescue systems. The article is based on investigations of two tunnel fires in Norway in addition to data from a workshop with tunnel fire response experts. The data has been analysed using systems engineering approach combined with an understanding of learning. This study has revealed tunnel fire safety concerns related to the Norwegian emergency response personnel’s state of competence both in the pre- and post-accidental phases. The situation on tunnel fire safety is unclear and fragmented, and the knowledge sustains accordingly weaknesses. The future will bring many complicated road tunnels, many subsea that challenges all parties; road owners, road users, vehicle producers, emergency responders and authorities. Norway needs facilities for tunnel safety training that can complement existing facilities and provide new knowledge.

KEYWORDS: Major fire, first response, competence, subsea tunnel, training

INTRODUCTION
In the wake of the tunnel disasters in Tauern, Mont Blanc and St. Gotthard some 15 years ago, the fire events and safety management systems in the Oslofjord tunnel [23 June 2011 - 1] and the Gudvangatunnel [August 5th 2013 - 2] have been critically considered by the Norwegian society. The Accident Investigation Board Norway (AIBN) has carried out its investigations with the aim to provide lessons to be learned. Of particular concerns are the interactions between the public roads authorities, the tunnel systems, the emergency response systems and the road-users. The society does not accept fire disasters in road tunnels, thus knowledge about the fire safety is demanded. The actors within these systems have a common goal to avoid major accidents and fire situations. However, albeit the good intentions, the current status of knowledge is restricted to few events, some experience data from traffic accidents, experimental tests from low scale facilities, exercises and fire simulation tools. In Norway, the Runehamar tunnel is a full-scale test tunnel. This tunnel has been employed for various fire experiments and research projects [cfr. for example 3, 4-7].

Norway has an increasing number of long and complicated road tunnel designs. Today the road infrastructure consists of over 1000 tunnels. There are 31 subsea tunnels and 10 mountain tunnels with steep slopes (> 5%), and these tunnels comprises 4 % of the length of the Norwegian road tunnels. The Norwegian Government has decided to build the world’s longest and deepest subsea road tunnels. The Ryfast tunnel will be completed in 2019 and will be 14.3 kilometres long, 290 metres below sea at the deepest with a maximum gradient of 7.9 %. Five years later the Rogfast tunnel is scheduled, with a planned length of 26.7 kilometres, a depth of 390 metres below sea and maximum gradient of 5%. Both tunnels will be dual tube.

In the period from 2008 until 2011, 44 % of the registered fires occurred in these 41 tunnels described above. Heavy goods vehicles (HGV) were involved in most of these fires, mainly caused by technical malfunctions [8]. The fires in the Oslofjord and Gudvanga tunnels in 2011 and 2013 both started in
HGVs, both tunnels are bi-directional single tubes, they have steep slopes and primary emergency exits through the tunnel entrances. Another situational resemblance in the events was the location of the fire related to the ventilation direction, which caused large portions of the tunnels being filled with smoke. There were no fatalities in the fires, but many people were trapped in the smoke, 34 in the Oslofjord tunnel [1] and 67 in the Gudvanga tunnel [2], many which sustained acute smoke injuries and psychological traumas. Neither the tunnel-owners nor the rescue services were in control of the smoke flows and the concentrations of toxic gases in those events.

The road-users’ expected emergency response behaviours in tunnel fires is based on the self-rescue principle. This means that the road-users are supposed to evacuate from the tunnel by own means, either by car or by foot. Experiences from the tunnel fires mentioned are that not all road-users evacuate. Some of them stay in their vehicles (mostly HGVs) with recirculating air condition [1, 2]. Professional rescuers are on call and the predominating approach is to extinguish the fire as soon as possible in order to provide access for the rescuers to reach people trapped in the tunnel. In single tube tunnels the fire ventilation is a vital tool for the firefighters to provide access to the fire, and significantly dilute the smoke concentration downstream to improve the conditions for the evacuating people. The fire ventilation direction is usually predefined, based on the idea that the most capable fire department shall be in charge of the fire and rescue operation. However, the fire and smoke dispersion modelling and related validation as basis for the strategy chosen is scarce and there has been a major discussion whether this strategy is better than suppressing ventilation in order to increase the time margins for all road-users with urgent need for evacuation.

The study presented in this paper challenges the knowledge dimension of the road tunnel fire and rescue systems including the individuals involved. Knowledge is related to phenomena, tasks, communication and interaction abilities, and how the actors approach tunnel fire safety in general. We were interested in how representatives from responsible road tunnel fire and rescue services expressed their uncertainties and expectations. We analysed the data material in a systems engineering approach combined with an understanding of learning addressing change, confirmation and comprehension of the crisis response systems.

SYSTEMS ENGINEERING THEORY TO SAFETY MANAGEMENT

The Norwegian tunnel fire and rescue services
The fire and rescue services in Norway are governed by the municipalities. The 428 Norwegian municipalities range from only 200 inhabitants to 600 000 in the largest. Some municipalities have engaged in partnerships regarding operation of the fire and rescue service. The total number of fire and rescue services is about 295; 26 are organised as inter-municipal companies, 205 are independent, and the remaining are involved in some kind of cooperation with neighbouring municipalities. The smallest fire and rescue services cover less than 3000 inhabitants while the biggest cover more than 250 000 [9].

The Norwegian preparedness structure is founded on four principles: responsibility, proximity, similarity and cooperation. These principles states that those who are responsible for and involved in day to day crisis management, at all levels, are tasked with the same responsibilities and works during major tunnel fire events as in the daily work. The cooperation principle is especially interesting, and it implies that authorities, voluntary, private and official actors are individually responsible for establishing appropriate interactions with relevant parties regarding the fire and rescue situations. Good cooperation between the different actors in the tunnel system is vital for the planning and performance of the fire response. The public roads authorities, the fire and rescue service, the police and the ambulance service must agree on and understand each other’s roles and responsibilities. Establishing effective emergency response cooperation requires coordinated response plans, procedures and routines as well as regular exercises and training involving all relevant parties. Thus, the knowledge and competencies within, across and along organisational units is of vital importance.
Complex sociotechnical systems

Nancy Leveson [10] claims that the complex sociotechnical systems of our society require a safety management approach based on systems engineering. The approach views the systems and accident factors holistically instead of decomposed into individual components, units or subsystems malfunctioning in linear processes. Events, actions and the behaviour of different components can only be understood by considering its “role and interaction within the system as a whole” [10, p. 70]. Safety is seen as a control problem solved by imposing constraints upon the performance of the system in design and operation. “Constraints represent acceptable ways the system or organization can achieve the mission goals. Not exposing bystanders to toxins and not polluting the environment are constraints on the way the mission (this case: transport through road tunnels) can be achieved” (p. 11). Safety constraints are provided through hierarchical structures, cf. figure 1, “where each level imposes constraints on the activity of the level beneath it” (p. 80), and thus form the framework for practice and performance. This hierarchy of control is based on adaptive feedback mechanisms and communication to ensure that “the information needed for decision making is available to the right people at the right time” (p. 307).

Figure 1 Road tunnel systems based on Leveson’s model [10].

Perrow [15] characterises complexity by interactions in systems: “unfamiliar sequences, or unplanned and unexpected sequences, and either not visible or not immediately comprehensible” (p. 78). Leveson [10] nuances complexity and describes different forms related to: interaction among system components (interactive complexity); changes over time (dynamic complexity); structural and functional decomposition not being consistent (decompositional complexity); and no direct or obvious relation between cause and effect (nonlinear complexity). Norwegian road tunnels have special characterisations affecting the ability to combat and rescue from tunnel fires, such as length, gradient, location, high traffic volume, high proportion of HGV traffic, fuel composition, number of people trapped, knowledge etc. The different components in the tunnel system interact in various ways that
are difficult to understand, and can result in escalating fire incidents. The fire and rescue services’ ability to predict such incidents is associated with considerable uncertainty. Our connotation of “complex tunnel systems” includes the abovementioned characteristics. Examples of complex road tunnels are thus long bi-directional single tube tunnels with emergency exits only through the tunnel entrances, subsea bi-directional single tube tunnels, densely crowded dual tube tunnels and long subsea dual tube tunnels. Complexity seems to increase and makes it difficult to understand the systems’ potential behaviour, thus Leveson [10] defines complexity as intellectual unmanageability. Epistemology is a vital dimension.

We conclude that many of the Norwegian road tunnels are complex sociotechnical systems; a system description is presented in figure 1. The Norwegian government and the Ministry of Transport and Communications constitute the top level in a road tunnel system, and develop and maintain the legislation and choose regulation regime. The levels beneath comprises Directorates and regional and local authorities which administers regulations, standards and guidelines regarding safety requirements for road tunnels. The Norwegian Public Roads Administration (NPRA) is a complex organisation having responsibilities and roles from directorate level to detail planning and building of tunnel systems, as well as operations and maintenance of the same systems. The Norwegian Directorate for Civil Protection administer regulations, inspect and supervise organisation and dimensioning of the municipal fire and rescue services. The municipal fire and rescue services are involved in both the planning and operations of the tunnel systems, for example they participate in planning processes and risk assessments, and they constitute an essential part of the tunnel systems’ emergency preparedness during both construction and operation. The fire and rescue services also function as supervisory authority of the road tunnels in their area (municipality/-ies) regarding fire safety, considering preventive measures or mitigation. The fire and rescue services thus need comprehensive knowledge about the tunnel systems. Leveson claims that the systems are exposed to variation and changes in the environment and this will subsequently evolve and change over time. The tunnel system will for example be exposed to variations in annual average daily traffic (AADT), distribution of heavy goods vehicles, ageing, fouling and road users’ driving behaviour.

The tunnel systems contain a high number of actors with a common goal to avoid major accidents and fire situations. The feedback mechanisms depicted in figure 1 provide decision makers on each level with opportunities to learn from accidents, incidents, analyses, inspections and audits. Good information about potential causes of accidents in the system and the state of implemented control mechanisms is necessary in order to establish a knowledge based risk perception [10]. Investigating incidents and accidents is not enough; such processes must be followed by recommendations and assignment of responsibilities for implementing lessons and knowledge provided.

**Learning and training**

Learning is central in systems thinking applied to safety, and human behaviour is seen as “a product of the environment in which it occurs” [10, p. 47]. Rather than assuming that most accidents are caused by human errors and violations, Leveson [10] emphasizes contextual mechanisms that generate behaviour, and performance of safety constraints. Thus, it is important that everyone involved in the safety control systems understand the rationale behind the systems design, including their own roles and responsibilities. Knowledge regarding potential hazards associated with the operation of the system is necessary to make people able to recognize precursors to accidents. The system operators must “have an in-depth understanding of the controlled physical process and the logic used in any automated controllers they may be supervising”, an understanding that involves much more than learning procedures [10, p. 411].

The first responders are an essential part of the tunnel system’s operational safety. Sommer, Njå & Braut’s [11] model for learning in emergency response work combines socio-cultural and individual cognitive premises. This model sees learning as “changes in structures, behaviours or working methods, confirmation of existing knowledge and/or comprehension of existing practice” (p. 151). The learners are the individual actors, and it coincides with Leveson’s view on human behaviour as a product of the surrounding factors. Learning is described as a continuous process where experiences
mix with continuous reflection, controlled exercises, training and lecturing activities, and the contents are both practical and theoretical. The emergency organisation’s traditions, culture and the embedded knowledge influence how the individuals think and behave in fire and rescue situations. Sommer et al. [11] also state that the goal for learning in emergency response work is to make emergency workers able to consider relevant cues in their decision-making. The same account is made by Leveson [10] when she argues that “decision makers at all levels of the safety control structure also need to understand the risks they are taking in the decisions they make: Training should include not just what but why” (pp. 410-411). This also yields the first responders in action on site, who need to be flexible assessing situational demands, but at the same time having internalised the procedures and interacting practices. These properties were demonstrated at the Elstangen command point for receiving evacuees from Utoya Island during the terrorist attack in Norway 2011 [12].

STUDY APPROACH
In the study we challenge the knowledge dimension of the road tunnel fire and rescue systems. The data material is gathered from two sources; 1) two fire event cases – the Oslofjord tunnel fire (2011) and the Gudvanga tunnel fire (2013); and 2) a workshop in June 2015 at the Societal Safety Centre in Rogaland (SASIRO). The study reflects the challenges with tunnel fire safety seen from the first responders’ points of view about competencies and knowledge of the different organisational levels in the tunnel system. Our analytical dimensions are uncertainties and insufficient abilities to respond to tunnel fire events, based on the inputs from the workshop participants and the written material from the events. We define uncertainty as something that can be doubted, discussed or even not known, related to tunnel fire safety. Insufficient abilities are the first responders’ own views of lacking capabilities to conduct necessary tasks.

The workshop was organised by Rogaland Fire and Rescue, the University of Stavanger and the Norwegian Public Roads Administration (NPRA). The participants (26) were mainly representatives from different Norwegian fire and rescue services (18), and ambulance services (2) with experiences from fire prevention, supervisory activities and planning processes regarding road tunnels, and/or firefighting, rescue operations and incident command in tunnel fires. In their work all operational personnel were subjected to complex road tunnels. In addition there were participants from the NPRA, Directorate for Civil Protection, academic institutions, a private consultancy company, and a transportation company (6 in total) with tunnel fire safety experience from research, regulation, fire prevention, supervisory activities, planning processes and transport activities. The participants represented only some of the levels in the tunnel system’s operation structure, mainly depicted in figure 2, of which we restrict our analysis.

![Figure 2](image-url)  
*Figure 2 Extract of the road tunnel model for data analysis.*
The workshop was organised with two group sessions where the participants were divided into three different groups. In the first session the groups were asked to elaborate on their personal experiences from real incidents or training in complex tunnel systems. The discussion focused on situations that represent great challenges for the fire and rescue service today, critical phases in the rescue operation and the interaction with other actors (emergency services). The second session focused on lacking and inadequate knowledge regarding situations and conditions related to road tunnels, how this challenges the Norwegian emergency response system, the need for enhanced knowledge and how to achieve better competencies in order to meet critical tunnel fire situations. All the group sessions were recorded and transcriptions made subsequently. The written material comprised of various reports and evaluations made after the tunnel fire accidents in the Oslofjord tunnel on June 23rd 2011 and the Gudvanga tunnel on August 5th 2013. Knowledge and competencies were also here basis for the analysis of uncertainties and inabilitys to respond sufficiently, with special attention towards the reports’ analyses of the fire and rescue services roles and responsibilities.

CONCERNS ABOUT TUNNEL FIRE SAFETY
We split the findings from the workshop and events into pre- and post-accidental phases and their subsequent uncertainties and insufficient capabilities. The weight is put on first responders’ perspectives, and we do not elaborate on critics from the accident investigations addressing omissions or erroneous commissions of tasks by the tunnel owners.

The pre-accidental phases
These phases include all aspects before a fire situation is detected. Being at this stage, the design principles, motivational and competence philosophies related to personnel, organisational development, etc. are important arrangements. Thus, it includes all scenarios that govern the tunnel preparedness levels and how the tunnel preparedness systems are operated and maintained.

Uncertainties
Neither the workshop participants nor the data material from the events provided information about the traffic conditions, the road-user behaviour or the goods that travelled through the various complex tunnels. Some mentioned the annual average daily traffic (AADT) and other the portion of HGVs as measures they meant were important. How these measures relate to the tunnel designs and their own responsibilities were not discussed at all, thus the relation between AADT, HGV distributions and fire accident scenarios is unknown to first responders. One workshop participant from the eastern part of Norway claimed that 90% of the HGV coming to Norway at the border between Norway and Sweden were foreign vehicles and generally understood as having lower technical and operational standard than the Norwegian HGVs. Also from the eastern part of Norway major concerns were related to congestions, their occurrences and how people behave in critical situations given congestions.

Risk and vulnerability analyses as planning tools for tunnel fire safety were criticised by many participants. First of all the probability concept and messages from analyses were emphasized as problematic. For example analyses saying that frequencies of major events is one per 300 years was regarded ridiculous and not of any use to them. The uncertainty seems to be more related to concepts, purposes and characteristics with the analysis tools than contents of modelling and the data material employed. Concepts such as risk, design fires, heat release rate and megawatt are difficult for first responders to grasp and relate to their firefighting and rescuing activities. The representatives from the fire and rescue services that had been involved in risk analysis processes were less critical, but they did not object to those who criticised the analyses. One representative said that in the eastern Norway risk analyses assumed the firefighting units to be in action within four minutes, which he said was a false premise. There seem to be major ambiguities on how the fire and rescue services should design their combat systems and develop frameworks for their emergency response. Furthermore; which toxic, heat and psychological exposures must be included in the tunnel design and addressed to the various parties, is an unanswered question.

Ventilation strategies were considered a big issue at the workshop when discussing preparedness measures. Concerns and uncertainties were forwarded due to functionalities of the ventilation systems.
of their respective tunnels and whether there might be a universal and right solution to this issue. One representative from the preventive and supervisory part of the fire and rescue services claimed that the experts gave different advices, and he was supported by others who said that there were too much subjectivity in expert assessments, too many studies and reports that they could not transfer to applicable measures. Another similar representative claimed that the NPRA did not maintain its equipment and that inspection reports were neglected. Failures of the ventilation systems were often experienced with the many old and narrow single tube tunnels in western Norway. Representatives from northern Norway also complained about lacking communication with the NPRA and thus the lack of mutual understanding of challenges with their tunnels. Mobilisation time for the firefighting units for some of the tunnels was said to be approximately one hour, which was regarded as meaningless with respect to saving lives.

Personal experience seems to be very important as a reference for expressing magnitude of crisis contents and uncertainties involved. One physician experienced a major accident with a Swedish bus hitting a tunnel wall nearly 30 years ago. A big accident killing 16 persons of which 12 kids, many of them were crushed to death. It was a mass casualty situation putting heavy loads on triage, treatment and first response activities. This representative had a very humble attitude to the phenomenon tunnel fires, causing stressful situations with heavy noises, severe heat conditions and difficult working situations. He saw no other solution than developing training programs preferably involving all the cooperating emergency response actors. Frequent training was regarded a prerequisite to cope with tunnel fire situations in the future.

The local fire department’s supervision activities of the Oslofjord tunnel began well before its operation phase (June 2000) and the findings were that the tunnel’s safety equipment did not ensure personal safety for road users and rescue personnel. The fire chief issued directives regarding CCTV monitoring of the Oslofjord tunnel already in 2000. NPRA refused to comply, and the Directorate of Civil Protection supported NPRA’s appeal. During the following years the fire department several times requested updated risk analysis and emergency response plans. At one occasion the NPRA replied that the existing risk analysis from the planning process was considered sufficient. During the investigation process after the fire in the Oslofjord tunnel the local fire department passively committed that they did not possess special expertise regarding fire risk in road tunnels and thereby no basis for overruling the risk analyses done by the tunnel owner [1, pp. 30-31]. Thus, it could seem that the risk analyses were more a tool to confuse rather than clarify safety issues for the fire and rescue services.

Insufficient capabilities
Some workshop participants believed that the fire and rescue services would need solid knowledge about the tunnel fire safety subject to meet and correct the dominant NPRA in planning processes and supervisory activities. The experiences shared at the workshop pointed at the need for better quality in the supervisory reports when presenting deviations found through inspections and audits. This would provide the fire and rescue services with a better tool to influence NPRA’s safety efforts. The AIBN, in their investigation report after the Oslofjord tunnel fire also points to the need for adjusting the fire department’s supervisory role to provide a better corrective in relation to the NPRA’s safety management and manuals [1]. It is difficult to comprehend the AIBN’s justification of its statement, but it is a structural problem that the supervisory authority (the fire department) lacks instruments in order to enforce the tunnel owner to follow up deviations and safety problems presented in inspection reports. A workshop participant referred to an audit he made in his region, where he claimed that his comprehensive comments regarding weaknesses of the technical safety systems were completely neglected. He said that he had now come to a conclusion that inspections was waste of time, changes to the tunnel equipment must be achieved by other means, for example concrete testing and demonstration activities. However, the AIBN faces the same structural challenges as the fire and rescue services when the agency submit its report to the Ministry of communications and transport. The AIBN cannot follow up its own recommendations. The investigation of the Gudvanga tunnel fire refers to a risk analysis conducted by the NPRA in April 2013, which identified the same critical scenario that occurred four months later, and it pointed out that the NPRA thus was familiar with the
tunnel’s poor safety level. The investigation board found that the supervisory audits done by the local fire department in the Gudvanga tunnel were not appropriate to identify safety critical factors for the self-rescue premises, because there were only conducted system audits and no on-site inspections [2, pp. 64-65].

Even though there is a requirement to carry out risk analysis for all tunnels longer than 500 m, participants at the workshop referred to the prevailing codes and norms providing pre-accepted solutions. In this way actors in the tunnel design do not challenge the safety level, but mere keep a compliance perspective. The design of the emergency response systems is not subjected to scenarios that are governing the design. The AIBN argues that the fire department could be more involved in the drafting of the emergency response plans for road tunnels [1, p. 70]. A representative from the fire and rescue service from the western Norway said that the emergency preparedness plans were of low quality, not coherent, not related to reliable and validated performance assessments and often with standard information impossible to apply for designing specific operations procedures. Performance analysis of emergency preparedness measures was said to be very rarely seen and in fact the workshop participants only knew of a single one related to the Rogfast project.

The post-accidental phases
These phases include all aspects after a fire situation is detected. Thus, it includes all systems established to respond to fire and crisis situations in tunnels. If no or inappropriate corrective compelling actions are taken, the consequences will become severe. In order to clarify competencies we analysed the data material for uncertainties and lacking capabilities in the response activities.

Uncertainties
The workshop gave a clear picture of the great variation across the country, due to both the organisation and dimensioning of the fire and rescue services, but also the safety level in the road tunnels. Entering tunnels filled with smoke is a major problem for firefighters. Their self-contained breathing apparatus will only last for approximately half an hour after entering the tunnel, which implies major uncertainties regarding the firefighting and rescuing performance. Another ambiguity and difficult concept is the principle of self-rescue. Many participants from the fire and rescue services expressed uncertainty regarding the concept and how this concept should be understood in the design of the response strategies. Nobody seemed to have experienced the self-rescue principle as an integral part of their planning processes, but some participants stated that it is not possible to equal the self-rescue principle in buildings (industry, shopping centre, residential houses) with tunnels (often more than 5 km long).

Firefighters that approach a tunnel with smoke coming out of the entrance face major uncertainties. There might be no communication means working, the functionality of the ventilation systems is unclear, water supply is of concern etc., other uncertainties are both related to fire intensity and toxicity, which for the incident commander and fire chief is complicated due to critical assessments of the health issues of the first responders in action. This is an explanation of why the ventilation strategy complies with the immediate action from the predefined firefighting department set up to access the fire, independent of where the fire is located. The drawback of this strategy is that it does not coincide with the self-rescue principle and neither a performance based emergency response system. A major uncertainty is; what influences decisions made in fire scenarios?

The fire ventilation was a much discussed issue at the workshop. There was a consensus among the different fire and rescue services of the need for more knowledge regarding fire ventilation strategies. Today various experts hold different theories and recommendations. The AIBN is as uncertain as the other parties are, and it cannot provide scientific based knowledge about fire ventilation strategies in general and neither concerning the specific tunnel fires. Better knowledge is needed which is also pointed at the context and conditions of the specific tunnels [1]. The investigation of the Oslofjord tunnel fire reviewed different reports related to safety and risk assessment made since the opening of the tunnel. A fire analysis from 2000 recommends a performance based situation specific firefighting tactic regarding ventilation. NPRA’s risk analysis from 2003 [1, pp. 27-28] supports this issue.
The workshop participants agreed that the interaction between the NPRA’s traffic control centre and the fire and rescue services’ emergency centres are crucial for the outcome of the rescue operation. Today there is a lack of training and exercises involving these actors. At some emergency centres it seems to be a problem that the operators do not know what to look for or what questions to ask when they communicate with the traffic control centre. Representatives from some fire and rescue services regarded the traffic control centres’ competencies and knowledge as insufficient, but this impression varied across the country. In the eastern part of Norway, around the Oslo area, the traffic control centre was claimed to be highly competent.

After the fire in the Gudvanga tunnel, a medical scientist analysed the health situation for the victims trapped in smoke. The persons that walked up and out of the tunnel were exposed to major toxins and five of them were diagnosed with very serious injuries. They walked in 95 minutes. The event has raised concerns whether it is a good strategy to evacuate after the smoke has reached the road-users. A person struggling and using power to evacuate the tunnel consume significant more air, which might worsen the health condition. However, there is no scientific evidence on the survivability difference between evacuation strategies.

A representative from the fire and rescue service in the western part of Norway said he had been at the incident commander’s operations centre on scene working as the leader of the fire and rescue operations. The leader of the health operation often asks if it is safe to send his or her staff into the building. This is a structural dilemma, because the physician is trained to assess smoke and toxin exposure upon humans, not the firefighter. The Police officer who is the Incident Commander has normally no idea in this respect. The workshop participant saw the situation as very problematic for the leader of the fire and rescue operations, being the expert on scene. He did not regard himself prepared for the expert role.

**Insufficient capabilities**

An interesting observation was that representatives from the eastern Norway were content with their tunnels, their collaboration with the NPRA and the safety systems, while representatives from west, middle and north were unsatisfied and expressed little confidence in the prevailing safety systems in general. The attitude was that the quality of the systems; detection, visualisation, ventilation, communication means, extinguishing equipment, etc. varied very much from region to region and tunnel to tunnel. A representative from the middle region of Norway said that they always experienced problems with the communication means, either between the traffic control centres at the NPRA and the dispatch centre at the fire department or between the traffic control centre and the fire department in action. The representative from the transport industry also raised concerns about how their HGV-drivers should approach firefighting situations, balancing risk of injuries and the extinguishing possibilities in the early phases of the fire situation.

Several participants mentioned that the detection and alarm systems could be improved. Today HGV drivers and other road-users are very reluctant to stop and contact the traffic control centre using the SOS-telephones. Cell phones are preferred tools and hence it delays the response operations. The red lights outside the tunnels are easily misunderstood and not fit for purpose. Even the actors’ respect of warnings had been experienced as very low, of which a situation was highlighted with a breakdown truck that disregarded the red lights, reopened the tunnel and reported to the traffic control centre. The traffic control centre applauded his work, which was completely against the procedures.

The AIBN criticised the predefined ventilation strategy in the Gudvanga tunnel fire claiming that both the fire department and the NPRA prioritized firefighting over rescue and evacuation [2, p. 56]. AIBN recommended a situation-based strategy for the fire ventilation, although realising that such decisions will represent a challenge for the fire and rescue service. The AIBN had no solution on how to solve the performance based ventilation strategy besides addressing the need. A similar discussion at the workshop emphasized this dilemma, to which several participants had experienced that firefighting had been the main concern for the rescuers at the expense of the victims’ urgent need for self-rescue. The professional fire and rescue services saw their roles to maintain rescue and evacuation, thus they
could only rely on own resources to become in control of the situation. Most of the participants viewed the fire and rescue services as responsible for decisions regarding ventilation strategies in tunnel fires. The incident commander can choose other strategies than the one predefined in the emergency response plan. Discussions at the workshop concluded that the incident commander is viewed as the fire and rescue expert on scene; he or she is expected to make tough decisions that require some kind of expertise, but in reality there is a lot they do not know. Several participants at the workshop expressed doubts concerning how realistic it is to expect such expertise in every Norwegian fire and rescue service considering the great diversity around the country. Questions were asked if it would be suitable to offer some kind of regional or national support resources, some kind of expert network.

A representative from the fire and rescue service in the western part of Norway was concerned about the construction phase of tunnels, and possible fire situations that might occur. In the construction phase the technical safety systems are preliminary and vital services might be omitted, such as firewater, ventilation or communication means. The interaction between coordinating parties in the construction phase was regarded a major challenge.

A representative from the fire and rescue service in the northern part of Norway had experienced the so-called “Goat cheese” fire in the Brattli tunnel. This fire lasted for four days, based on the first attempt to put out the fire failed due to not enough fire water and foam. According to the workshop participant the fire was almost extinguished. The fire clearly demonstrated the consequence of insufficient equipment. Another frustration forwarded by the representatives from north and west was their knowledge of ill-equipped tunnels, for example some of them lacking road barriers as a measure to stop traffic entering the tunnel in case of fires. In general, the concerns from many of the workshop participants were due to unfamiliarity with fighting tunnel fires. The formal general training activities at the academy have no or very little information and practices on tunnel fires.

**DISCUSSION**

Nancy Leveson’s holistic model based on control and feedback mechanisms, and establishing constraints is interesting when we analyse the tunnel system actors’ self-assessments of their knowledge and competencies. A pattern seen is that the members of the upper hierarchy level, representatives from the Directorates, viewed the situation significantly more positive than their system collaborators closer to the sharp end. Another tendency seen from the workshop was that the actors had a narrow perspective discussing their own activities, while the interactions horizontally and vertically in the tunnel system were very scarcely considered. An interesting observation is that Leveson criticizes risk and vulnerability analyses for its simplifications and linear explanations of scenarios, while the workshop participants found risk and vulnerability analyses as alienating and complicating their picture of fire safety in tunnels. Introducing constraints, especially onto the interactions between various actors is a huge task, a paradigm shift, but it seems to be necessary in order to increase safety levels and general understanding of tunnel fires. Risk and uncertainty related to tunnel fire is difficult to grasp, and Leveson’s presentations of the concepts are positivistic, which is impossible to defend ontologically [13]. Risk is an epistemological concept only, hence reflections on methodologies, models, data, studies and learning activities are crucial for obtaining a foundation for improvement strategies.

The fire and rescue services have extensive tacit knowledge, which is unexploited and will remain so if experience transfer and teaching is still downgraded. The findings from the investigation reports after the two tunnel fires in 2011 and 2013 clearly show that the tunnel systems had substantial weaknesses related to safety constraints and feedback, and this way of thinking was absent from both the tunnel owners and the emergency response systems. Amongst a comprehensive set of analytical tools adapted to tunnel safety, risk analysis is promising, especially related to post accident phases. However we observe analyses carried out with the only purpose to mechanistically document risk accept through results describing expected number of fatalities and serious injuries. This is the perspective of the authorities (EU and national authorities), and thus the objections raised by the workshop participants are reasonable and understandable. Such analyses are of no use to the fire and
rescue services. Risk and vulnerability analysis is an approach to obtain system knowledge, raise objections and critics to the tunnel system (solutions), facilitate learning of important features of the system (in a Leveson perspective) and establish a foundation for the decisions made. Risk informed decisions would then be demystified and applied at various levels in the fire and rescue services [14]. This will encourage individual members of the tunnel safety system to develop their own risk images, which is an interesting prerequisite for learning and increasing competence levels as described by Sommer, Braut & Njå [11].

The workshop participants called for more learning using arenas for exchanging experiences on tunnel safety. They also questioned how accident/incident reports and evaluations could contribute to learning. Making use of investigation reports and shared experiences can contribute to reflection, which is one of the components in the continuous learning process described by Sommer, Braut & Njå [11]. However, there have been very little concerns about how the various actors learn to approach and resolve tunnel incidents and fire scenarios. Strong voices at the workshop argued that today’s education, training and follow up of fire and rescue personnel lack structure and planning. The leader education at the Norwegian Fire Academy were by some of the workshop participants regarded as insufficient, the amount of training and education related to tunnel safety seems not to be a prioritized area for the academy. The NPRA and the Directorate for Civil Protection offer a two days course at the Runehamar test tunnel twice a year. Some of the workshop participants recommended this course for inter alia understanding effects of fire ventilation. The workshop participants stressed the need to make a clear and consensual definition of what kind of scenarios the emergency response system is supposed to handle, in order to harmonize training activities. Taking the 13000 employees of the fire departments working with prevention, mitigation and supervision tasks into consideration, the capacity and effort provided for increasing tunnel fire safety competence is weak. The fire and rescue service is only one actor in the coordinated system of tunnel fire safety management. There is a need for a structural change to upgrade the competence level across units and organisations, changes that include arenas for comprehensive tunnel fire safety training.

Many road tunnels in Norway are complex structures containing traffic flows of varying high-energy substances in a fairly little controllable environment. A huge number of subsystems and units might interact in unpredictable ways. Some of the tunnels could be characterised as tightly coupled with complex interactions [15]. Are these tunnels properly governed? After the devastating Piper Alpha accident in 1988 the UK offshore oil and gas installations have been subjected to “Safety Case” regulations, based on the Norwegian performance based regulation (“Lex Ognedal”). We claim that many of the Norwegian road tunnels represent larger complexity and worse potential consequences in case of fires than for example unmanned offshore oil and gas facilities. Both systems are remotely operated, which makes it plausible to discuss Safety Case requirements also for road tunnels. There exists an extensive amount of scientific literature across various industries that support this regulatory approach [16-20]. Introducing Safety Case will also clarify the NPRA’s various roles, and through this establish the municipality fire and rescue service’s responsibility and sanctioning ability as the supervisory agent. Furthermore, the fire and rescue services will be involved in the Safety Case and holistically assess the performance of the tunnel system as such.

CONCLUSIONS
This study has revealed tunnel fire safety concerns related to the Norwegian emergency response personnel’s state of competence both in the pre- and post-accidental phases. Some of the uncertainties were:

- Little knowledge about traffic conditions, road-user behaviour and contents of goods travelling through various complex tunnels
- Understanding the purpose, concepts, contents and benefits using risk and vulnerability analysis.
- Comprehension of ventilation strategies, and the vast number of experts in the field recommending various solutions.
- Situation awareness when meeting a tunnel with smoke coming out.
- The self-rescue principle seen in the context of crisis response.
• Interaction between parties that need to communicate.

Some of the insufficient capabilities were:
• Supervisory tools and sanctioning abilities of the fire and rescue services in their inspection activities and communication with tunnel owners.
• Dimensioning practices of tunnel designs and use of risk and performance analyses.
• Huge variation between technical safety systems across the country, leaving some fire and rescue services with few opportunities in the fire response.
• Knowledge and expertise in fighting tunnel fires

The situation on tunnel fire safety is unclear and fragmented, and the knowledge sustains accordingly weaknesses. The future will bring many complicated road tunnels, many subsea that challenges all parties; road owners, road users, vehicle producers, emergency responders and authorities. We need facilities for tunnel safety training that can complement existing facilities and provide new knowledge based on systems engineering.

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Fire Exposed Sprayed Concrete Inner Lining

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ABSTRACT

The fire resistance of a sprayed concrete inner lining for tunnels has been investigated experimentally. During the experiment the cross section, hanging from rods from a supporting system, was exposed to the hydrocarbon fire curve for three hours. The test results show that the insulation and integrity criteria were maintained for the whole test period. As 2kg/m³ or polypropylene fibres were included in the concrete mix only a limited amount of surface spalling was observed. The thermal properties of the tested concrete were measured with the transient plane source method. The thermal properties of the sprayed concrete were shown by experiments to be in the bounds of what is defined in the Eurocode 1992-1-2.

KEYWORD: Sprayed concrete, Fire resistance, Thermal properties

INTRODUCTION

Large road and rail tunnel projects have to consider numerous design aspects when designing concrete inner linings in rock tunnels. This could include different types of concrete inner lining systems, costs and lifecycle aspects, experiences drawn from previous tunnel projects, accessibility and provisions for inspection, accident loads etc. One major aspect to consider is also the fire resistance and the risk of spalling. Regarding sprayed concrete inner linings for tunnels there are few code provisions, and limited practical experience about which level of fire resistance to expect. The Stockholm Bypass Project is an on-going large Swedish infrastructure project where this topic has been of particular interest.

The project will lead the E4 road around Stockholm, and involves the construction of 21 km of new road. A total of 18 of the 21 km will be located in tunnels, mainly rock tunnels but there are also some parts consisting of cast in place concrete. Construction of the project was initiated in August 2014 and will continue for another 10 years. The budget is approximately € 3 billion. In 2012 the Stockholm Bypass Project and the Swedish Transport Administration applied for and was granted funding from the EU Trans-European Transport Network (TEN-T) for project related research, and one part included the issue of fire resistance of sprayed concrete inner linings in rock tunnels.

After investigative studies of different inner lining systems for the tunnel, a specific design was chosen by the project. The system consists of a sprayed concrete inner lining, sprayed in situ in the tunnels, and hanging from steel rods anchored in the surrounding rock material. Whereas the chosen solution fulfilled various criteria such as accident loads, lifetime requirements, waterproofing etc., questions still remained regarding the fire resistance level inherent in the design. The question was not unique to this particular project, but also to other projects using a similar tunnel inner lining solution. There has been uncertainty regarding how the fire resistance can be calculated for sprayed concrete inner lining systems, as well as how much polypropylene fibres that could be added to limit the risk of spalling.

In order to further investigate these questions, extensive experimental fire testing was performed in a
special test oven in a laboratory environment at the SP Technical Research Institute in Borås, Sweden. The fire resistance and mechanical behaviour of the system was studied, and measurements of the thermal properties were performed. The aim of the study on mechanical behaviour was to investigate if the calculation methods in the Eurocode 1992-1-2 could be used for calculating stresses in the rods. This comparison between measurements and calculation of mechanical behaviour is not described in this paper but can be found in reference 1.

MATERIAL AND CROSS SECTION

The spayed concrete mix used in the experiments was a C35/45 mix containing aggregates of maximum size 8 mm and a cement content of 500 kg/m³. The water/cement ratio was 0.43 and 2 kg/m³ of polypropylene (PP) fibres, with designation SIKA Crackstop, were added to the mix. The reason for choosing 2 kg/m³ PP-fibres was that the concrete was relatively young during testing, 49 and 51 days. Young and moist concrete is known to be prone to spalling during fire exposure [2]. The young age was due to a tight schedule in the project, but if following EN 1363-1 [3] specimens should be stored for at least three month before fire tests with the aim to reach the strength and moisture content expected in normal service.

Two fire tests were performed on the sprayed concrete system where the test specimen was covering the horizontal furnace at SP with an opening of 3 x 5 m². The first test was on a 3 x 5 m² slab and the second test on two 3 x 2.5 m² slabs. The purpose of the second test was to investigate if some scaling effects were present. In this paper details and results from the test on the large specimen is given. Nominal thickness of all slabs was 120 mm, but due to technical challenges there was a spread in thickness during spraying. In Figure 1 a map of the deviation from nominal thickness 120 mm is shown. The average deviation from nominal thickness was 31 mm making the average thickness of the specimen 151 mm with the highest thickness 217 mm and lowest thickness 99 mm.

During the test the specimen were hung using a rod system as shown in the cross section in Figure 2 and figure 3 shows the test setup placed on the horizontal furnace at SP.
Figure 2  Drawing of cross section of test specimens including support system. During the test the specimen was hanging from the supporting system and exposed to fire from underneath.

Figure 3  Test specimen and support system on top of the fire resistance furnace. The sprayed concrete roof is during the test hanging in 12 rods, placed 1.2 m apart, which is attached to a steel frame made of HEB 100 beams.

THERMAL PROPERTIES

The transient plate source method (TPS) was used for measuring the thermal properties of the sprayed concrete [4][5]. With this method it is possible to determine both the thermal conductivity and the thermal diffusivity with one measurement. When doing the measurement the specimen must be in thermal equilibrium with the surroundings. During the experiment the specimen is exposed to a small well controlled heat wave and by analysing the temperature response curve developed the thermal properties can be determined, see more details in reference 5. When doing a test the method determines the properties at a chosen temperature, i.e. it is not a method scanning the properties like a
scanning calorimeter. Further on, the method cannot accurately include effects from evaporation of water or chemical transformations. Despite this limitations a good correlation between temperature predictions based on measured properties with this method when compared with fire resistance experiments have been found [4]. When looking at the test results it is important to consider that the thermal properties are related in the following way:

\[
\alpha = \frac{\lambda}{\rho C_p}
\]

\(\alpha\) = Thermal diffusivity [m\(^2\)/s]
\(\lambda\) = Thermal conductivity [W/mK]
\(\rho\) = Density [kg/m\(^3\)]
\(C_p\) = Specific heat [J/kgK]
\(\rho C_p\) = Volumetric specific heat [J/m\(^3\)K]

The main purpose of measuring the thermal properties of the sprayed concrete was to see how they correlate with the specified properties in the Eurocode 1992-1-2 [6]. In the Eurocode a higher and a lower curve is defined for the thermal conductivity (which also influences the thermal diffusivity, see formula 1 above). The definitions in the Eurocode were developed by locking the specific heat and creating a best fit of the conductivity in calculations to match as many experimental results as possible. Note that also included in the best fit of the thermal conductivity are effects from convective moisture transport. Therefore the thermal conductivity in the Eurocode is an “effective conductivity” not the true conductivity. Inside the span of the lower and higher curves in the Eurocode a national choice can be done; in Sweden Boverket have chosen the lower curve of thermal conductivity.

Figure 4 shows the thermal diffusivity measured at the temperatures 22, 150, 170 and 300°C. A physical interpretation of thermal diffusivity is how fast uneven temperature distributions inside materials are evened out when not having any heat exchange with the surroundings. It is obvious that the lower curve of thermal diffusivity is not representative for the three lowest temperatures investigated, but at 300°C the thermal diffusivity is close to the lower curve defined in the Eurocode.

![Figure 4](image.png)

Figure 4  Thermal diffusivity measured with TPS compared with values from the EN 1992-1-2 [6] for a density of 2260 kg/m\(^3\) and no moisture effect. The moisture influence by latent heat of evaporation between 100 and 200°C is taken away as this is not a phenomenon covered by the TPS measurement.

In Figure 5 the measured values of thermal conductivity and volumetric specific heat from the TPS
measurements are compared with the values in the Eurocode. Due to the connection between the thermal properties (Formula 1) it is important to not only compare the thermal diffusivity with the Eurocode as the heat transfer through the boundaries involves not only the thermal diffusivity. To summarize, the results on thermal properties measurements show that we are in the span between the lower and upper curve in the Eurocode.

Figure 4 Thermal conductivity and volumetric specific heat, measured compared with the values defined in the Eurocode [6]. The peak of volumetric specific heat in the Eurocode is adjusted depending on the moisture content. In the TPS measurement the moisture is not present at temperatures over 100 °C so the measurement shall be compared with a value for concrete without a moisture peak.

FIRE RESISTANCE TEST METHOD

The fire resistance of the inner roof of spayed concrete was tested in the horizontal furnace at SP. The thermal exposure following the hydrocarbon curve defined in EN 1363-2 was controlled with 10 plate thermometers in the furnace. Thermocouples were attached to the reinforcement before spraying and additional thermocouples for measurement within the concrete cross section and at the unexposed surface of the specimen were drilled in or attached after spraying. This was due to the rough mechanical impact during spraying which might destroy or change the position of thermocouples. In total 42 thermocouples were drilled in at depths of 0, 30 90 and 110 mm from the cold side or mounted on the reinforcement. The drilled holes are then filled with mortar. Due to the unevenness of the sprayed concrete surface all thermocouple depths initially defined from the cold surface had to be recalculated based on the depth in the mapping of the surface.

To estimate the stresses developed in the rods fixing the specimen to the support structure, strain gauges were attached at mid height on 6 of the 12 rods. The gauges were mounted in three locations around the circumference of the rods, at a separation angle of 120 degrees, to be able to detect the normal force and any bending moments present.

During the fire test the upper surfaces of the test specimens were scanned with a HDS7000 terrestrial laser scanner. This was to measure the deformations of the concrete upper surfaces and the supporting steel beam system. Additionally the temperature development of the upper non-exposed surface was monitored during the test with a thermal camera. The exact temperatures from this type of measurement with a thermal camera in this experimental situation are associated with large potential errors but, from the relative temperature distribution, thermal images can be used to monitor the development of cracks at the surface of the specimen.

RESULTS

The fire resistance test of the 5 x 3 m² large slab specimen continued for 3 hours with the hydrocarbon thermal exposure. After 3.5 minutes of exposure spalling started in the north east corner of the specimen and continued until 8 minutes. Water starts to pour out in cracks on the non-exposed surface of the slab after 22 minutes. This is very common during fire testing of concrete and it was first described by Woolson as early as 1905 [7]. After 80 minutes of fire exposure a lot of cracks could be
seen on the surface, Figure 5. When the heating phase was finished after 180 minutes the specimen was left on the furnace and all temperatures and strains in the rods were measured during the start of the cooling phase until a time of 236 minutes from the start of the test.

![Thermal image indicating the crack development on the upper surface after 80 minutes of fire exposure.](image)

**Figure 5**  
Thermal image indicating the crack development on the upper surface after 80 minutes of fire exposure.

In figure 6 the stresses developed in the rods are shown (6 out of 12 rods were instrumented). The starting point is zero meaning that the initial weight is not included in the measurement only changes of stresses. As shown rods D and F are in compression during the whole test, which is caused by thermal bowing of the slab, this is happening in two directions during heating of slabs [8]. The reason for the spread in results between points A and C is probably due to the unevenness of the surface illustrated in Figure 1.

![Change in axial force in the rods during the test. Compressive force is negative in the diagram.](image)

**Figure 6**  
Change in axial force in the rods during the test. Compressive force is negative in the diagram.

During the test, unfortunately, there was some deformation of the supporting system; the beams shown in Figure 2 and Figure 3 were not stiff enough to resist the developed forces. These
deformations were monitored with the laser scanner, so it was possible to use the results for comparison with theoretical calculations, more details and measurements can be found in reference 1.

During the test spalling occurred in 4 areas of the slab despite the inclusion of 2 kg/m³ PP fibres in the concrete mix. However no progressive or deep spalling as would influence the fire resistance occurred, see table 1. Deviations in initial thickness were much larger than the spalling depth. It is also important to note that the test specimen was fairly young with high moisture content, around 7% by weight, measured on parallel stored samples with the same thickness. Young age and high moisture content is commonly considered to result in more spalling.

### Table 1  Estimated depth and dimensions of spalled areas during the fire test.

<table>
<thead>
<tr>
<th>Spalling depth [mm]</th>
<th>Size, X [mm]</th>
<th>Size, Y [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 10-30</td>
<td>800</td>
<td>1200</td>
</tr>
<tr>
<td>B 10</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>C 10-30</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>D 10-30</td>
<td>500</td>
<td>1200</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The test results showed that the insulation and integrity criteria were maintained for the whole test period. Only a limited amount of surface spalling was seen, due to the 2 kg/m³ of polypropylene fibres included in the concrete mix. Moreover an approach for measurement of stresses in the supporting system was presented. This combined with a laser scanning of the whole upper surface can be used for comparison with numerical modelling. Finally the thermal properties of the typical Swedish sprayed concrete, was shown by experimentation to be within the bounds of what is defined in the Eurocode.

**ACKNOWLEDGEMENT**

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Design, assessment and application of passive fire protection in the Port of Miami tunnel according to NFPA 502

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ABSTRACT

For the Port of Miami tunnel project the concrete spalling behaviour in case of fire is assessed by on-site fire tests using the Efectis MobiFire mobile furnace [2]. By doing so, it was possible to assess separately the spalling behaviour of the Port of Miami tunnel concrete itself and its passive fire protection, enabling to draw conclusions about the compliance of the fire protected concrete structure to the NFPA 502:2008 [1] requirements.

KEYWORDS: fire spalling, on-site fire tests, NFPA 502, passive fire protection, project, construction process

INTRODUCTION

The Port of Miami tunnel is a highway tunnel connecting the Port of Miami via Watson Island to interstate highway I-395. The tunnel has a length of 1300 m and consists of two 13 m diameter bored tunnel tubes with two lanes each. The tunnel was opened in August 2014. It is the first tunnel in the United States where passive fire protection is applied according to the NFPA 502:2008 [1] “Standard for Road Tunnels, Bridges and Other Limited Access Highways”. The 2008 edition differs from previous versions as fire exposure according to the RWS fire curve and spalling of concrete has to be considered.

Traditionally, fire tests are done on loaded concrete segments in combination with the fire protection system. In this project a different approach was chosen, where the assessment of the spalling behaviour was done separately from the assessment of the fire protection systems. Note that the current version of the NFPA 502 is the 2014 edition.

The research performed for the Port of Miami tunnel consists of two phases:
1) Project specific fire tests on precast concrete tunnel segments, determining the maximum thermal conditions (heating of the concrete) at which the concrete does not spall,
2) Based on (existing) test data, determining the suitability of fire protection systems to meet the temperature criteria.

The separate assessment of the concrete and its fire protection system proved to be suitable to draw conclusions about the compliance of the fire protected concrete structure to the NFPA requirements. At the same time, the separate assessment brings a number of advantages compared to the traditional approach of combined testing.

Some characteristics of the tunnel geometry are given in Table 1 and an overview of the Port of Miami tunnel project is given in Figure 1.
Table 1  Geometry of the Port of Miami tunnel tunnel segments.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of segments</td>
<td>Varying from 1.68 m to 1.74 m</td>
</tr>
<tr>
<td>Thickness of segment</td>
<td>0.61 m</td>
</tr>
<tr>
<td>Inner ring diameter</td>
<td>11.27 m</td>
</tr>
<tr>
<td>Angle of segment</td>
<td>45°</td>
</tr>
<tr>
<td>Shortest distance 2 faces of segment (calculated)</td>
<td>4.31 m</td>
</tr>
<tr>
<td>Arc height of segment (calculated)</td>
<td>0.43 m</td>
</tr>
</tbody>
</table>

Figure 1  Overview of the Port of Miami tunnel project.

STRUCTURAL FIRE PROTECTION IN NFPA 502

The requirements for structural protection in the NFPA 502 include temperature requirements on concrete and reinforcement as well as requirement for concrete spalling when exposed to the RWS fire curve for 120 minutes. In paragraph 7.3.3 it is described that during 120 minutes exposure to the RWS fire curve the following criterion shall be met:

1. no explosive spalling of concrete.

Additionally, in paragraph 7.3.4 it is stipulated that for cast in situ tunnel linings (such as immersed or cut&cover tunnels) the following additional criteria apply:

2. maximum concrete surface (interface) temperature of 380 °C;
3. maximum reinforcement temperature of 250 °C.

For the part of the Port of Miami Tunnel that is constructed using a tunnel boring machine (TBM) only the first criterion, that prohibits explosive spalling of concrete, is applicable since this part of the tunnel consists of pre-fabricated concrete segments.

Spalling of concrete is dependent on many different parameters, related to geometry, mechanical boundary conditions, concrete ingredients and storage conditions and the temperature and duration of the fire. These factors influence the internal stresses in concrete, mainly due to expansion and migration of moisture, thermal expansion, load induced thermal strain and chemical degradation. As no practically useable model is available that can theoretically predict these phenomena in a reliable way, (the absence of) spalling can only be demonstrated by fire testing. Therefore, spalling tests have been
carried out especially for the Port of Miami tunnel project to verify the corresponding requirement.

The NFPA 502 requirements considers “explosive spalling”. Within the scientific world, different definitions of forms of spalling exist, and there is no generally accepted definition of which forms of spalling should be considered “explosive”. In the Port of Miami tunnel research, it was decided to interprete the term explosive spalling as violently releasing concrete in layers with thicknesses more or less equal to the grain diameter of the coarse aggregate. Secondly, explosive spalling can be observed audibly by a loud bang. The behaviour is deemed acceptable, if falling off of pieces of the concrete is limited to the cement skin (approx. 1 - 2 mm). If explosive spalling would occur, it is expected that the damage is substantially higher, spalling depths normally are in the range of 10 - 100 mm, over a large area. Such spalling depths are considered as failure (unacceptable).

ASSESSMENT OF SPALLING BEHAVIOUR OF THE CONCRETE MIXTURE

For the Port of Miami tunnel project the spalling behaviour is assessed using fire tests. The aim of this first part of the assessment was to determine the maximum allowable temperature development of the surface of the concrete tunnel lining at which spalling does not occur. The fire tests were performed on actual tunnel segments, where the concrete surface was exposed to representative interface temperature curves, simulating a situation in which the tunnel element is protected with a passive fire protection material. These fire tests were carried out using the Efectis MobiFire mobile furnace [2]. In each fire test, the concrete surface was exposed to a predefined interface temperature curve. Tests were repeated with varying curves until a non-spalling result was obtained.

Consequences of separate assessment of concrete spalling and fire protection

The physical absence of the final passive fire protection system during the fire test could in theory influence the behaviour of the concrete, even if the temperature curve at the concrete surface would be the same in both cases. In order to be able to verify the concrete and the fire protection system separately, one has to assess what could be this interaction and determine their potential influence.

1. Moisture migration
One of the mechanisms contributing to spalling of concrete is the build-up of pore pressures inside the concrete due to heated (pore and physically bound) water in an impermeable medium. Fire protection systems are several orders of magnitude more permeable than concrete, and therefore do not influence the moisture distribution inside the concrete during the fire test.

2. Mechanical stresses
Another mechanism contributing to spalling of concrete is the build-up of thermal stresses, possibly in combination with external mechanical loads. As the passive fire protection is implemented once the tunnel segments have been installed and thus loaded, only a redistribution of the stresses by creep could lead to alter the actual stress distribution within the tunnel concrete. As the thickness and material stiffness of usual fire protection systems are one or more orders of magnitude smaller than the thickness and stiffness (Young’s modulus) of the concrete structure, this redistribution is very minimal. Therefore, the presence or absence of a fire protection system does not influence the stress distribution inside the concrete.

3. temperature profile
If the fire protection system is fixed parallel to the concrete surface, the heat transfer is one-dimensional. In that case, there is no difference between a protected and an unprotected concrete structure.

Most fire protection systems are equipped with (stainless) steel anchors to ensure proper fixing to the concrete. Such anchors may lead more thermal energy into the concrete locally. In the experience of Efectis, this effect is negligible if the anchors are embedded in the fire protection and the heads not directly exposed to the fire. If the anchors have a diameter of maximum 6 mm, for usual fire protection
thicknesses the local heating is negligible even if the anchors protrude through the fire exposed surface. Moreover, also in the on-site fire tests for the Port of Miami tunnel project 15 anchors with a diameter of 6 mm were included in the fire exposed surface of each test slab. These anchor held a dummy fire protection board in place.

**Test setup**

For simplicity of the test setup, especially for the loading equipment, original tunnel segments were cut to approximately half their size. Using the MobiFire mobile furnace, the fire exposed area on a half segment was approximately 1 x 1 m². This area is smaller than in traditional tests, where the full internal surface of a segment is exposed to fire in a laboratory furnace. Nevertheless, the area is considered as sufficient because:

- spalling is not allowed; size and edge effects only start to play a role after spalling starts. Spalling depths tend to be smaller closer to the edges of the specimen. But in this case, any spalling depth beyond the cement skin is not allowed.
- the fire protection system is not included in the test, so aspects related to fixing/bonding of the material and its relevant dimensions (anchor pattern, board sizes etc.) do not play a role.

The test setup is displayed in Figure 2, Figure 3 and Figure 4.

![Figure 2](image-url)  
**Figure 2**  Test setup including mobile furnace (top view).
In order to avoid flame impingement and turbulence of hot gases directly at the concrete surface, the exposed area is covered by a dummy passive fire protection board material. The dummy board is anchored to the concrete using 15 anchors diameter 6 mm uniformly distributed over the exposed surface. This board will limit the interface temperatures, compared to the furnace temperatures that are expected to rise a bit faster. However, the piloting of the test is based on the concrete surface temperatures, not on the gas temperatures in the furnace itself.

The concrete surface temperatures (“interface temperatures”) during heating of the specimen are recorded with 9 thermocouples in a matrix of 3 x 3. The matrix has a gridsize of 20 x 20 cm and is positioned in the centre of the exposed surface. The thermocouples are placed at sufficient distance to avoid edge and boundary effects. These are twisted wire thermocouples of type K used to determine the actual interface temperature. The average value of these 9 interface thermocouples is considered as ‘the interface temperature’.

The test specimens are loaded during the fire test using a horizontal loading frame. The required stress in the segment was equal to the stress in most unfavorable case for the Port of Miami tunnel during the service life of the tunnel in order to investigate spalling properly. The worst-case scenario for the stress in the tunnel segments during standard operation is 9.4 MPa compression at the exposed surface. Over
the arc length of the specimen, the arc height of the load gradually decreases, which slightly influences the compression at the exposed surface. Since the value of 9.4 MPa is based on the worst-case location in the tunnel perimeter, it is also taken as the maximum required value in the test setup which may gradually decrease to the side of the segment; about 8.0 MPa at the edges of the exposed surface. As the actually applied load during the tests appeared to be significantly higher than the required load, the gradually decreasing stress towards the sides is considered as irrelevant. Almost the entire exposed surface was subjected to a compression stress higher than required, which is conservative with respect to the results obtained for concrete spalling.

Targeted interface temperature

The Port of Miami tunnel test specimens are exposed to different generic time-temperature curves. The generic interface temperature curves represent shapes that may be expected when testing different thicknesses of typical insulation materials. The curves are not specific for one type of material but are based on Efectis’ experience with different tunnel fire protection systems.

An interface temperature curve includes in general the following phenomena:
1) Moisture plateau (interval of constant temperature around 100 °C. Its length depends on the amount of moisture present in the passive fire protection layer and in the concrete skin).
2) Temperature increase after the moisture plateau according to thickness and the thermal conductivity properties of the product.

In Figure 5 some characteristic interface temperatures curves are shown for an arbitrary passive fire protection material. The characteristics are clearly seen from the figure: (1) moisture plateau up to 50 minutes and (2) temperature increase after the moisture plateau.

![Example interface temperature curves](image)

**Figure 5** Example interface temperature curves of common fire protection materials during 120 minutes RWS fire curve.

In order to have a generic interface temperature curve, the interface temperatures shown above were fit with a parameterized temperature curve, which consists of two parts: (1) the part up to 100 °C, which includes the moisture plateau (2) and the part after the moisture plateau up to the final temperature.
Five characteristic points were chosen as basis for curve fitting to determine the generic reference curves, see figure 6.

![Characteristic interface temperature curve](image)

**Figure 6**  Characteristic points on the interface temperature curves for curve fitting.

Based on existing test results with many different passive fire protection materials for tunnels it is expected that the calculated interface curve will envelope the interface fire curves for most of the passive fire protection materials available on the market.

**Test result**

Fire tests were carried out iteratively with changing concrete surface temperature curves until spalling did not occur during exposure. In total 7 tests were performed on Port of Miami tunnel segments. In Table 2 all test results are summarized, including the decision that was taken after each test for the continuation of the test programme.

**Table 2**  Summary of test results and decision outline of the fire test sequence.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Interface reference curve (°C)</th>
<th>Spalling occurred? (yes/no)</th>
<th>Time of occurrence of spalling (min)</th>
<th>Average interface temperature at time of spalling (°C)</th>
<th>Decision for next test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>250</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>Move to reference curve 380 °C</td>
</tr>
<tr>
<td>Test 2</td>
<td>380</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>Repeat the 380 °C test</td>
</tr>
<tr>
<td>Test 3</td>
<td>380</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>Perform a test with steep curve 800 °C*</td>
</tr>
<tr>
<td>Test 4</td>
<td>800</td>
<td>Yes</td>
<td>22</td>
<td>322</td>
<td>Perform a test with reference curve 450 °C</td>
</tr>
<tr>
<td>Test 5</td>
<td>450</td>
<td>Yes</td>
<td>67</td>
<td>323</td>
<td>Perform a test with reference curve 420 °C</td>
</tr>
<tr>
<td>Test 6</td>
<td>420</td>
<td>Yes</td>
<td>79</td>
<td>335</td>
<td>Perform a test with reference curve 400 °C</td>
</tr>
<tr>
<td>Test 7</td>
<td>400</td>
<td>Yes</td>
<td>90</td>
<td>338</td>
<td>Test sequence finished.</td>
</tr>
</tbody>
</table>

* this was a special curve in order to determine the temperature range where spalling could roughly be expected.
The average recorded interface temperatures for all tests are given in Figure 7. As is clearly shown by
the figure, temperature curves reaching about 320-340 ºC within slightly over 90 minutes show
spalling at the moment that this temperature is reached. However, slightly slower heating, with 320-
340 ºC being reached around 100 minutes, avoids spalling altogether and an interface temperature of
380 ºC after 120 minutes can be reached without spalling. The figure clearly shows the relation of
spalling not only with the temperature at the concrete surface but also with the rate of temperature
increase. Therefore, the interface temperature curve with a maximum of 380 ºC (test 2, which is
slightly below test 3) is chosen as the limiting value to avoid spalling of concrete.

Figure 7 The average recorded interface temperatures during the tests.

ASSESSMENT AND SELECTION OF PROTECTION SYSTEMS

Determination of temperature criteria

In the verification phase of the research fire test reports supplied by the manufacturers/suppliers of
fireproofing material for the Port of Miami tunnel were validated on their ability to limit the
temperatures in order to avoid spalling on the calcareous concrete slab of the Port of Miami tunnel.

In order to verify the thermal performance, the interface curve with a maximum of 380 ºC was
simplified to a set of temperature criteria. For spalling of concrete, not only the final (maximum)
temperature after two hours is relevant but also the temperature-time path during the fire test. After all,
a fast initial temperature rise might lead to spalling whereas a more gradual temperature rise would not.
This was also clearly demonstrated by the fire tests. Therefore, the temperature curve which resulted
from the mobile furnace tests was translated into three temperature criteria: maximum concrete
temperatures after 60, 90 and 120 minutes. By defining these three points, the shape of the concrete
temperature curve is also defined and too high heating rates are excluded.

In order to investigate the thermal behaviour of a certain system, the provided existing fire test reports
were evaluated. A significant number of fire tests was done on concrete slabs containing siliceous
aggregate, whereas the concrete of the Port of Miami tunnel contains calcareous aggregate. From
previous experience of Efectis as well as from the Eurocode for concrete (EN 1992-1-2) it is known
that the aggregate type affects the temperature results. Due to the higher conductivity of siliceous aggregate, this will result in lower interface temperatures than concrete with calcareous aggregate. This means that the same fire protection system (thickness, anchoring, etc.) will result in higher temperatures on a calcareous aggregate concrete slab than on a siliceous aggregate concrete slab.

In order to be able to use fire test data obtained from siliceous slabs, the temperature criterion has also been defined for siliceous aggregate concrete slabs. This conversion is made based on 1-dimensional thermal calculation which is based on the thermal properties mentioned in the Eurocode (EN 1992-1-2, section 3.3.2 and section 3.3.3) in combination with available test data with different fire protection material products.

The temperature criteria after 60, 90 and 120 minutes for this curve are given in Table 3. Each of those three criteria should be met by a fire protection system, because both the rate of temperature rise and the final temperature are limited.

Table 3: Temperature requirements for both siliceous and calcareous aggregate concrete mix, suitable to avoid spalling for the Port of Miami tunnel.

<table>
<thead>
<tr>
<th>time (min)</th>
<th>maximum interface temperature for verification fire tests performed with siliceous aggregate concrete (calculated values) (°C)</th>
<th>maximum interface temperature for verification fire tests performed with calcareous aggregate concrete (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>216</td>
<td>246</td>
</tr>
<tr>
<td>90</td>
<td>275</td>
<td>314</td>
</tr>
<tr>
<td>120</td>
<td>334</td>
<td>380</td>
</tr>
</tbody>
</table>

The maximum temperature after 120 minutes in case of calcareous aggregate concrete appeared to be 380 °C. It is a mere coincidence that this value coincides with the temperature criterion for in situ tunnels as given in NFPA 502 and other widely used standards. For other tunnels with different geometries, loading levels and concrete mixes, the temperature criteria resulting from fire tests will be different.

**Evaluation of fire protection systems**

The performance of a fire protection system depends on its thermal characteristics (is the insulation value sufficient) and on its mechanical characteristics (does the material remain intact and in place during fire exposure). More in detail, the following relevant aspects were verified:

- Insulation thickness in relation to thermal criteria,
- Moisture content of the fire protection,
- Type of concrete used in the fire test, in order to be able to compare the thermal conductivity of the concrete in the test and in POMT,
- Suitability for curved concrete surface,
- Method of fixing to the concrete (type of anchors, spacing).

For the fire protection system, the fire test results had to fulfil the established temperature criteria, while the moisture content of the fire protection material before the test needed to be at equilibrium.

For the suitability of the fire protection system for application on a curved concrete surface, the method of installing and fixing was evaluated. For example, the application of a board material on a curved surface will lead to air gaps, V-shaped joints, need for cover strips, etc. Therefore, the size of the boards, the positioning and types of anchors and other geometrical aspects in the provided test results
were compared in detail with the actual geometry of the Port of Miami Tunnel.

**Chosen fire protection system**

Several fire protection systems were evaluated. These evaluations helped Bouygues Civil Works Florida to make a motivated choice for a certain fire protection system. The chosen fire protection system for the circular tunnel consists of Promat-T boards. These boards are applied as a post-fixed faceted lining system, with cover strips behind the joints, see Figure 8. The main panels have dimensions of 2500 x 600 mm. The main panels and the backer strips are anchored to the concrete by means of 10 each 6 mm mechanical expansion anchors with 30 mm washers both 316 stainless steel. The distance of the anchors to the edge of the boards was 50 mm so the anchors would hold the main panels and longitudinal backer strips in placed. The anchors are spaced equally at 600 mm.

![Figure 8 Facetted board system during application in the tunnel.](image)

**CONCLUSIONS**

The separate assessment of the concrete and its fire protection system proved to be suitable to draw conclusions about the compliance of the fire protected concrete structure to the NFPA requirements. At the same time, the separate assessment brings a number of advantages compared to the traditional approach of combined testing.

A main advantage is that the test programme can be done fast and with full flexibility. With the traditional approach, before starting the preparations of the test specimens, a choice must be made of the fire protection system and thicknesses to be tested. Then, especially in the case of spray mortars, a conditioning time is required in order to reach equilibrium moisture content. At the time of testing it is not possible anymore to make any changes. If flexibility at that time is needed, in the initial stage a large number of different test specimens should have been made.

With the separate assessment using the MobiFire mobile furnace, a larger number of tests can be performed, giving a more detailed view of the spalling behaviour. Whereas a traditional test will mainly result in a conclusion “pass” or “fail”, the larger number of fire tests provides a better understanding of the heating rates and maximum temperature curves that lead to spalling, given the concrete mix and loading conditions of the actual tunnel.

The use of existing test data is in principle an advantage, as long as the assessor is aware of the large number of aspects that need to be verified. Therefore, even if the assessment consists of two separate parts (fire testing to determine spalling behaviour, evaluation of test data of fire protection systems) it is recommended that both parts of the work shall be done by the same party, which shall be an independent institute with sufficient knowledge of spalling of concrete and passive fire protection.
REFERENCES


Concrete Explosive Spalling Test for the Ohio River Bridge East End Crossing Tunnel

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ABSTRACT

An innovative approach for fire design of the concrete final lining of the Ohio River Bridge East End Tunnel was developed. As a result from a proposed fire suppression and tunnel ventilation system, the design heat release rate (HRR) was able to be reduced from 300 MW to about 50 MW. With this HRR, a final concrete lining without passive fire protection system is possible. Concrete explosive spalling tests are needed to assess the adequacy of the proposed tunnel final lining concrete mix, given the possibility that during a fire the concrete explosive spalling may occur and jeopardize the safety of the fire respondents and damage to the tunnel lining structure. Since no standard concrete fire explosive spalling testing procedure exists, the proposed fire testing procedure primarily follows guidelines and recommendations from two industry practices and modified as necessary to suit this project’s needs. Based on fire tests conducted, it is concluded the proposed concrete lining (with the fire suppressing and tunnel ventilation system) without passive fire protection, will not experience explosive spalling during the design fire. This is the first application of this concept in the US.

KEYWORDS: Explosive spalling, fire loading, NFPA 502, Heat Release Rate (HRR), humidity, passive fire protection, Computational Fluid Dynamics (CFD)

INTRODUCTION

The Ohio River Bridge East End Crossing (ORBEE) Tunnel is part of a Public Private Partnership (PPP) project, which will connect transportation network between Louisville, Kentucky and southern Indiana. Located in Louisville, Jefferson County, Kentucky, the twin-tube highway Tunnel provides northbound and southbound lanes of the Kentucky approach to a new bridge across the Ohio River. Tunnel lengths are approximately 1,675-ft (511m) and 1,685 (514m) for the northbound tube and the southbound tube, respectively. Connected by two cross-passages, both tubes have a roadway width of 40-ft (12.2m), for 3-lane traffic, and a vertical clearance of 26.5-ft (8m).

Figure 1. Typical tunnel cross section at cross passage
Design fire

The project Technical Provisions (TP) requires fire size to be determined by an assessment of the expected type of vehicles in the tunnel, but should not be less than 300 MW (based on tanker trucks in the tunnel, as noted in NFPA 502 [1], Annex A). The TP also allows the consideration of using a fire suppression system as a means of reducing the fire magnitude. The Fire Life Safety Report [2] documented the technical design approach to protect the environment and the structure by reducing the fire size and cooling the environment using a water based fixed fire suppression system with 3% aqueous film forming foam (AFFF) and enhanced tunnel drainage system to capture flammable liquid spills to reduce the fuel pool size.

Full scale fire tests with the proposed fire detection and fixed fire suppression system were performed in Seattle and witnessed by Harrods Creek Fire Department, the Authorities Having Jurisdiction of this project. The tests demonstrated the fast fire detection and suppressing system is able to constrain a 300 MW flammable liquid fire growth to 50 MW in 2.5 minutes after the fire ignition. Figure 2 shows the design fire growth curve [3].

CFD MODELING [3]

The computational fluid dynamics (CFD) software package Fluent was used to simulate the design fire event of this project, with the following parameters:

Simulation timeline

The flammable liquid cargo fire would be detected in 30 - 60 seconds after ignition, which was demonstrated by the full scale fire tests. The fixed fire suppression system will be semi-automatic and remotely operated from the Operations Support Facility. A 60 second activation delay is built into the system to allow for the operator to stop of the activation should the operator note a nuisance alarm.

After the sprinkler system is activated 60 seconds from fire detection (120 seconds after fire ignition), the water would take 15 seconds to flow from the deluge valve to the farthest sprinkler head of the deluge zone, and the full sprinkler system discharge pattern would be achieved in another 15 seconds.

Total of 6 pairs of jet fans will be installed in the northbound (downward grade) tube and 6 in the southbound (upward grade) tube. The tunnel ventilation would start automatically after the fire
detection. Due to the electrical limitation, multiple fans may not start at the same time and a 10-second interval of fan activation between adjacent locations was considered. To avoid disruption of the smoke layer initially, the fan(s) that are farthest away from the fire location are operated first, followed by the second-farthest with 10 seconds delay, third-farthest fans with additional 10 seconds delay, etc. in the CFD analysis. The fan(s) closest to the fire is not activated in the CFD analysis. The jet fan(s) at fifth in the sequence, which is the last required fan(s) in the CFD analysis, would start 100 seconds after the fire starts. Figure 3 shows the assumed operational timeline of jet fan and sprinkler system.

Figure 3. Operational timeline of jet fan and sprinkler system

Fire locations

Table 1 and Figure 4 present schematic fire locations and plan. The tunnel grade is about 0.6% to 4%, in a downward direction from south to north.

Table 1. Summary of fire location

<table>
<thead>
<tr>
<th>Tunnel (Tube)</th>
<th>Fire ID</th>
<th>Fire location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northbound</td>
<td>NB1</td>
<td>100 ft. (30.5 m) from south portal</td>
</tr>
<tr>
<td></td>
<td>NB2</td>
<td>Center</td>
</tr>
<tr>
<td></td>
<td>NB3</td>
<td>100 ft. (30.5 m) from north portal</td>
</tr>
<tr>
<td>Southbound</td>
<td>SB1</td>
<td>100 ft. (30.5 m) from north portal</td>
</tr>
<tr>
<td></td>
<td>SB2</td>
<td>Center</td>
</tr>
<tr>
<td></td>
<td>SB3</td>
<td>100 ft. (30.5 m) from south portal</td>
</tr>
</tbody>
</table>

Figure 4. Schematic fire locations

Critical CFD results for explosive spalling test

Based on the CFD model results, only three fire events indicate concrete lining surface will experience temperature exceeding 716 °F (380 °C), which is the concrete spalling criteria/temperature. These fire events are Fire IDs NB3, SB1, and SB2. Their time-temperature curves at tunnel lining surface are shown on Figures 5 to 7.
From these curves, it is noted that tunnel lining surface may experience a temperature exceeding 716°F.
(380°C) for less than 90 seconds of time. Though it is expected this short duration of high temperature would not cause damage to the tunnel cast-in-place concrete lining, Indiana Financial Authority (IFA, the consortium who manages this project) requested a fire test to prove that no concrete explosive spalling will occur.

EXPLOSIVE SPALLING TESTING PROCEDURE [4]

As requested by IFA, concrete explosive spalling tests are needed to assess the adequacy of the proposed tunnel final lining concrete mix, given the possibility that during a fire the concrete explosive spalling may occur and jeopardize the safety of the fire respondents and damage the tunnel lining structure. The result of this fire test can also be used as the basis of fire design of the proposed concrete lining without a passive fire protection system.

Since no standard concrete fire explosive spalling testing procedure exists, the proposed test primarily follows guidelines and recommendations from the following two publications and modified as needed:

- Fire Testing Procedure for Concrete Tunnel Linings [6].

Fire loading

Three (3) fire-temperature time curves were proposed for concrete explosive spalling test, as shown on Figures 5, 6, and 7. Additional conservative measure was taken such that the fire tests will be conducted with a peak temperature that is 10% higher than the design peak temperature.

During fire tests, the furnace was shut down following each temperature time curve. The test specimen was then left for a minimum of 30 minutes before being moved. Temperature measurements in the specimen was continued and reported until the temperature of the thermocouples embedded in the concrete and nearest the furnace exposed face fall to below 400 °F.

The maximum deviation of the fire-temperature time curve shall be within + 15%/-0% from the target value. In other words, the actual temperature at a given time may be up to 15% higher than that stated by the fire temperature-time curve, but it cannot be lower.

Test specimens

Two fire tests are required for each fire load, one for low humidity test specimen and one for high humidity specimen.

The proposed thickness of the tunnel concrete final lining is 16 inches (406 mm). Since the tunnel lining will be exposed to a potential fire for a short period of time only, the potential impact from fire exposure to the tunnel lining extrados face is expected to be insignificant. In addition, the primary purpose of the test is to investigate the potential of concrete explosive spalling during a fire; therefore, we proposed 10-inches (250mm) thick specimens for concrete explosive spalling testing purpose.

To avoid edge effect, the length and width of the test specimens are selected to be at least 6 to 8 times the thickness of the specimen.

In summary, the nominal test specimen geometry is as follows: 10-inches thick by 60-inches wide and 60-inches long (250 mm thick by 1,500 mm wide and 1,500 mm long). The width and length each was extended a minimum 12-inch (300 mm) to provide a “furnace overlap”, as shown on Figure 8.
Concrete mix and reinforcement

The concrete mix of the test specimens is as follows: compressive strength: 30 Mpa at 28 days; maximum aggregate size: 25 mm; air content: 6.0 ± 2.0 %; Water/Cementitious ratio: 0.41; Slump: 50 mm to 100 mm; cement, Type I/II: 232 kg; class F Fly Ash: 58 kg; water: 31.5 gallon.

Tunnel final lining reinforcing design requires #6 (#19M) or #7(#22M) flexural reinforcement at 12” (300mm) on center, each face. Longitudinal temperature and shrinkage reinforcement consists of #4 (#13M) at 12” (300mm) on center, each face; therefore, the proposed reinforcing pattern of the test specimen is as follows:

- Transverse reinforcement, flexural reinforcement: #7 (#22M) at 12” (300 mm) on center, each face.
- Longitudinal reinforcement: #4 (#13M) at 12” (300mm) on center, each face, placed between...
(inside) the #7 (#22M) bars.

- Concrete cover: 3-inches (75mm) and 2-inches (50mm) at the bottom and at the top surfaces of the test specimen, respectively, as the in-situ tunnel lining concrete cover condition.

Lifting eyes are casted into the top face of the specimens, but away from the thermocouples locations.

**Thrust load**

To simulate the tunnel lining in-situ condition, a thrust force of about 63 kips/ft. (920 kN/m) was applied transversely to the specimen before testing by post tensioning threaded rods.

**Thermocouples**

All thermocouples in the concrete test specimen are Type "K" (cased), diameter 1.5 to 3.0 mm, according to DIN 584 or IEC584. Temperature measuring equipment was calibrated and the date of last calibration was recorded. Thermocouples were set in the concrete test specimen in a way that ensures a high coupling efficiency, avoiding any air space and providing a full physical contact between the thermocouple and the concrete. Thermocouple plan and elevation locations are shown in Figures 8 and 9, respectively.

**Specimen preparation and storage**

The test specimens were cast into horizontally-orientated moulds (i.e., laying flat) in order to match the orientation of the concrete pour at the crown of the tunnel. Two test regimes were given, a low humidity test specimen and a high humidity test specimen. In addition to the specimens, 3 cylinders are casted from the same batch of concrete for compressive strength testing in accordance with ASTM C39 [7]. Two of the cylinders were tested at 28 days (to obtain f'c); the third cylinder was tested at the time of the fire testing.

Two 300 mm diameter cylinders were casted and cured alongside each fire test slab and cored and tested as indicated in low and high humidity specimen conditioning, as described below. These specimens were stored in the same conditions as the fire test specimens.

**Initial curing**

The test specimens were removed from the mould at any time after 24 hours.

From the time of casting, the slabs were cured at >90 % RH for at least three (3) months prior to humidity conditioning as detailed below. (Note: >90 % RH curing may be achieved by the use of wet burlap covered with plastic sheeting. The burlap shall be kept wet at all times.)

Alternatively, specimens may be cured under water in a heated water bath until the equivalent age of the concrete is greater than 90 days prior to humidity conditioning, as detailed below. The equivalent age of the concrete shall be determined using maturity from thermocouples embedded in the concrete.

**Conditioning specimen**

Note - The average annual relative humidity in the Louisville area is 80% during the morning and 58% in the afternoon; note: °C = (°F - 32) * 5/9.

After initial curing, low humidity test specimen was stored at 70 ± 4 °F and 50 ± 10 % RH for a further 28 days, and high humidity test specimen was stored underwater at 70 ± 4 °F for 21 days. The high humidity specimen was then stored at 70 ± 4 °F and >90 % RH for at least 7 days.
Alternatively, specimens shall be conditioned such that the humidity at 2 in. (50mm) from the surface of the concrete is 55 ± 10 % for low humidity specimen and 80 ± 10 % for high humidity specimen when the ambient temperature is 70 ± 4 °F. Provided the specimens are uniformly conditioned, the internal relative humidity shall be measured from the back side of the specimen at >300 mm from the edge using RapidRH sensors at www.rapidrh.com.

Immediately prior to fire testing, two 50 mm diameter x 75 mm deep cores and two 50 mm diameter x 50 mm deep cores were removed from each of the back (top face) corners of the test specimen or from the 300 mm diameter cylinder. The two 75 mm long cores were weighed, and then dried to constant weight at 230 °F to determine the free moisture content of the concrete. The 50 mm long cores was prepared and tested for in-situ compressive strength. The test specimen was fire loaded within 4 hours of removal from the storage condition.

**Furnace**

All specimens were placed on a top opening furnace, as shown in Figure 10.

![Figure 10. Furnace top opening in direction of transverse reinforcement](image)

The furnace has a minimum nominal top opening of 60-inches by 60 inches (1,500 mm x 1,500 mm) to accept the specimen.

The furnace was designed to support the specimen on two opposite sides (which are perpendicular to the transverse reinforcements of the specimen) only. The top is sealed with ceramic packing or similar arrangement to prevent heat escaping from around any of the sides of the specimen during the test.

The furnace can be fired with an oil burner or a gas burner and shall have the capacity to increase the temperature up to 1,650 °F at the time intervals required by the tested fire curves.

The furnace temperatures should be measured at not less than 4 points 0 ± 5 mm below the face of the specimen and not less than 100 mm from the walls of the furnace in order to show compliance with the fire load curve. The individual and average values shall be reported.

**During testing**

Video record the area below the specimen to provide visual evidence of explosive spalling. It is understood that this may not be possible or provide clear visual evidence in all furnaces. Use a suitable low strength material on the bottom surface of the furnace that will show physical evidence of explosive spalling. Such material may dent significantly as a result of the spalling. Audio record the test in a manner that explosive spalling can be recorded. This may involve placing the microphone or acoustic sensor on the back side of the test specimen.
Acceptance criteria

If explosive spalling occurs during the fire testing using the proposed time-temperature curves, the concrete mix design will be deemed as inadequate for the final tunnel lining or passive fire protection shall be installed.

Explosive spalling is defined as spalling involving the projection of chips or pieces of concrete from the concrete mass at a high velocity. Explosive spalling does not include chips or pieces of concrete that drop out from concrete mass under gravity alone.

FIRE TEST

During the process of trial fire tests, it is determined the controlling specimen for explosive spalling is the high humidity specimen; therefore, only high humidity specimen were tested. Testing was performed on April 2, 2015 using the “high humidity” specimens performed by CTL Group in Chicago. Figure 11 shows the furnace during a trial run without a test specimen [8]. Gas supply pipes are on the lower left side, the red arrows; silver ducting, the yellow arrows, houses video cameras to see within the test furnace, and horizontal pipes support 6 thermocouples, the green arrows indicate the measurement tips and the green box outlines one of the thermocouples, for measuring and controlling furnace temperatures.

![Figure 11. The furnace during a trial run without a test specimen](image)

Results

During test, no explosive spalling was heard, and no explosive spalling was visually observed or recorded by the video cameras directed into the furnace.

The specimen remained on the furnace for 30 minutes after testing was complete as required, during which time the temperatures of the 16 thermocouples in the specimen were recorded.

Figures 12 to 14 show the post-testing photo for specimen using fire curve NB3, SB1, and SB2, respectively.
Figures 12 to 17 show the average measured temperature vs distance above the fire tested specimen surface using fire curve NB3, SB1, and SB2, respectively. The horizontal axis represents time from start of fire test in seconds and fire test is complete at 240 seconds.
Note: °C = (°F - 32) * 5/9, for all figures below...

Figure 15. Average temperature vs distance above specimen surface, fire curve NB3

Figure 16. Average temperature vs distance above specimen surface, fire curve SB1

Figure 17. Average temperature vs distance above specimen surface, fire curve SB2
CONCLUSIONS

From Figures 12 to 14, no spalling was observed for all tested specimens, even though the surfaces of test specimen have experienced a temperature exceeding 1,500 °F (800 °C). This phenomenon can be the results from the short fire exposure time and the relatively high permeable normal strength concrete characteristic.

From Figures 15 to 17, it is not surprised that no spalling was observed, since the temperature profile along the specimen section is well below the expected spalling temperature, which is about 716 °F (380 °C) for this normal strength concrete. Also observed was the temperature increasing of the specimen with time even the test fire is shut down. This is because the test specimen was left on the furnace for another 30 minutes before it is removed.

This paper describes the rational in providing the concrete fire explosive spalling testing procedure for the Ohio River Bridge East End Crossing Tunnel project. Through the laboratory fire tests, it is proved that with the proposed fire suppressing and tunnel ventilation system, no concrete explosive spalling will occur for the project design fire and no passive fire protection of the tunnel final lining is needed.

ACKNOWLEDGEMENT

The author thanks Dr. Igor Maevski and Yuan Li of Jacobs Engineering for their preparations of the Tunnel Fire Life Safety Report and the Tunnel CFD and Egress Analysis Report to make this unique scheme works.

REFERENCES

Developing a Technique to Predict Concrete Spalling for Design of Tunnel Liner Exposed to a Major Fire Event in a Tunnel

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ABSTRACT

Exposure of a tunnel concrete liner to a high temperature created as a result of fire will severely impact the performance of the liner. Heating up of the liner will result in degradation of strength and stiffness of the concrete and reinforced steel. Moreover, additional stresses and strains occur in the liner as a result of heat exposure which potentially could lead to spalling. These conditions may severely impact the structural integrity of the tunnel and related structures. This paper presents a method to predict the response of concrete liner during a major fire event in a tunnel. As a first step, temperature profile on the liner surfaces was determined using CFD analysis representing a major fire event within the tunnel. Then the temperature profiles were used as input for structural analysis of the liner. Structural analysis includes a model for pore-pressure build-up caused by heating of moisture. The outcome of the model for spalling prediction is presented and compared against the experimental results.

KEYWORD: Concrete spalling, Precast concrete lining, Fire load, Computational Fluid Dynamics, FLAC3D, Concrete pore pressure

INTRODUCTION

As widely known, exposure of a reinforced concrete member to high temperature will severely impact the performance of its components. The heating of components will result in degradation of strength and stiffness of the concrete and reinforcing steel. Moreover, additional stresses and strains will occur as a result of exposure to the heat; hence spalling may also occur. These conditions could severely affect the structural integrity of any reinforced concrete member in tunnels including precast concrete tunnel lining (PCTL). Therefore as a part of tunnel design, structural performance of PCTL during a major fire event requires to be evaluated for exposure to a major fire event within the tunnel. Based on specific requirements of a few recent projects, this paper discusses details of an approach developed to predict concrete spalling for design of tunnel liner exposed to a major fire event. The methodology presented incorporates Computational Fluid Dynamics (CFD) analysis to predict the growth of the fire within the tunnel under different fire scenarios. Fire scenarios include a light rail vehicle (LRT) fire inside the tunnel with and without mechanical ventilation. Mechanical ventilation condition refers to the tunnel ventilation systems’ operation philosophy during the course of fire growth including push-pull, pull-pull or no ventilation condition. The outcomes of the CFD analysis then were used for explicit modeling of the concrete and the reinforcing steel. FLAC3D model (a finite-difference program for engineering mechanics computation developed by ITASCA Consulting Group [1]) was used in the numerical simulations to represent a portion of the tunnel. The model is mechanically restrained against translations normal to the face at its external boundaries except at the top boundary, which is unrestrained. Thermally, the model’s external boundaries are set as adiabatic boundaries, while the temperature at the liner intrados surface is set to a pre-determined temperature extracted from CFD analysis. The intrados temperature will be evaluated and adjusted during the analytical run, in accordance with the temperature development over time during a major fire event. The simulations include an explicit modeling of the concrete and the reinforcing steel. The behavior
of the concrete and steel reinforcement under high temperature was simulated using the models provided in Eurocode 2 Part 1.2 [2] in order to obtain a representative behavior of the PCTL under fire. In addition, pore-pressure build-up caused by heating of moisture in the concrete was also simulated to predict the occurrence of concrete spalling.

OVERVIEW OF THE DEVELOPED TECHNIQUE

Modeling of the fire event
Computational Fluid Dynamics (CFD) was used as a numerical technique to simulate fluid flow, heat and mass transfer subject of this study. After creating the mesh the model was setup using appropriate boundary and initial conditions. The governing equations for fluid dynamics (Navier-Stokes equations) are solved iteratively, until a converged solution is reached over each control volume within the computational domain. In a transient simulation, this process is repeated and convergence verified at each time step.

Modeling has been carried out using Ansys Fluent® (Version 14 maintained and distributed by ANSYS, Inc.). ANSYS Fluent® [3] is a general purpose finite volume based commercial solver which allows for fully unstructured meshes.

A three-dimensional transient analysis approach was used to represent flow of smoke in the tunnel as a result of fire. Turbulence effects were accounted for using a K-ε turbulence model.

Instead of modeling combustion and burning of train components, at each time period, the fire load was matched with a source term to create equivalent heat load of the fire.

Figure 1 provides model representation of the tunnel including the components considered in the analysis: A three-car train within the tunnel, concrete lining, and other tunnel components including: invert, annulus grouting and soil. Fire creates flame and hot gas accumulating close to the upper portion of the tunnel and moving toward the exits on both sides of the tunnel. The heat transfer occurs by the means of radiation (from high temperature surfaces to the concrete lining) and convection (as hot smoke move along the tunnel). Then, conduction directs the transferred heat from the hot smoke to the concrete lining and to the surrounding components, including grouting layer and soil. A temperature boundary condition of 10°C was considered at the upper boundary of the model for the analysis, representing temperature of the soil (ground level temperature). The other boundaries of the model were considered to be no-heat flux condition.

The model developed for CFD analysis accounts for 150 m length of the tunnel. The train has three cars and fire initiates within the middle car and grow within the tunnel.

Figure 1 Model representation of the fire.

The growth of fire within a vehicle was represented by a series of volumetric source elements. Each of these volumes was assigned as a heat and species (soot) source. Fire starts at the middle of the car and then spreads evenly outward until all volumes representing fire within the model are active. The fire is assumed to be contained within one car and does not spread to other cars in the three-car train. The maximum extent of fire spread within the car corresponds to the peak fire load.

Species production is accounted for in the model by specifying volumetric mass production rates as a
function of time for the volume sources defining the fire. For a given heat release rate, the mass production rate is calculated using Eq. (1). In this representation the “species” represent the solid fuel evolved into gaseous form through pyrolysis and consumed during combustion

\[
m = \frac{Q^*}{\eta \Delta H_c},
\]

Where \( Q^* \) is the instantaneous mass production (kg/s/m³), \( \eta \) is the combustion efficiency and \( \Delta H_c \) is Heat of combustion (J/kg). The combustion efficiency is assumed to be equal to 100%.

Determining the load of the fire on the concrete lining

The most critical fire scenario impacting concrete liner is to have a train stopped within the tunnel. The fire originates below the train floor and burns through power and control cables, causing the train to stop in the tunnel between stations. Initial (FHRR) for an under-car fire originating below the train is 1 MW. Then fire grows into the train adopting a medium growth rate for the interior. This medium growth rate, established by NFPA 92B, corresponds to a fire growth rate constant of 11.72 W/s². After 15 minutes, the fire burns through the car floor and grows at a medium fire growth rate until the Fire Heat Release Rate (FHRR) reaches 14.5 MW (the sum of FHRRs of an under-car fire and an interior fire). The flame temperature of a car combusting was assumed to be 1,100°C. The study adopts operational procedures including emergency preparedness procedures and fire plans to guide the actions of all those involved with fire incidents. The potential impact of fire location (within different cars of the train) was investigated by comparing the effects of the air flow blockage by other cars and also back layering effects; it was concluded that burning of the middle car generates the highest temperature on the concrete lining. As for this scenario, the blockage exists downstream and upstream of the middle car. The blockage on both sides of the car undergone fire exposes a larger portion of the concrete lining to higher convection effects. In addition the back-layering effect upstream of the middle exist. Further details for potential impact of fire location on the load on the liner can be found in Ref [4].

The potential impact of ventilation system on temperature profile on the liner was also investigated by performing analysis at different operating condition of ventilation system. The highest concrete lining temperature after 2 hours was determined to be 512°C for the tunnel without having any mechanical ventilation in place. With operation of mechanical ventilation, the maximum concrete lining temperature dropped to 372°C. Compared to the condition in which ventilation system operates, hot smoke for non-ventilated tunnel has a longer residence time to heat up liners. Figure 2 shows temperature profile on the tunnel lining intrados after two hour without mechanical ventilation.

![Temperature profile on the tunnel lining intrados after two hour (No mechanical ventilation).](image)

Figure 3 compares the predicted temperature-time history of the hottest portion of tunnel lining intrados for both cases, with ventilation and without mechanical ventilation. The inputs for the FLAC3D analysis were extracted from these curve. The maximum lining temperature after a two hour
A fire event was predicted to be 512°C without mechanical ventilation and 372°C at the presence of mechanical ventilation.

Figure 3 Temperature-Time history on the tunnel lining intrados for different operating ventilation conditions.

**Heat Transfer analysis through the liner**

The FLAC3D model used in the numerical simulations is depicted in Figure 4; it represents a 6 m long portion of the tunnel liner. The model was mechanically restrained against translations normal to the face at its external boundaries except at the top boundary, which is unrestrained. Thermally, the model’s external boundaries were set as adiabatic boundaries, while the temperature at the PCTL intrados surface was set to a pre-determined temperature. The intrados temperature was evaluated and adjusted during the analytical run, in accordance with the temperature development over time during a major fire event.

FLAC3D solid elements were used to model the ground and the concrete, and linear-elastic cable elements were used to model the reinforcing steel. Each PCTL segment was modeled explicitly, with the PCTL rings connected one to another through sixteen dowels uniformly spaced along each circumferential joint. Compression-only frictional interface elements were provided at the extrados, the circumferential joints, and the radial joints of the PCTL to model the stress transfer between ground and the PCTL and between PCTL segments. Ref. [6] provides further details about FLAC3D model.

Figure 4 FLAC3D Model.
For the purpose of this study, the tunnel springline and the groundwater table were considered to be 33 m and 30 m below the ground surface, respectively. The stratigraphic profile of the soil is listed in Table 1, and the mechanical and thermal properties of the soil are listed in Table 2.

<table>
<thead>
<tr>
<th>Soil Unit</th>
<th>Depth (m)</th>
<th>Tunnel Springline</th>
<th>Groundwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand/Silt</td>
<td>0.0 -14.0</td>
<td>-33.0</td>
<td>-30.0</td>
</tr>
<tr>
<td>Till</td>
<td>-14.0 -29.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand/Silt</td>
<td>-29.0 -54.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Geotechnical Properties.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Till</th>
<th>Sand/Silt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Unit Weight (kN/m³)</td>
<td>16.1</td>
<td>16.1</td>
</tr>
<tr>
<td>Saturated Unit Weight (kN/m³)</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>Elastic Modulus (MPa)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Effective Cohesion (kPa)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Effective Friction Angle (°)</td>
<td>28</td>
<td>32</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Effective Horizontal/Vertical Stress Ratio</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m.°C)</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Specific Heat (kJ/kg.°C)</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion (°C)</td>
<td>15×10⁻⁶</td>
<td>15×10⁻⁶</td>
</tr>
</tbody>
</table>

Loads considered in the analyses included dead loads (in-situ soil stresses and self-weight of the soil and PCTL), hydrostatic pressure, and fire loading. The fire loading was modeled as the intrados surface temperature that varied over the course of the fire event, as illustrated in Figure 3. The duration of the fire was assumed to be two hours.

Figure 5 Development of the PCTL Intrados temperature during a 2 hour Fire

Consideration for pore pressure generation

Heating of moisture in the concrete pores may cause the moisture to undergo transformation from liquid to gaseous phase. This phase change leads to steam pressure build-up inside the concrete. If this internal pressure build-up continues to accumulate, concrete surface will start to spall. In order to simulate this phenomenon, pore-pressure was applied to the concrete elements. Pore-pressure generation in the ground as a result of volumetric straining was considered. A linear elastic-plastic constitutive model with Mohr-Coulomb failure criterion was used to evaluate the mechanical behavior of the ground. In modeling the concrete, FLAC3D’s strain-softening constitutive model was
employed. The cohesion and friction angle of the concrete material were defined using a piecewise-linear hardening/softening function of the plastic shear strain, and the tensile strength was also defined using a piecewise-linear softening function of the plastic tensile strain. These strength parameters, as well as the modulus of elasticity and the thermal properties, were adjusted during the analysis runtime based on the calculated temperature, total plastic shear strain, and total plastic tensile strain, to conform to the concrete stress-strain relationships. To accurately model the behavior of the reinforcing steel, the strength parameters, the modulus of elasticity, and the thermal properties of the linear-elastic cable elements representing the steel were also adjusted during the analysis running time based on the calculated temperature. For all elements, isotropic heat conduction was used to model the heat transfer.

The magnitude of the applied pore-pressure varied depending on the calculated element temperatures, and was derived from the experimental study done by Phan [6]. The variation of the pore-pressure as a function of the concrete temperature is illustrated in Figure 6. Spalling was considered to occur when the concrete element was failing in tension and the maximum shear strain in the element exceeded 0.1 (a large though rather arbitrary chosen value). The spalling element was then deleted, and the element under the spalled element would be subject to the surface temperature. Note that although Phan [6] observed that the pore-pressure varied depending on its location with respect to the heated surface, the pore-pressure magnitude used in the model was assumed independent of its location. Note also that a concrete moisture content of 1.5% was considered.

Provisions of Eurocode 2 Part 1.2 [2] were used to describe the variation in the compressive and tensile stress-strain relationships and in the thermal properties of the concrete and the reinforcing steel under high temperature[5].

**COMPARISON OF MODELING PREDICTIONS VERSUS TEST RESULT**

In order to compare the outcome of developed model to predict spalling using the methodology described in this paper, specimen I-1.5-13-M-5 tested by Phan [6] was modeled. Specimen I-1.5-13-M-5 was a 200×200×100 mm concrete block with a concrete compressive strength of 75.3 MPa and containing 1.5 kg/m³ of 13 mm long polypropylene fibers. During the test, the specimen was insulated on all faces but the front face, to which heat was applied with a rate of 5°C/min. Details of the test setup can be found in Phan [6].
In the study, Phan found that the specimen survived the heating exposure without spalling. The presence of the polypropylene fibers helped in providing an interconnecting network that enabled steam movement through the concrete. The pore-pressure measured during the test is illustrated in Figure 7; this pore-pressure was applied to the concrete elements during the course of the verification study. All other strength, deformation, and thermal parameters were calculated as previously described.

In contrast to what was observed during the test, the model predicted the spalling of concrete after 144 minutes of heating exposure. The variation of the concrete tensile strength, concrete principal tensile stress, and pore-pressure predicted at the concrete surface during the analysis runtime are shown in Figure 6.
Figure 7. As illustrated in the figure, an increase in the surface temperature resulted in an increase in the concrete principal tensile stress. As the temperature increased, the concrete tensile strength deteriorated and pore-pressure was generated in the concrete, in accordance with the prescribed behavior. At 100°C, just before the concrete tensile strength dropped to 90% of the characteristic tensile strength, the concrete tensile stress was predicted to be 2.43 MPa, 85% of the characteristics tensile strength. When the concrete tensile strength dropped, the tensile stress exceeded the strength and redistribution of stress occurred until equilibrium was attained. Redistribution of stress also occurred when the concrete became plastic (i.e. when the tensile stress exceeded the tensile strength and the tensile strength dropped to its nominal residual value). These processes occurred repeatedly throughout the duration of the heating exposure. Spalling was triggered when the sum of the pore-pressure and the tensile stress exceeded the tensile strength; equilibrium could no longer be maintained when this occurred. In the analysis, spalling was predicted to occur when the temperature reached 310°C.

There are three possible reasons that may explain the discrepancy between the experimental results and the analysis prediction. First, due to lack of available information, estimations were made on the tensile strength, modulus of elasticity, and thermal properties of specimen I-1.5-13-M-5 using available empirical relationships. Second, cracks may have developed during the heating exposure. The cracks may have helped in dissipating the pressure build-up faster than the rate of steam leaking through pores alone; such allowance has not been reflected in the model. Third, the pore-pressure magnitude used in the model was assumed independent of its location, in contrary to what was observed by Phan [6].

MODEL PREDICTION AND DISCUSSION

The results of the analyses performed to evaluate the PCTL structural integrity in the event of a major fire are summarized in Table 3. The PCTL forces were calculated by integrating the element stresses across the lining thickness. As indicated in the table, initially, an increase in concrete temperature resulted in an increase in the axial compression and bending moment in the PCTL. The stresses in the circumferential and longitudinal reinforcement, as well as in the ties, also increased. When the concrete has been exposed to heating for 68 minutes, the sum of the pore-pressure and the calculated concrete tensile stress in some portion of the PCTL exceeded the concrete tensile strength. This triggered concrete spalling of the portion, as indicated in Figure 8. Spalling of concrete progressed throughout the remaining duration of heating exposure. The occurrence of spalling reduced the PCTL thickness and thereby increased the flexibility of the PCTL ring. As a result, reductions in bending
moment and the reinforcing steel stresses were predicted as the PCTL was further exposed to heating. The axial compressive force in the PCTL, however, continued to increase with further heating.

Table 3 Maximum PCTL Internal Forces Predicted by the Analysis.

<table>
<thead>
<tr>
<th>Heat Time (min)</th>
<th>Concrete</th>
<th>Steel Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Circ. Axial Force (kN/m)</td>
<td>Circ. Bending Moment (kN/m)</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>min</td>
</tr>
<tr>
<td>0</td>
<td>-1492</td>
<td>-1963</td>
</tr>
<tr>
<td>30</td>
<td>-1369</td>
<td>-2049</td>
</tr>
<tr>
<td>60</td>
<td>-1065</td>
<td>-2151</td>
</tr>
<tr>
<td>90</td>
<td>-1143</td>
<td>-2618</td>
</tr>
<tr>
<td>120</td>
<td>-1029</td>
<td>-2721</td>
</tr>
</tbody>
</table>

Figure 8 Prediction of Spalling at 68 Minutes of Heating Exposure.

Figure 9 PCTL Predicted Axial Force and Bending Moment.
Despite the occurrence of spalling, the PCTL was predicted to be able to sustain the applied loading until the termination of heating exposure at 2 hours. Only the first intrados layer (i.e. the first 50 mm layer exposed to heating) was predicted to spall; no progressive spalling across the lining thickness was predicted. The PCTL internal forces were predicted to still lie within the concrete capacity curve, as indicated in Figure 9, and all reinforcing steel stresses were predicted to remain below the yield strength adjusted to account for the steel temperature.

![Figure 10 Deformation of PCTL due to fire loading only.](image)

The deformation of the PCTL throughout the duration of heating exposure is shown in Figure 10. Prior to spalling, exposure to heating resulted in expansion of the tunnels. Just before spalling occurred, the net diameter expansions (excluding deformation prior to heating exposure) across the springlines and across the crown and invert were predicted to be 1.78 mm and 2.28 mm, respectively. After the onset of spalling, an inward movement of the springline and outward movement of the crown and invert were predicted. At the end of the heating exposure, the net diameter expansion across the springline was reduced to a net diameter contraction of 0.66 mm, whereas the net diameter expansion across the crown and the invert was increased to 4.95 mm.

**SUMMARY AND CONCLUSION**

A model was presented here to predict concrete spalling of tunnel liner exposed to a major fire event in a tunnel:

- Computational Fluid Dynamics was used to predict the growth of the fire within the tunnel under different fire scenarios. Then FLAC3D was used to explicitly model concrete and reinforced steel during the exposure to the temperature determined from fire in the tunnel. The behavior of the concrete and steel reinforcement under high temperature was simulated using the models provided in Eurocode 2 Part 1.2 [2]. In addition, pore-pressure build-up caused by heating of moisture in the concrete was also simulated to predict the occurrence of concrete spalling.

- CFD analysis represented a condition in which the fire was originated below the train and burned through power and control cables, causing the train to stop in the tunnel between stations. Analysis included the effects of radiation from the high temperature flame to the tunnel surfaces and also convection from the hot gas moving along the tunnel surface.

- The potential impact of fire location (within different cars of the train) was investigated by comparing the effects of the air flow blockage by other cars and also back layering effects; it was concluded that burning of the middle car will generate the highest temperature on the concrete lining. The effects of ventilation condition on the fire load of liner was considered. It was determined that the highest load on the liner was corresponded to the condition of not having any ventilation in operation.

- Concrete surface temperature was increased during first 60 minutes of fire toward the predicted maximum value of 512°C without ventilation and 372°C with mechanical ventilation in place.
• Thermal analysis within the liner was performed using FLAC3D accounting for loading determined from CFD analysis defined as the intrados surface temperature that varied over the course of the fire event. Then the results of analyses to evaluate the PCTL structural integrity in the event of a major fire were calculated by integrating the element stresses across the lining thickness. Compression-only frictional interface elements were provided at the extrados, the circumferential joints, and the radial joints of the PCTL to model the stress transfer between ground and the PCTL and between PCTL segments.

• FLAC3D’s strain-softening constitutive model was employed. To accurately model the behavior strength parameters, as well as the modulus of elasticity and the thermal properties, were adjusted during the analysis runtime based on the calculated temperature, total plastic shear strain, and total plastic tensile strain, to conform to the concrete stress-strain relationships.

• Based on the experimental data from Phan [6] and calculated temperature of each element, a pore-pressure was applied to that element during calculation. Spalling was considered to occur when the concrete element was failing in tension and the maximum shear strain in the element exceeded 0.1. The spalling element was then deleted, and the element under the spalled element was subjected to the surface temperature.

• A comparison of the model prediction was presented against the experiment performed by Phan [6] for specimen I-1.5-13-M-5. Although no spalling was observed for this specimen during the test, the model predicted the occurrence of concrete spalling after over two hours of fire exposure.

• The discrepancy between the test result of specimen I-1.5-13-M-5 and the model prediction may be caused by:
  o The difference between the actual concrete properties and the properties estimated using the models provided in Eurocode 2 Part 1.2 [2].
  o The lack of consideration of crack formation during the heating exposure that may have helped in dissipating the pressure build-up faster than the rate of steam leaking through concrete pores alone.
  o The assumption that the magnitude of pressure build-up is independent of its location, in contrary to what was observed in the study performed by Phan [6].

• In the PCTL model, spalling was predicted to occur after 68 minutes of heating exposure. However, the PCTL was predicted to be able to sustain the applied loading and to remain stable until the termination of heating exposure at 2 hours, despite the occurrence of spalling. Spalling depth was predicted to be limited to the first 50 mm layer of concrete exposed to heating.

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Doing the Best with the Resources Available: Tunnel Safety and Security in a Severely Resources Limited World

Arnold Dix
Scientist & Lawyer, CEO ALARP group, Professor (Science Mental Health and Adversity - Subsurface Risks), Disaster School of Medicine, University of West Sydney, Australia

ABSTRACT
A declining global economy with an increased appetite for subsurface infrastructure, coupled with political demands for projects opening by fixed dates, decreased time and financial budgets for system commissioning and integration and a shortage of experienced tunnel professionals means we need new robust ways of safely opening and operating projects. This paper argues that there is increasingly a place for unorthodox approaches to “safe” system opening and operations. It uses the author’s real case studies to support its central finding that in an imperfect world there is a place for a more pragmatic approach for achieving operational safety and asset protection. There is a case for stepping outside the rules to get the job done safely.

KEYWORDS: Compromise, safety, pragmatic, black box engineering, judgement, standards, politics, law, ethics, professional standards, alternative solutions, safe enough, unorthodox solutions.

RESPONDING TO LEGITIMATE DEMANDS
Projects often open before they have been demonstrated to be safe or continue to operate when they are likely unsafe. Increasing complexity of subsurface infrastructure in terms of its intended performance, installed systems, system integration and network integration means it is often hard to determine what is “safe enough”. Projects are increasingly difficult to design, build and operate and degraded economic conditions internationally, a general shortage of experienced technicians and experts, fragile political supporters for projects, complex contractual and legal arrangements, difficult financing arrangements and often hostile critics of projects (for a range of political, economic and social reasons) contribute to complications for professionals when ensuring projects are “safe enough” to operate. This means that there is now a place for, and a legitimate engineering response to unconventional non-compliant safe interim operation and management solutions for tunnels.

THE ETHICAL AND PROFESSIONAL CONTEXT
The primary obligation of all engineering professionals is to protect the societies they serve. This is an ethical obligation and is entrenched within all of our professional registration bodies’ core ethics. [1] This means that an unorthodox approach to operating subsurface infrastructure must abide by the moral and ethical principles which guide us. In other words, to implement an unorthodox solution to deliver a safe subsurface infrastructure it is essential that the alternative solution be robust and justifiable on engineering grounds.

The temptation to “hide” asset functional deficiency, system malfunctions, interoperability failures and the like must be resisted. It is strongly proposed that an alternative solution which lists these deficiencies and suggests appropriate mitigation strategies is the appropriate professional alternative.
By relating each fault or deficiency in the infrastructure to a defined and robust risk mitigation strategy the engineer can properly inform their clients to the risks that are faced and explain robustly the mitigation strategies which are required, the way in which the performance of those mitigation strategies will be monitored and the implementation pathway.

There is no simple “standard” as to how this can be done. What is proposed is to illustrate by example projects which were successfully operated “safely” and in accordance with our strict ethical and moral obligations as engineers and professionals while at the same time neither meeting nor purporting to meet the contractual designs and operational standards that were attended to apply for their use.

**Is there a Standard to Follow?**

For subsurface infrastructure the standards to be applied change regularly. Our understanding and expectations of what constitutes safe subsurface infrastructure changes quickly.

For example, NFPA 130 2017 edition will supersede 9 earlier versions since 1990 [2] [3] [4] [5] [6] [7] [8] [9] while and NFPA 502 2017 will supersede 6 earlier versions since 1990 [10] [11] [12] [13] [14] [15] [16]. PIARC has publishes new documents regularly, in fact some 30 key documents in the last decade and one half. [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36] [37] [38] [39] [40] [41] [42] [43] [44] [45] [46] [47], and sovereign countries and states are regularly producing their own documents and standards for local consumption while specific projects specify bespoke requirements on a project by project basis.

It is clear that there is no shortage of rules and regulations. What constitutes “safe” or “acceptable” varies in time and space as our knowledge and appreciation for what constitutes acceptable risk ebbs and flows.

These “Rules” become entrenched in the framework of project deliverables, requirements and outcomes. Each project capturing aspects in its requirements of the agreed wisdom at the time of its inception. But, in the face of legitimate demands – there can be other ways to achieve project safety.

**LEGITIMATE “REAL LIFE” DEMANDS**

At the beginning of a project proponents (usually politicians) secure the necessary arrangements for funding and require parties to undertake certain promises as to project performance and completion date. Inevitably these requirements are entrenched in contractual promises or legislative requirements and are linked to terms of political office. Failure to meet these dates and requirements will almost certainly result in severe financial consequences for all parties involved in a project and likely severely impact the political supporters of the project. Within these contractual frameworks are entrenched the “Rules”. These technical rules usually set out what is technically required to be achieved to open and operate the project.

In 2003 it was suggested that these political risks may be a far greater threat to tunnel safety than residual technical risks.[48] 13 years later the political demands upon technical and engineering professionals to develop new methods to achieve a “practical” safe subsurface infrastructure operation are even more acute.

In short it must be acknowledged that despite the contractual and regulatory arrangements projects will often open despite not meeting their contractual and technical obligations in order to meet overarching political or operational objectives.
In summary:

I. In the absence of genuine support from the engineering and technical community the projects will still open
II. It is incumbent upon us as a technical community to inform the client of the risks and, where there is no alternative, to use our best endeavours to develop alternative solutions to open or maintain operations.
III. There are a range of techniques to achieve safe operations in such degraded and demanding circumstances
IV. The method by which such alternative solutions are deployed will vary from time to time and place to place but must be the subject of the same rigor as would a conventional solution
V. Close monitoring of the alternative solution is required
VI. Endorsement of decision makers to the alternative solution is mandatory
VII. Such alternative solutions usually deliver a time limited safe operational period.
VIII. Each project must be viewed on its own merits

EXAMPLE1: METRO OPERATION – IMMINENT THREAT OF TERRORIST ATTACK

A metro system received intelligence information that as a result of the visit and of a dignitary a terrorist attack was likely. The metro system comprised several underground stations within a CBD area. Detailed analysis of the metro system revealed that the operational control systems were vulnerable to single point failure and that there was little knowledge or capability within the metro to respond quickly and effectively in the event of a fire or other intentional harm event within the metro.

Options available for the management of this issue included:

I. Shut the metro
II. Operate the metro knowing that the response would be bad at best and in the alternative probably contribute to the nature and extent of the damages inflicted
III. Develop an alternative strategy to operate the metro

Field investigation of the operational performance of the ventilation and communication systems revealed that:

I. The knowledge of the ventilation system had been lost to the corporation and was not held by any of the existing operators
II. There was no time to train the new operators on how to use the systems in a range of emergency scenarios
III. Full scale testing of the ventilation system revealed that it did not perform as it was understood by the operator

The Response

I. A pragmatic analysis was conducted of the underground station network
II. Various ventilation configurations were trialled and the resultant ventilation regimes documented
III. A single “emergency” mode was created
IV. The single mode was “hard” encoded into each of the motor control drives for the metro network
V. A new “soft” emergency mode was documented
VI. A new emergency mode procedure was created and taught to the existing operators
VII. The new mode was taught to emergency services personnel via a simple operational procedures
Execution

I. The simple mode of execution was activated prior to the event that was considered the likely target for the terrorist attack
II. The emergency mode was maintained for one week without mode change
III. The strategy for all stations, staff and emergency services was simplified.

Conclusion

At the end of the event (for which there was no terrorist attack) the mode was soft encoded within the system for the metro and is now used as their primary emergency mode.

Discussion

This simple and robust approach to dealing with the management of an existing metro system in the face of a credible risk of attack highlights the importance and place for alternative engineering solutions which meet and exceed our requirements as professional engineers and professionals.

By finding a single mode of operation and ventilation operation, and removing the need to activate or manage it in an emergency, removed all of the risk associated with detection and implementation of an emergency mode. Furthermore by having the emergency mode run for the entire period of the event, all personnel became familiar with what this meant from an airflow point of view. This meant that all training for all personnel, whether railway related or emergency services was in the context of understandable emergency airflows and a well understood evacuation and emergency response plan.

This alternative solution was endorsed by the client and now forms a robust option for emergency response within that major city. This is an example of an alternative solution which does not meet the requirements of existing standards or literature but which nonetheless discharges our obligations as professionals.

EXAMPLE 2: STRATEGIC ROAD TUNNEL

A 5 kilometre trans border road tunnel had to be opened by a certain date in order not to disturb a planned presidential election and stabilise regional security interests.

The tunnel was not complete. The tunnel has no normal lighting, no communications, no supervisory control, no proper road surface, no administrative authority and no tunnel operator.

Method

An analysis of the likely mix, number and nature of traffic flow in the tunnel if it was open was undertaken. A climatic analysis of the conditions between the two ends of the tunnel was undertaken and an informed view of the likely predominant air flow direction ascertained. An analysis of the capacity of the installed jet fans was conducted as was a review of their controllability. A review of the tactical capabilities of the local emergency services was undertaken and a review of their capacity to respond to an emergency prepared. From this analysis it was clear that:

I. There would likely be a strong predominant wind flow in one direction through the tunnel
II. There was no possibility of remote or even local control of the jet fans other than in a simple individually operated mode
III. There was no prospects of communications being implemented in the tunnel
IV. There was no possibility for searching all vehicles using the tunnel for dangerous goods etc
V. There was no possibility of regulating what type of vehicles went through the tunnel
VI. The local emergency services were neither trained nor appropriately equipped to deal with an incident in the tunnel
VII. If the tunnel did not open the alternative route posed a real and serious risk of fatality as it was via a poor quality and long road

**Interim Operational Strategy**

An alternative safe operational solution was developed.

I. Ventilation – a ventilation strategy which maintained an air flow in one direction only (with mechanical assistance) was developed with maximum air speeds identified and maintained through manual activation of installed jet fans

II. Traffic flow was restricted to convoys in alternative directions

III. The convoys were limited in length and the types of vehicles divided and arranged in increasing level of risk. i.e. passenger vehicles first, buses second, trucks and conventional vehicle third, fuel tankers and military equipment fourth

IV. Vehicles were inspected externally before entering the tunnel for fitness to pass

V. Special emergency services personnel were trained (with assistance from UN firefighters)

VI. Special light vehicles fitted with rapid intervention firefighting equipment were prepared and led the convoy from the front and followed the convoy from the rear

VII. Only one convoy through the tunnel at a time

VIII. External firefighting and emergency vehicles outside the tunnel on standby

IX. In the absence of communications convoys could only enter the tunnel when after arriving convoy had exited

X. In the event that no convoy exited the tunnel within a predetermined period of time (and in the absence of smoke) emergency responders would enter the tunnel to conduct a survey and offer assistance if required

**Outcome**

The tunnel was opened “on time” and the elections were held without incident. The tunnel operated safely without incident. The achieved level of safety within the tunnel was likely superior to that which would have been achieved under a technically “compliant” operational regime in accordance with the contractual, regulatory and standards requirements. The clients were content. There was the necessary sign off required to show that expert judgement had been utilised to develop the alternative solution and that which had occurred was reasonable and professional.

**EXAMPLE 3: ROAD TUNNEL – SAFE OPERATIONAL REGIME REQUIRED ON AN INTERIM BASIS**

**Circumstances**

A short strategic two tube multi lane road tunnel was complete but contractors had demobilised several years earlier and there was no informed corporate knowledge of how to bring the tunnel into operational readiness. A review of the systems revealed that the supervisory controls had not been built. Sub systems were installed on an incremental basis and had not been integrated. There was a reluctance for any party to take responsibility for the opening and operation of the tunnel but there was a real and immediate need to open it safely.

**Method**

The following approach was implemented to open the tunnel promptly and safely.

I. Conduct a system operability and function check.

II. Develop an interim operationally safe system

III. Train and exercise necessary staff on interim operational regime

IV. Operate
Analysis of the tunnel revealed that there was enough installed ventilation capacity to establish the necessary longitudinal velocities to manage smoke in the case of an emergency but there was no overarching control system to operate the jet fans and there were existing faults that rendered the direction of operation of several of the jet fans wrong and a lack of system integration.

Analysis of the CCTV, thermal, smoke and gas detection alarm systems revealed that they were inoperative, non-integrated, and mostly not properly commissioned.

There was no workforce.

Analysis of the system revealed that at the PLC level there was a way to sequentially operate the systems within the tunnels based upon low level programming. This system involved manual activation of thermal alarms – originally designed for fire alarm testing.

A detailed series of exercises revealed that reliable activation of the thermal alarm system manually would trigger a controlled emergency ventilation response by the installed ventilation system coupled with satisfactory emergency lighting and lane use control changes.

**Interim Operational Strategy**

An interim operational procedure was developed and staff trained to operate the tunnel in a degraded mode. Dozens of exercises were undertaken with the tunnel operational staff and local emergency services in order to ensure that a robust system of operation could be demonstrated. The robust system of operation was implemented and demonstrated to be effective over a range of real traffic incidents and during multiple emergency exercises.

**DISCUSSION**

Each of the three examples cited above are real. While their identity are not disclosed and their details have been obscured in order to maintain client confidentiality, they illustrate that there is a place for “alternative” unconventional, extraordinary engineering to deliver safe operational solutions for tunnels which are distressed for a range of legitimate reasons.

While it is traditionally considered outside the scope of engineering to certify as safe a tunnel which does not comply with its contractual, regulatory and standards requirements it is increasingly a requirement of engineers to deliver a safe tunnel in such degraded conditions. A robust approach to delivering the fundamental requirements for safety is therefore required. The procedure suggested in this paper is not strict but reflects how the ethical and professional obligations of an engineer can be discharged in degraded conditions.

Although only briefly discussed in this paper, the use of “black box” engineering where the detailed understanding of why the systems operate in a particular way is not understood but robustly demonstrating a particular output in the event of a particular input is, it is submitted, an acceptable method for delivering short term safe tunnel operations in extreme circumstances. What is proposed in this paper is no substitute for performing our professional service “to the letter” of contracts, standards and regulatory requirements. However, in the face of not negotiable “will open anyway” constraints with projects it is our obligation as engineers to discharge our duties professionally and ethically by noting the deficiencies that we are aware of and developing robust operational risk mitigation strategies.

Coupled to these alternative solutions must be ways of measuring our performance and the determining when the alternative strategy is no longer acceptable or requires further adjustment.

Reference to the standards, contracts and regulations may often form the basis for defining what does and does not constitute acceptable practice. However, as engineers, we have the capacity to develop alternative solutions in response to adversity. How we professionally respond to adversity defines our
level of professionalism and helps us rise above merely delivering a “recipe” from a set of standards to delivering alternative safe solution for the overall protection of our communities.

REFERENCES


47. PIARC Technical Committee 5 Road Tunnels., "Fire and Smoke Control in Road Tunnels". *World Road Association Journal*, 05.05.BEN, ISBN2-84060-064-1, p.290, 1999.
Towards a Risk-Informed Approach for Specifying Design Fire Size in Transit Tunnels

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ABSTRACT

Tunnel ventilation system designs for passenger rail, metro and Light Rail Transit tunnel projects presently assess the worst case fire scenario using hazard analysis, followed with a design to control the resulting predicted smoke and heat. The probability of occurrence is given little consideration. Recent theoretical and experimental research has identified the potential for larger fires. This suggests a need for an increase in ventilation capacity for designed systems. In addition, an increase in calculated critical velocities has been identified. These developments take place against a backdrop of ever-improving fire performance of rolling stock. Real-world instances of worst case fires are becoming rarer as older vehicles are removed from service and new vehicles replace them, and societal changes such as smoking bans are implemented. Statistical surveys of tunnel fires show that nearly all fire events are minor in nature. Studies of initiating events suggest that extremely large ignition sources are required to initiate the worst case fires typically used for sizing tunnel ventilation capacity. These initiating events can be unrealistic, particularly when rolling stock fire performance standards are considered. Additionally, the adoption of on-board fixed fire-suppression systems, while still in its infancy, offers the prospect of greater ability to combat an initiating event before it has the opportunity to spread significantly. Can a more holistic, risk-informed, approach reasonably be used to reduce the ventilation capacity without effectively reducing fire and life safety? Such an approach could yield significant benefits for owners and projects. This paper reviews current industry practice in the development of tunnel ventilation capacity, current vehicle fire resistance standards, and fire incident data. It proposes a path towards a risk-informed approach to fire size definition, with analogy to quantitative risk-informed approaches utilised in other sectors such as road tunnels, implementing probability analysis of fire risk and initiating events. The issue of risk acceptance criteria will be examined and ideas for establishment of suitable criteria will be discussed. Examples will be presented to support the proposal and a way forward for developing the proposal further will be identified.

KEYWORDS: Tunnel ventilation design, rail, metro, Light Rail Transit, LRT design fire size, risk-informed approach

INTRODUCTION

A key fire safety system in a fixed guideway transit tunnel is the mechanical emergency ventilation system. Correct sizing of the system capacity is therefore of critical importance in achieving the fire safety objectives for the tunnel.

Research, both theoretical and experimental, has tended over time to identify the potential for larger passenger train fires than previously envisaged. Prescriptive tunnel safety standards and project design guidelines have shown a trend of using increasing design fire sizes for sizing tunnel ventilation system (TVS) capacity. In general, current design practice for TVS utilises hazard analysis to assess the required capacity, regardless of the probability of occurrence, and regardless of the cost implications for the project.
However, this practice runs counter to improvements in the fire performance of rolling stock, prompted by the adoption of standards such as EN 45545, BS 6853, NFPA 130 and DIN5510. These standards control likelihood of ignition of materials used in construction, suggesting that the probability of large fires involving materials used to construct new rolling stock should be expected to be lower than with historical rolling stock. Furthermore, the recorded incidence of serious fires on trains in tunnels is low, with available data suggesting that such events are statistically rare. Additionally, the nascent adoption of new technologies such as on-board fixed fire-fighting systems (FFFS) increases the potential for restricting the fire growth early in the fire’s development.

This raises the question of whether the current practice for TVS design remains best practice, or whether there is an opportunity, by introducing risk assessment techniques, to deliver benefits to the project and to the operator by improving the methodology used to size the TVS. This paper examines the issues and proposes a possible implementation of such an approach.

ROLLING STOCK

The largest potential fuel source in a transit tunnel is the train itself. Hence the worst case fire event is typically determined by the fire potential of the rolling stock in question. This should account for numerous factors, such as the type and age of the fleet(s) that will use the tunnel, construction of the rolling stock, motive power, type of usage, any fire-safety systems present on the vehicles, etc.

Fire performance standards

Jurisdictions worldwide have adopted stringent fire performance standards for rolling stock. These include BS 6853[1] in the United Kingdom, EN 45545[2] in the European Union, which also has DIN 5510 [3] in Germany, and NFPA 130 [4] in the United States. These standards have also been adopted by countries that lack their own standards.

Each standard specifies that materials selected for use must successfully resist a specified initiating fire event without allowing spread to the material. Cone calorimetry verifies the properties of each specific material. Each standard varies slightly, but the general range of initiating event is in the region of 100-150kW, with the latter forming an upper limit to the set of standards. Furthermore, each standard specifies that the passenger compartment must be fire-separated from the under-floor equipment such as traction power, bogies, ancillary equipment, etc.

On-board fire-fighting systems

Traditional on-board fire-fighting systems have been limited to portable fire extinguishers that could be used by staff or members of the public. However, on some networks, these were subject to vandalism and/or mischief, and numerous operators, particularly in the United Kingdom, removed them from active service.

More recently, interest has grown in the implementation of on-board fixed fire-fighting systems (FFFS). The intent is to control the growth of the fire at an early developmental stage by rapid deployment of the system. There is a growing body of work in this area. For example a recent paper by Ong et al[5] suggests that early deployment of an on-board FFFS could reduce the post-deployment peak HRR to 1MW from an unsuppressed peak HRR of 10MW. Italy has recently made the installation of such systems mandatory on all new rolling stock for the Italian rail network. While implementation is minimal at present, the rate of implementation will extend significantly in future.
HAZARD ANALYSIS: ASSESSMENT OF DESIGN FIRE SIZE

Design fire size for rolling stock is calculated using a hazard analysis methodology. Annex E of NFPA 130[4] gives guidance for a typical process for determining the design fire size. It can be summarized as (i) define the context, (ii) define the scenario, (iii) calculate the hazard, and (iv) evaluate the consequences. The process is nominally deterministic, but requires a great deal of knowledge and judgement to be exercised by those involved. At every step decisions have to be made regarding appropriateness, accuracy and acceptability. The process does not assess the probability of occurrence for the postulated emergency. Specific types of hazard-based assessment are listed below. The techniques described are, in general, typical current practice and are currently judged by consensus to provide the best estimate of a worst case fire appropriate to the design of the TVS.

**Full scale fire test data**

Full scale fire testing is not typically used to size the design fire. This is for a number of reasons, including the cost of conducting such testing on the rolling stock, which may not be constructed; logistical issues such as selection of scenarios and initiating events to replicate in full scale tests; and uncertainties in measurement. Additionally, such is the expense of such a test, it is found that often the initiating event is deliberately made more onerous to ensure the train progresses to full involvement if the original initiating event is not successful in achieving this. These tests give an idea of the general potential magnitude of the worst case fire.

There is now an extensive set of full scale fire research that includes both entire rail vehicles and items and materials from rail vehicles. Ingason[6] provides a useful summary of full scale tests through 2006. These may be augmented by significant tests by Lonnermark et al[7] and Hadjisophocleous et al[8]. Table 1 summarises key data from these references.

<table>
<thead>
<tr>
<th>Type of vehicle, test series, test no., (U=) longitudinal ventilation [m/s]</th>
<th>Calorific value ((GJ))</th>
<th>Peak HRR ((MW))</th>
<th>Time to peak HRR ((min))</th>
<th>Peak temperatures in tunnel ceiling (\left({^\circ}\text{C}\right))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joined railway car – 2 half-cars, 1 aluminum, 1 steel, EUREKA 499, (u=6)–8/3–4m/s</td>
<td>55</td>
<td>43</td>
<td>53</td>
<td>980</td>
</tr>
<tr>
<td>German ICE passenger railway car (steel construction), EUREKA 499, (u=0.5)m/s</td>
<td>63</td>
<td>19</td>
<td>80</td>
<td>830</td>
</tr>
<tr>
<td>German IC passenger railway car (steel construction), EUREKA 499, (u=0.5)m/s</td>
<td>77</td>
<td>13</td>
<td>25</td>
<td>720</td>
</tr>
<tr>
<td>British Rail Class 415 passenger railway car (steel construction)(^a)</td>
<td>NA</td>
<td>16</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>British Rail Sprinter passenger railway car, fire retardant upholstered seatings, steel construction(^a)</td>
<td>NA</td>
<td>7</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>METRO Project, original interior[7]</td>
<td>NA</td>
<td>77</td>
<td>12.7</td>
<td>1081</td>
</tr>
<tr>
<td>METRO Project, refurbished interior[7]</td>
<td>NA</td>
<td>77</td>
<td>118</td>
<td>1118</td>
</tr>
<tr>
<td>Hadjisophocleous et al, train car[8]</td>
<td>Est 50</td>
<td>32</td>
<td>18</td>
<td>NA</td>
</tr>
<tr>
<td>METRO</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>German subway car (aluminum construction), EUREKA 499, (u=0.5)m/s</td>
<td>41</td>
<td>35</td>
<td>5</td>
<td>1060</td>
</tr>
<tr>
<td>German metro steel car, EUREKA 499, (u=0.3)m/s</td>
<td>33</td>
<td>NA</td>
<td>NA</td>
<td>630</td>
</tr>
<tr>
<td>Hadjisophocleous et al, metro car[8]</td>
<td>Est 23</td>
<td>53</td>
<td>2.5</td>
<td>NA</td>
</tr>
</tbody>
</table>

\(^a\) Test report was confidential and no information was made available on test set-up, test procedures, measurement techniques, ventilation, etc.

While the range of peak HRRs recorded is diverse, the data is conclusive that significant fires can occur with rail and metro/ Light Rail Transit (LRT) vehicles given the correct circumstances. In
particular, the more recent data from [7] and [8] has caused a general re-evaluation of potential rolling stock fire sizes.

**Initiating events: Luggage fire test data**

Test data for combustion of potential ignition sources has been collected by a number of different projects for the purposes of assessing and/or verifying a design fire size. However the data thus acquired has traditionally been treated as confidential by the projects, and consequently little of this data has been openly published.

Test data in this category typically investigates larger fires than those specified within the design standards. Larger initiating events fall into the generalized categories of ‘luggage fires’ or ‘trash fires”, while extreme initiating events (e.g. Daegu fire arson attack) can be generalized as arson/terrorist attack scenarios. The UK Crossrail project commissioned a series of tests of burning luggage in 2010[9]; the results are cited with the permission of Transport for London and Crossrail, and are summarized here. A 3m cone calorimeter was used to assess peak heat release rates (HRR) for a variety of luggage, each piece fully packed to represent the state of the luggage when in use. All luggage pieces were purchased new for the test i.e. they satisfied the applicable fire safety standards for luggage at the time of the test. Six tests were carried out, five of which burned a single piece of luggage, and one that burned two pieces of luggage arranged vertically side by side. Types of luggage ranged from a laptop computer bag to large travel suitcases.

In each case, the spread of fire following ignition was quite slow, and in some cases achieving ignition was difficult. In all cases the peak HRR was not observed until approximately 600s after ignition. The observed peak HRRs for the single pieces of luggage ranged from 57kw to 158kw, depending on the size and type of luggage. The peak HRR in the 2 pieces test was observed to be 284kW. Typical fire development behaviour consisted of a period (anywhere from 3 to 10 minutes) of smouldering at an HRR of the order of 10kW, followed by a growth to peak HRR over a period ranging between 3 and 6 minutes. Peak HRR was sustained for a time that varied significantly from test to test (between approximately 2 minutes and 6 minutes). This was followed by steady decay until the termination of each test. Depending on the test, the HRR decayed to a value approximately between 20% and 50% of the peak HRR. All tests were terminated prior to self-extinguishment.

As an example, the 284kW test smouldered at less than 10kW for 200s, then ramped up, reaching 250kW at approximately 560s after ignition and reaching peak HRR of 284kW at approximately 580s after ignition. The fire was sustained above 200kW until approximately 680s after ignition, following which the fire decayed to below 100kW by approximately 1000s after ignition. The fire then further decayed to a quasi-steady-state level of approximately 70kW by approximately 1200s after ignition. Following this the fire continued to decay at a slower rate until the test was terminated just after 1800s from ignition.

In each case, this smoulder/growth/peak/decay pattern was observed, and none of the tests resembled a ‘persistent’ fire behaviour wherein the HRR remains constant throughout. Of particular note is the consistency of the smouldering period, and the lengthy growth period. The 284kW case was the fastest to reach peak HRR, all others took longer. Additionally, the report repeatedly notes the difficulty experienced in achieving ignition of the luggage.

The data surveyed suggests that the fire growth rates typically used for initiating events in the hazard assessments of train vehicle fires represent a very conservative assessment of the likely fire growth rate of an actual initiating event.

**Calorific value method**

A common method of assessing the peak HRR of a rail vehicle fire is to determine the calorific value of each component part of the vehicle and sum the total. This has the advantage of being simple to calculate, provided the materials have been suitably tested. However it does not account for the fact
that different components may be consumed at different times and at different rates, depending on the fire spread mechanics and the materials’ fire resistance. This method eliminates much of the subjectivity inherent in other hazard analysis techniques, as initiating events, scenarios, etc are not considered. Instead it is assumed that, through some unspecified set of circumstances, the vehicle is fully involved. However the method does so at the expense of accuracy of representation of the fire and is likely to lead to conservative estimates of design fire size.

**Computational simulation**

The advent of inexpensive large-scale parallel computing hardware and reliable computational fluid dynamics tools, such as FDS, CCM+, CFX, Fluent and others, has led to the feasibility of simulating the spread of fire within a rail vehicle. This requires much skill from the practitioner but offers potentially the greatest accuracy in prediction of the worst case fire. However the method is subjective, being dependent on simulation quality, scenario selection and initiating event selection.

This method currently provides the potential for the most accurate determination of the design fire size, provided that (i) the analysis is carried out according to industry best practice; (ii) that the simulated scenarios have been carefully selected; (iii) that initiating events have been chosen carefully to replicate real world hazards, and, most importantly, (iv) that the process is adequately peer reviewed.

**RISK ASSESSMENT**

However, the probability of occurrence of train vehicle fire event is not addressed. This failure to address probability means that no proper assessment of the risk is carried out. This is in marked contrast to the situation in road tunnels, particularly in Europe, where the road tunnel fire disasters of the late 1990s and early 2000s triggered a large amount of investigation and development of risk management techniques for highway tunnels. References [10]-[14] give a sampling of the work undertaken to implement guidance for risk assessment in the road tunnel sector.

It is also in contrast to other industries such as the energy (oil and gas) sector, where risk management forms an essential part of the design and approvals process. References [15]-[17] are examples of regulatory guidance documents that are used within the energy sector to set guidance for risk analysis.

Additionally, there are standards available that provide guidance on fire safety risk assessment, such as NFPA 551[18].

There are four steps to a probabilistic risk assessment:

- Step 1 – Probability Analysis
- Step 2 – Consequence Analysis
- Step 3 – Risk Estimation (Individual Risk and Societal Risk); and
- Step 4 – Comparison with Risk Acceptance Criteria

The first step, probability analysis, can be undertaken via a number of methods: historical data analysis, fault tree analysis, event tree analysis and human reliability analysis. As these techniques are susceptible to uncertainties in the probability estimation it is important to recognize this and exercise due care in the development of the probability analysis.

To illustrate how probability analysis could be used to develop a risk assessment for train fires, two examples are given here.
Fire incident data – probability analysis

Here, two studies of historical data of fire occurrences on rail networks are used to develop probabilities for train fires.

**UK - Statistical Survey of Fires on Trains**

The UK Railway Safety and Standards Board (RSSB) carried out an extensive statistical analysis of the occurrence, causes and consequences of train fires over the period 1992-2000[19]. The total number of fires observed on trains in service was 2911 of which 2266 occurred on passenger trains. Out of this total, 22 had a tunnel listed as the location, however only 5 were definitely confirmed as having occurred in a tunnel. In the remaining 17 cases, the "tunnel location" was used due to the reporting system listing the tunnel as the nearest reportable location, even though the fire actually occurred outside the tunnel. There was one case where a fire occurred outside a tunnel portal and smoke was blown by wind into the tunnel. The following data analysis is inclusive of all fires recorded in the report, i.e. it is not limited to fires in tunnels.

Eight "significant events", i.e. major incidents, were recorded during this time, one of which was the Ladbroke Grove disaster of October 5, 1999. This occurred when two passenger trains, one High Speed Train (HST) and a Diesel Multiple Unit (DMU), collided and ruptured the DMU's fuel tank with a subsequent ignition of the escaping fuel oil. This accident resulted in 31 fatalities, a number of which were due to the collision, however some were due to the effects of the subsequent fire. The exact number of fire-related deaths however was not stated by the report, however it is understood that 30 of the 31 fatalities were due to the collision, and only 1 due to the fire itself.

Apart from the Ladbroke Grove fatalities, the total number of train fire-related fatalities over the period studied was 1 passenger (1995-96) and 1 "other person" (1996-97). The latter was a vagrant who had entered the toilet of a train stabled in a station and who was fatally injured when Fire Brigade personnel entered the toilet. There was 1 major injury to a passenger (1995-96) over the same period. There was a total of 16 minor injuries to passengers and 131 minor injuries to railway staff, most of which were related to "smoke inhalation".

The data showed that 44% of all train fires and 56% of passenger train fires were arson-related. For Electric Multiple Units (EMU) the percentage was even higher: 75% of fires on EMUs were arson-related. Technical causes accounted for 39% of all train and rail vehicle fires. Non-EMU types accounted for 77% of the technical-cause fires over the period studied. Reference 19 also found that the risk of fire from train faults is generally higher for diesel and diesel-electric traction-powered types of rolling stock than for electrical traction-powered rolling stock.

The RSSB report also presented normalised rates of fire occurrence for passenger train traffic and for all types of train traffic. Over the period studied, passenger train fire rates averaged 1.14 fires per million train miles (PMTM), varying between an annual low of 0.95 fires PMTM to an annual high of 1.23 fires PMTM. For all types of traffic the rate averaged 1.31 fires PMTM, varying between an annual low of 1.21 fires PMTM to an annual high of 1.41 fires PMTM.

If a "serious fire incident" is defined as one resulting in major injury/injuries or fatality/fatalities, then it can be seen that there were no more than 4 of these reported over the period studied:

- Ladbroke Grove collision and subsequent fire
- Fatality of single passenger in 1995-96
- Fatality of vagrant in 1996-97
- Major injury to passenger in 1995-96
Note that the report does not state whether the 1995-96 major injury and fatality were part of the same incident. It is assumed that they were in two separate incidents. Thus over the period studied, the ratio of "serious fire incidents" to all train fires was \( \frac{4}{2911} = 0.14\% \) of all train fires in the period. Thus the normalised rate of occurrence for a "serious fire incident" (all causes) occurring anywhere on the network was as follows:

- Passenger trains = \( 0.14\% \times 1.14 \text{ fires PMTM} = 0.0016 \text{ serious fires PMTM} \)
- All train types = \( 0.14\% \times 1.31 \text{ fires PMTM} = 0.0018 \text{ serious fires PMTM} \)

This assumes that train fires are no more or less likely to occur on passenger trains than on all types of trains. If we further assume that "serious fire incidents", based on the RSSB definition, are no more or less likely to occur in tunnels than on the surface network, then the probability of a “serious fire incident” in a tunnel would be:

- Passenger trains = \( \frac{5}{2911} \times 0.14\% \times 1.14 \text{ fires PMTM} = 2.74 \times 10^{-6} \text{ serious fires PMTM} \)
- All train types = \( \frac{5}{2911} \times 0.14\% \times 1.31 \text{ fires PMTM} = 3.15 \times 10^{-6} \text{ serious fires PMTM} \)

Note that this number encompasses fires that occurred on all types of train vehicles (EMU, DMU, etc). The report did not quantify the annual train-mileage figure for EMUs only, so it is not possible to isolate a normalised fire probability for EMUs only from the data presented in the report. The normalised figures presented are thus derived from the data for the whole passenger fleet.

More recent data from the RSSB on number of train fires is found in Reference 20. This data lacks the detailed breakdown found in Reference 19 but it can be seen that the incidence of fires (all of which are classified as ‘Not Potentially High Risk’ by the RSSB) has decreased by 88% over the past fifteen years, from 263 incidents in 2001-02 to 31 in 2013-14, as seen in Table 2.

**Table 2. RSSB Passenger Train Fire Data, 2001-2014 [20]**

<table>
<thead>
<tr>
<th>Reporting Period</th>
<th>No. of Fire Incidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001/02R</td>
<td></td>
</tr>
<tr>
<td>2002/03R</td>
<td></td>
</tr>
<tr>
<td>2003/04R</td>
<td></td>
</tr>
<tr>
<td>2004/05R</td>
<td></td>
</tr>
<tr>
<td>2005/06</td>
<td></td>
</tr>
<tr>
<td>2006/07R</td>
<td></td>
</tr>
<tr>
<td>2007/08R</td>
<td></td>
</tr>
<tr>
<td>2008/09R</td>
<td></td>
</tr>
<tr>
<td>2009/10R</td>
<td></td>
</tr>
<tr>
<td>2010/11R</td>
<td></td>
</tr>
<tr>
<td>2011/12R</td>
<td></td>
</tr>
<tr>
<td>2012/13R</td>
<td></td>
</tr>
<tr>
<td>2013/14</td>
<td></td>
</tr>
</tbody>
</table>

**USA Data**

The United States through the Federal Transit Administration’s (FTA) National Transit Database (NTD) catalogues incidents recorded on public transit in the United States. The most recent report [21] covers data from 2002-2014. The reporting methodology is different from the RSSB report in a number of ways.

First, data is recorded for all types of public transit, including buses, trams, LRT, heavy rail, etc. Second, the criterion for reporting an incident is different. In particular, the criterion for definition of a
The ‘major’ incident is different. Third, the data does not record the number of casualties in each major incident. Last, the data does not record the casualties for each type of incident, rather only the total number of casualties is recorded.

The NTD data defines a ‘major’ incident as per the definition in the NTD Safety and Security Reporting Manual 2015[22] as follows:

- A fatality has occurred
- 1 or more persons require immediate transport away from the scene for medical attention
- Estimated property damage is in excess of $US25000
- An evacuation for life safety reasons is required

So, in contrast to the definition of a ‘significant event’ in the RSSB data, an incident may be deemed ‘major’ in the NTD data even if no casualties are sustained. Transport for medical attention does not ensure that the person is eventually found to be a casualty, and certainly does not ensure that the person is a major casualty.

For all types of transit vehicles that are covered by NFPA 130 definitions, i.e. ‘fixed guideway transit and passenger rail’ the normalised rate of occurrence of fires resulting in any kind of fire incident was 10.586 incidents per million train revenue miles (MTRM). For LRT types only, the normalised rate of occurrence was 1.069 per MTRM. It should be noted that the ‘all types’ rate of occurrence is skewed by the heavy rail category, which contains the vast majority of fire incidents recorded on the US public transportation network. The LRT-only figure of 1.069 per MTRM is comparable to the 1.14 incidents PMTM for passenger rail observed in the RSSB data.

For all types of transit vehicles that are covered by NFPA 130 definitions, i.e. ‘fixed guideway transit and passenger rail’ the normalised rate of occurrence of fires resulting in a ‘major’ incident was 0.1298 incidents per MTRM. For LRT types only, the normalised rate of occurrence was 0.1174 per MTRM. At first glance these rates appear to be significantly higher than those observed in the RSSB data, however the NTD’s broader definition of a major incident needs to be taken into account when analysing the data.

To attempt to get a better correlation between the US and the UK data, we can look at the number of fatalities recorded in the US LRT-only data. The normalised fatality rate on US LRT vehicles for the period is 0.01532 fatalities per MTRM. No data is supplied to allow an assessment of how many incidents resulted in fatalities, so it is possible that the incident rate resulting in fatality is lower than this [i.e. there may have been incidents that resulted in multiple fatalities per incident], however it is definitely not higher than this. The figure of 0.01532 per MTRM is significantly higher than the RSSB data for ‘significant events’ (i.e. that resulted in serious injuries or fatalities) of 0.0016 PMTM. However, it must be remembered that the US data does not tally fatalities by the type of incident i.e. the fatality totals recorded represent the total number of fatalities from all types of incident including collision, derailment, security and other causes, as well as fire.

The data suggests that the rate of occurrence of any type of fire incident on US LRT services is likely to be approximately similar to that observed on the UK passenger rail network in the RSSB data. Differences in reporting methodology make it difficult to draw more detailed conclusions about the relative safety of the UK and US public transit systems.

**Initiating event data – probability analysis**

Accidental luggage fires are commonly used as an example of the ‘most likely’ larger initiating event type of fire. It is therefore worth attempting to quantify the actual probability of such an event. Reports of accidental luggage fires are rare, and little statistical data relating to trains is available. The
most common cause of accidental luggage fires is due to electrical faults developing within devices such as laptop computers, mobile phones, etc. The US Federal Aviation Authority (FAA) in 2007 published a summary of globally reported incidents in aviation spanning 1991-2007[23]. Over the 18 year period reported, a total of 86 incidents were reported. 35 occurred on passenger flights, with the remaining 51 incidents occurring on cargo flights. In the 35 incidents involving passenger flights, only 3 resulted in minor injuries and only 1 resulted in major injuries, with no fatalities recorded. On the 24th August, 1999, a UNI Air flight from Taipei to Hualien in Taiwan experienced an explosion and resulting smoke and fire in the forward part of the cabin. Investigators found that a motorcycle battery and container of gasoline had been brought into the passenger cabin. It is believed the gasoline leaked from its unmarked plastic bottle onto the battery causing a short circuit and fire. The aircraft was destroyed by the fire. 14 passengers suffered critical injuries, 14 passengers suffered minor injuries. There were no fatalities.

According to data from the World Bank [24], there were approximately 344 million passenger flight departures over this period. From this data, the probability of an accidental luggage fire, due to electrical device faults, occurring where passengers are present can be estimated to be 35 in 344 million, or a probability of 1 in 9.8 million (1.0x10^{-7}). From the World Bank and FAA data, it can be estimated that the probability of a serious fire incident (where ‘serious’ implies major injuries, as per the RSSB report definition) involving luggage/battery fire is approximately 1 in 344 million (2.9x10^{-9}). Due to the unique nature of the serious fire incident in question, the probability could be argued to be even lower.

Note that the probability of occurrence of a fault is unrelated to the mode of transport being used by the carrier of the luggage, rather it is derived from the reliability of the electronic device itself. Thus, although this data derives from the aviation industry, it is reasonable to assume that the probability would not vary significantly for other public transportation types.

PROPOSAL FOR A RISK-INFORMED APPROACH

Known potential train fire sizes are getting larger. However the ignitability of trains is decreasing. The rate of occurrence of train fires is low. The rate of occurrence of worst-case initiating events and of serious fire events is extremely low. The level of residual risk accepted by owners, operators, insurers and approvers is therefore very low. TVS systems are major sources of cost on underground transit projects, not merely from the equipment needed to create the airflows, but also from the construction space requirements to house the system and the electrical and SCADA requirements to operate and control the system. It is therefore possible that by implementing a risk-informed approach, the TVS-related costs of a project could be reduced by significant amounts without compromising the level of safety.

We propose a high-level framework for a risk-informed methodology, taking guidance from road tunnels and other sectors with developed risk-informed approaches. Elements of the approach are:

Hazard Analysis

Commonly accepted methodologies are already in use. These would continue to be used.

Probability Analysis

Use tools appropriate to system under consideration. These may include one or more of: historical data analysis, fault tree analysis, event tree analysis, and/or human reliability analysis.

Consequence Analysis

This can be done with existing coupled CFD + pedestrian modelling tools to estimate the Fractional Effective Dose (FED) and consequent probable casualty levels. Pedestrian modelling tools also allow
the consequences of differing human response behaviours in an emergency to be assessed. Alternatively, it would also be possible to use historical data and expert judgement as appropriate.

**Risk Estimation**

Individual risk is the estimation of probability that an individual receptor will experience the consequence. Societal risk is the estimation of probability that the population of receptors will experience the consequence. There are commonly used methodologies for estimating the risk level in use in sectors including road tunnels and the energy industry that would be transferrable to transit tunnels. Reference [25] from the UK Health and Safety Executive provides a comprehensive overview of the concept of societal risk and techniques for estimation. Societal risk may be represented either by FN curves or by a risk integral.

FN curves are plots of cumulative frequency ($F$) of various scenarios against the number of casualties ($N$) anticipated. $N$ is sometimes refined to refer only to fatalities. An individual scenario has a frequency, $f$, and with its expected $N$ forms an $f$-$N$ pair. Cumulative frequency, $F$, is the sum of all individual frequencies that could lead to $N$ casualties.

Risk integrals can be represented by the Expectation Value ($EV$), also sometimes known as Potential Loss of Life ($PLL$), which represents the annualized average number of persons experiencing the specified harm. $EV$ is sum of the products of all the $f$-$N$ pairs:

$$EV = \sum [fN]$$

The $EV$ is useful since it can be used directly in Cost Benefit Analysis and ALARP estimations as it can be multiplied by the Value of a Statistical Life to determine the value of benefit that could be gained by reducing the risk. Thus, the value of altering TVS capacity by a specific amount can be directly quantified.

**Comparison with Risk Acceptance Criteria**

The assessed risk must be compared against acceptance criteria before a design can be finalized. The criteria would need to be established and would require acceptance of owners, operators, insurers, approvers and designers and contractors. Issues such as definition of the residual risk, ownership of the residual risk, safety factors, etc would need to be resolved. While this may initially occur on a project by project basis, ultimately it would benefit from some sort of industry-wide collaboration to establish guidelines for risk acceptance criteria, similar to what has occurred in other sectors.

The issue of societal risk is likely to be most contentious. Guidance on societal risk in particular can be found in acceptable risk levels from other industries and/or from owners who currently have such figures in their operations plans. Two examples are cited here.

**Example 1. Road tunnels**

Work has been done in Europe to establish road tunnel risk acceptance criteria as detailed in References 10 and 13. For example, the Netherlands has stipulated the following acceptance criteria for individual risk of $10^{-7}$ per person-kilometre per year and for societal risk of $10^{-7}/N^2$ per km per year [Ref 10, p 85], where $N$ is the annualised number of fatalities.

**Example 2. Propane storage facilities.**

Reference 15 states acceptable levels of risk for proximity to a propane storage facility. Table 3 summarises the acceptable levels of public (societal) risk.
Table 3. Acceptable levels of public risk for land use around hazardous facilities. Reproduced from Figure 3 in Reference 15.

<table>
<thead>
<tr>
<th>Risk contour</th>
<th>Allowable uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 1 in 10000 ($&gt;10^{-4}$)</td>
<td>No other land uses except the source facility</td>
</tr>
<tr>
<td>1 in 10000 to 1 in 100000 ($10^{-4}$ to $10^{-5}$)</td>
<td>Uses involving continuous access and the presence of limited numbers of people but easy evacuation, e.g. open space (parks, golf courses, conservation areas, trails, excluding recreation facilities such as arenas), warehouses, manufacturing plants</td>
</tr>
<tr>
<td>1 in 100000 to 1 in 1000000 ($10^{-5}$ to $10^{-6}$)</td>
<td>Uses involving continuous access but easy evacuation, e.g., commercial uses, low-density residential areas, offices</td>
</tr>
<tr>
<td>1 in 1000000 to 0.3 in 1000000 ($10^{-6}$ to $0.3x10^{-6}$)</td>
<td>All other land uses including institutional uses, high-density residential areas, etc., except for sensitive receptors, such as schools, hospitals, elderly and child care facilities</td>
</tr>
<tr>
<td>Below 0.3 in 1000000 ($&lt;0.3x10^{-6}$)</td>
<td>All land uses without restriction</td>
</tr>
</tbody>
</table>

This data is useful as it quantifies the societally acceptable level of public risk from a facility type with the potential for significant catastrophic failures, including vapour cloud explosions and BLEVEs. Table 3 shows that a risk level of $10^{-6}$ is adjudged to be sufficiently low that large numbers of persons may reside within the hazard zone (i.e. have a 100% exposure to the risk), with only exceptions being made for special categories such as schools, hospitals, and elderly and child care facilities.

Example 3. UK HSE threshold level

Reference [25] specifies three risk levels for facilities: ‘broadly acceptable’, ‘tolerable if ALARP’, and ‘unacceptable’. The document also specifies a threshold level for the acceptance of societal risk at the ‘tolerable if ALARP’-'unacceptable’ threshold. The specified value of the threshold is 50 fatalities at a probability of $2x10^{-4}$/year, i.e. $N = 50$ and $F = 2x10^{-4}$/year.

CONCLUSIONS AND NEXT STEPS

Modern rolling stock fire resistance and the extremely low occurrence of ‘design’ fires in rail, metro and LRT tunnels presents a case that the determination of the design fire for tunnel ventilation systems could be better assessed by using a risk-informed approach utilising widely accepted risk analysis methodologies, rather than the simple hazard analysis typically used at present.

Such an approach could yield significant benefits without compromising safety levels.

Risk acceptance criteria need to be established. This may initially occur on a project by project basis, but would be done most effectively via some form of industry-wide collaboration, analogous to those that have occurred in road tunnels and the energy sector.

REFERENCES

Safety in Road Tunnels – Safety Target Proposal

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ABSTRACT

The purpose of this paper is to propose a quantitative target for assessment of life safety in road tunnels and describe how such a target can be utilized and developed further. The target is developed from an analysis of initiating events, accident statistics and analytical approaches and it makes it possible to tailor the safety concept in individual tunnels to meet the target by means of quantitative risk analyses. The results indicate that the practice proposed is beneficial for both quality and transparency in the decision-making, as well as it can be judged to have the potential to improve cost-efficiency in the safety related work. It is concluded that the target should be calibrated and evaluated with data from real tunnels before implementation and that the resulting safety level from present ruling is assessed. Also, it is concluded that the total cost to realize the safety target is assessed. It is recommended to put more effort on general accident prevention in tunnels compared to surface roads in order to reduce the number of events that may escalate beyond control. It is also recommended that the road tunnel safety learning processes are improved by routine collection, compilation and evaluation of data on road tunnel accidents as well as vehicle-fires and dangerous goods accidents in road traffic as a whole.

KEYWORD: road tunnel, safety target, risk analysis, risk management

INTRODUCTION

It is important that road travelling can be conducted at a safe-enough level on all parts of the road system, both on surface roads and in tunnels. However, it is not presently known if that is the case, at least not from a Swedish standpoint. Even if road tunnels, so far, not can be blamed to burden statistics on road traffic accidents, a limited number do occur on a yearly basis resulting in traffic interruptions, material damage or slight to severe personal injuries. These outcomes, however, are not representative of the potential with tunnel accidents and therefore cannot provide the single base for designing road tunnel safety concepts. The potential with road tunnel accidents is better demonstrated by experience from very serious accidents, and which suggest that tunnel risks should be taken very seriously. The lack of data, however, prevents opportunities with empirical learning, analogue to the work on surface road safety, from being seized. This stalls the development of specifications for planning and construction as well as proactive risk management strategies. Presently, processes are not in place to fill this gap in the Swedish regulatory environment.

Historically road tunnels are not explicitly considered within the Swedish Vision Zero Initiative, the long-term ambition with the national road traffic safety work. Instead the Vision is founded on empirical learning from surface roads accident. Thereby, the Vision’s offensive targeting as well as the Safety Indicators in use (such as speed-limit obedience, use of seat-belts etc.) does not reflect the threats from very serious tunnel accidents. This is problematic since the governing rules, laws, regulations and standards do not answer to what extent and how these potentially very serious scenarios should be met, even if the need for analytical risk control is realized and risk analyses
prescribed for various specific cases. The problem lies with the lack of recommendations or guidelines regarding what risk level that can be accepted, a shortcoming that exposes tunnel design and construction to uncertainties that may lead to tunnels being put into operation with insufficient knowledge of how safe they are. The possibilities to evaluate the utility cost for this unspecified safety will obviously be limited. In fact, due to the complexity of many of the modern tunnel facilities, both the safety level and the cost efficiency of safety measures will be unknown. This leads to decisions on arbitrary bases concerning accident scenarios with a potentially large number of fatalities and safety measures requiring significant resources in terms of investments and operational cost. This may be quite far from the intentions behind the EU-directive 2004/54/EC regarding minimum safety requirements for tunnels in the Trans-European Road Network [1].

THE IDEA

The proposed target is intended to be used as a tool for decisions on what safety measures may be needed in order to provide a level of life safety in individual road tunnels that equals the safety on surface roads. The paper is based on a research study published by the Swedish Transport Administration [2]. The problem with traffic interruptions is not dealt with in the mentioned study. That is, however, studied extensively in [3].

The safety target proposed is built around a comparison of the risk for fatalities in accidents of various magnitudes on surface roads and in road tunnels. It is founded on statistics and analytical approaches, developed from a list of initiating events. The decision tool comprises the performance of quantitative risk analyses for the specific application and where the need for safety measures is identified by comparison with the target. The risk analyses are proposed to be performed as a part of the routine when tunnels are being planned and built but they also are applicable to tunnels in operation.

REFERRING TO SURFACE ROAD SAFETY

There are several motives to use surface road safety as a reference regarding road tunnel safety. Apart from being the obvious choice, it also considers the following:

- It can be deemed politically problematic to aim for different levels of safety in tunnels and on surface roads.
- It recognizes that present road traffic is performed at an acceptable level of safety and that traffic safety will improve in the future.
- It makes road tunnel risk communication more nuanced and transparent since it provides means to discuss both safety levels and safety measures simultaneously.
- It facilitates putting priorities to funding of competing interests since it increases the knowledge of the correlation between the cost for safety measures and safety effect.

The thought of an equivalent safety level in tunnels and on surface roads is not new. It has, for instance, earlier been proposed by PIARC [4] and the Swedish National Road Administration [5]. This paper revitalizes this thought by presenting a way to measure and verify safety in road tunnels.

INITIATING EVENTS

In order to compare risks in road tunnels and on surface roads it is necessary to identify a common basis for comparison. This has been defined as the accidents that result in fatalities, the initiating events. From the national Swedish road accident database STRADA (Swedish Traffic Accident Data Acquisition) it can be learned that the initiating events in road traffic comprise the following:

- Single vehicle accidents
- Collisions
It may be noted that the concept of initiating events refer to the original accident cause. By example, single vehicle accidents and collisions that result in fires are seen as single vehicle accidents and collisions, but with the twist that they also result in fires. The accident type fire therefore only refers to the situation when fire is the initiating event. The same logic is also used with dangerous goods accidents. The following two types therefore also may be identified:

- Fires
- Dangerous goods accidents

There are no lost lives to be found in STRADA from either fires or dangerous goods accidents, neither on surface roads nor in tunnels. It is however known from international experience that they may cause deaths, particularly in tunnels.

**SURFACE ROAD TRAFFIC SAFETY**

It was deemed that accident data from ten consecutive, recent, years was needed to achieve a reasonable solid statistical basis to characterize the modern surface road safety standard. It was also decided to restrict the data to accidents resulting in fatalities. In the end, only the national accident data basis STRADA was judged to provide the necessary information since it covers all accidents reported by the police. The years chosen for the study were 2003 – 2012 [2].

The accidents identified in the data basis then were catalogued according to initiating event, type of vehicle involved and number of fatalities in each accident. Also, in order to be representative for a reasonable modern road tunnel standard, only accidents involving cars, buses, trucks and motorcycles were included. Mopeds, bicycles, tractors, pedestrians and terrain vehicles thereby were excluded, as also accidents involving wild animals. Each of the resulting entities then were summarized per year resulting in the following, see Table 1.

<table>
<thead>
<tr>
<th>Initiating event</th>
<th>Number of fatalities per accident (2003 – 2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Single vehicle accidents</td>
<td>1 383</td>
</tr>
<tr>
<td>Collisions</td>
<td>1 245</td>
</tr>
<tr>
<td>Fires</td>
<td>0</td>
</tr>
<tr>
<td>Dangerous goods accidents</td>
<td>0</td>
</tr>
<tr>
<td>Sum</td>
<td>2 628</td>
</tr>
</tbody>
</table>

**Table 1**  The number of accidents resulting in different number of fatalities and from different initiating events (2003-2012).

In order to convert the annual accident averages into more calculable frequencies it was then deemed necessary to consider the amount of travelling needed to produce the accidents in question. A compilation of the relevant mileage was found in [6] and could be noted to vary between 71 000 and 77 000 million vehicle kilometres during 2003 – 2012. The mean value, 75 262 million vehicle kilometres, thereby was used to calculate the number of accidents per million vehicle kilometres, see Table 2.
Table 2  The frequency of accidents resulting in different number of fatalities (N) per year and million vehicle kilometres.

<table>
<thead>
<tr>
<th>N = 1</th>
<th>N = 2</th>
<th>N = 3</th>
<th>N = 4</th>
<th>N = 5</th>
<th>N = 6</th>
<th>N = 7</th>
<th>N = 8</th>
<th>N = 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5E-03</td>
<td>3.0E-04</td>
<td>4.7E-05</td>
<td>6.6E-06</td>
<td>8.0E-06</td>
<td>2.7E-06</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
<td>1.3E-06</td>
</tr>
</tbody>
</table>

If the resulting frequencies are presented as an F/N-diagram, a graphic representation of the correlation between frequencies and accident magnitudes for surface road traffic is achieved, see Figure 1.

![F/N-diagram](image)

Figure 1  Accident frequencies and magnitudes in surface road traffic displayed in an F/N-diagram (2003 - 2012). The scaling of both axes are logarithmic.

The frequencies are expressed as N or more fatalities per million vehicle kilometres. The consequences are expressed as Number of fatalities, N. It may be noted that both the size of the total risk (the area under the graph) as well as the various combinations of frequencies and consequences, reflect the status of the Vision Zero Initiative work for the period studied. The area also expresses the size of the total societal risk from road traffic accidents, i.e. the average risk in terms of expected number of fatalities per year.

ROAD TUNNEL SAFETY

There are no official statistics on road tunnel accidents in Sweden. A separate study based on data from STRADA thereby was compiled in order to get some idea of the number of them and their consequences [2]. The result indicate that it occurs about 3 - 4 accidents per year resulting in severe personal injuries and about 45 per year resulting in slight personal injuries (2003 - 2012). An injury is considered severe if it involves fractures, crush-injuries, lacerations, brain damage or internal injuries or is expected to lead hospitalization. An injury is considered slight if it is not classified as severe. Obviously, road tunnel accidents do occur in Sweden. For comparison, something like 3 000 accidents per year resulting in severe personal injuries and 15 000 resulting in slight personal injuries occurred during the same period on the surface road network [7]. These different outcomes can be explained by the different vehicle mileage performed in road tunnels and on the surface roads respectively. Seen from the perspective of accidents per vehicle mileage it thereby was judged that:
Accident frequencies in road tunnels can be appreciated to be the same as on surface roads if it is expressed per vehicle kilometre, all other parts considered equal.

The above also presupposes tunnels to be viewed as roads through “holes in the ground”, i.e. they do not contain any tunnel specific safety measures, at least not more than the regular surface road.

Regarding accident consequences, there were no fatal accidents identified in the road tunnel accident data. It can, however, be seen from international experience that very serious road tunnel accidents can happen and that they have the potential to be more serious than the corresponding accidents on surface roads, see Table 3.

Table 3  Examples of major road tunnel accidents in Europe [2].

<table>
<thead>
<tr>
<th>Year</th>
<th>Tunnel</th>
<th>Length</th>
<th>Consequence</th>
<th>Initiating event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>Mont Blanc</td>
<td>ca 11.6 km</td>
<td>39 fatalities</td>
<td>Fire</td>
</tr>
<tr>
<td>1999</td>
<td>Tauern</td>
<td>ca 6.4 km</td>
<td>12 fatalities</td>
<td>Collision (and fire)</td>
</tr>
<tr>
<td>2001</td>
<td>St. Gotthard</td>
<td>ca 16.9 km</td>
<td>11 fatalities</td>
<td>Collision (and fire)</td>
</tr>
<tr>
<td>2006</td>
<td>Viamala</td>
<td>ca 750 m</td>
<td>9 fatalities</td>
<td>Collision (and fire)</td>
</tr>
<tr>
<td>2012</td>
<td>Sierre</td>
<td>ca 2.5 km</td>
<td>28 fatalities</td>
<td>Single vehicle accident</td>
</tr>
</tbody>
</table>

The occurrence of tunnel accidents in Sweden demonstrates that there is a real threat from road tunnel accidents. Table 3 demonstrates that this threat also can result in very serious consequences, even if the likelihood is small. Thereby it can be stated that:

- Accident consequences in road tunnels can be appreciated to be more serious than with the corresponding accidents on surface roads, especially if they involve fire or dangerous goods.

If the reasoning above regarding similarities and differences with road tunnel and surface road accidents is applied to the risk profile outlined in Figure 1, the relatively unknown risk profile of road tunnels can be related to the more familiar risks of surface roads. Thereby, the following diagram can be constructed see Figure 2.

![Figure 2](F/N-diagram-exposing-the-estimated-difference-between-the-surface-road-risk-profile-and-the-road-tunnel-risk-profile-both-refer-to-the-studied-period-2003-2012.)

It is indicated in the figure that the road tunnel risk profile is positioned to the right of the surface road risk profile. This signals a higher total risk in tunnels compared to surface roads, all other parts equal.
The more precise size of this difference is, however, uncertain since the magnitude of the potentially worst case is not known. The Mont Blanc road tunnel accident indicates that it may be at least 30 - 40 fatalities. Accordingly, in the diagram, the scale of the consequence axis has been extended.

In order to get an indication of how serious the threats from these very serious scenarios may presently be, data from the Swedish Contingencies Agency’s database IDA (Indicator Data Analysis) has been analysed for the period 2010 - 2012 [2]. The focus was directed towards fires and accidents with dangerous goods.

On a yearly basis, Swedish rescue services are called out to about 4 000 fires in various kinds of vehicles. A majority of these, about 85 %, involve private cars and the rest involve buses, trucks and caravans. The data are, however, flawed since it also includes arson, fires in garages etc., at least if the number of vehicle-fires that occur in the traffic is to be appreciated. Therefore the data was manually searched for precisely these scenarios. The result indicated that it occur about 650 fires per year in vehicles that are out and moving in the traffic, signalling a measurable risk of a fire in a tunnel. Real events also confirm that this happen. Also, fires can occur from single-vehicle accidents and collisions. Further data-analysis (IDA) indicates that this happens about 25 times per year (2003 - 2012). So far, however, no serious accidents with vehicle-fires in road tunnels have occurred in Sweden. Apart from fire, also accidents with dangerous goods can result in very serious consequences if they occur in tunnels. Therefore, a similar search as with vehicle-fires was performed [2]. The data extracted from IDA thereby indicated that rescue services performed about 30 operations per year motivated by threats from accidents with dangerous goods out in the road traffic between the years 2010 - 2012. As with fires in vehicles, this signals a real threat. No serious accidents, however, involving dangerous goods in Swedish road tunnels yet have occurred.

According to the above, the dangers with fires and accidents with dangerous goods in tunnels can be considered to be real also in Sweden. Also, considering the number of people that may get involved in an accident if it occurs on a city highway in a tunnel at rush hour, it must be concluded that it is important to pay attention to accident prevention. In order to appreciate the weight of this threat and identify the best way to manage it, analytic risk assessment may prove critical. However, neither fire in vehicles or accidents with dangerous goods is presently a priority within the Vision Zero Initiative work. From a surface road safety perspective that is the natural choice. From a road tunnel safety perspective it is less so. It may even be seen as a choice that threatens the Vision Zero Initiative itself since it may only take one unfortunate tunnel accident to inflate the national safety target for one year beyond repair.

A ROAD TUNNEL SAFETY TARGET PROPOSAL

There are several options to choose from in order to transform the estimated road tunnel risk to the size of surface roads. It can be achieved either by reducing frequencies or reducing consequences for the various initiating events, or by various combinations of this. The most feasible way, however, can be appreciated to be reduction of the frequencies for the least serious accidents. This saves lives by reducing the number of accidents where people get injured or killed and it also reduces the number of potential worst-case scenarios, i.e. accidents that can escalate beyond control. In practice that involves frequency reduction for single-vehicle accidents, collisions, fires and dangerous goods accidents. The opposite choice can, as a strategy, be appreciated to be less feasible since it focuses on scenarios that, per definition, are beyond control. Therefore it may be critical in road tunnel safety management to value the possibilities to stay in control. Safety measures like separate lanes, stricter control of speed and less tolerance with car overtaking etc. may be seen as the appropriate, strategic, answer. Also, this may be coupled to an agenda to reduce the likelihood for vehicle-fires and dangerous goods accidents in road traffic in general. Even if this may not be news, the practice with a safety target and the systematic risk analyses offers the possibility to judge when safety may be satisfactory. If it is, the tunnel may be built. If not, complementing measures have to be evaluated in a revised risk analysis until the target is met.
The above reasoning may be reflected in the F/N diagram in Figure 2 by sliding the high-frequency end of the tunnel risk profile downwards along the frequency axis until the resulting area under the risk profile equals the area under the surface road risk profile. The frequency of the least frequent accidents, however, is not tampered with (the worst-case scenarios). The resulting, less inclined, road tunnel risk profile provides a graphic view of what it takes to achieve a total risk in road tunnels that equals the total risk on surface roads. See Figure 3.

Figure 3  The estimated road tunnel risk profile in Figure 2 has been tilted in order to achieve a total risk which equals that of surface roads.

The produced, less inclined, risk profile can be seen as the minimum level of safety acceptable in road tunnels in order to be equal to surface road safety. If also a second risk profile is placed in the diagram, below and parallel to the first, less inclined, profile an area with even less total risk can be outlined. This even higher level of safety, together with the original, forms an inclined area in the diagram that defines what may be named the ALARP area. In risk analytic practice this spells “As-Low-As-Reasonably-Practicable” and it defines the upper and lower limits for acceptable safety [8]. It is positioned below the original estimate according to the recommendations in [8], mainly to compensate for uncertainties. See Figure 4.

Figure 4  Upper and lower limits for acceptable safety in road tunnels compared to the risk in surface road traffic (2003 – 2012).
The ALARP area also composes the risk policy. By example, it defines which combinations of frequencies and consequences that can be allowed in order to achieve the safety target and which cannot be allowed. Above and to the right of the ALARP area the risk is considered to be high. Below and to the left of the ALARP area the risk is considered to be low. The following safety target for road tunnels thereby may be proposed, see Figure 5.

Figure 5 The proposed road tunnel safety target enables individual road tunnel’s risk profiles to be plotted in an F/N-diagram and compared to the safety target.

The frequency axis in Figure 5 has been adjusted in order to balance the diagram area and the safety target. Also, the right section of the risk profiles has been dotted in order to outline that it is less certain than the left section.

Apart from being expressed in an F/N-diagram, the safety target also can be expressed verbally in the following way:

Road traffic by motor vehicles in tunnels per vehicle kilometre should be as safe as surface road traffic by motor vehicles, excluding mopeds.

Apart from providing a quantitative target to be met in existing or new tunnels, the proposal also forms the basis for the safety policy. That, in itself, is no small thing. By example, it may be stated that the safety target indicates:

- That prevention of single-vehicle accidents and collisions in tunnels is good safety policy since it saves lives and reduces the number of accidents that can escalate beyond control.
- That prevention of vehicle-fires and dangerous goods accidents in road traffic in general is good safety policy since it reduces the likelihood of them occurring in tunnels.
- That mitigating measures must be considered if preventive measures fail to meet the safety target, in order to reduce the consequences from the accidents that do occur.

Road traffic safety is, however, not static. It improves, and in Sweden that has been a fact for a long time. Since the road tunnel safety target is built from surface road safety, this means that
improvements in the general traffic safety must be reflected in the safety target. Thereby, it is obvious that it has to be revised periodically. From a Vision Zero Initiative perspective that is not odd since it already contains sub-targets that are revised and adjusted to more stringent levels with time. But, before implementation, it may be good advice to check on the durability of the target proposed.

To assess this, the situation in the year 2025 has been tested. The prognoses on accident data and vehicle mileage thereby have been assessed from data covering the years 2003 - 2012. The number of accidents resulting in various numbers of fatalities per year during the period 2015 - 2024 thereby can be estimated to be 195 (1 fatality), 10 (2 fatalities), 2.5 (3 fatalities), 0.2 (4 fatalities), 0.2 (5 fatalities), 0.1 (6 fatalities), 0.05 (7 fatalities), 0.025 (8 fatalities) and 0.025 (9 fatalities). The vehicle mileage has been assessed to amount to about 79 000 million vehicle kilometres. The result is presented in Figure 6.

As expected, a part of the safety target has been consumed by the reduced number of accidents. This is mainly due to the steep reduction of the number of accidents during the start of the founding data period. This trend, however, cannot be seen to last. Instead, the reduction can be appreciated to wear off successively. It, therefore, may be realistic to anticipate a first revision of the safety target after 10 – 15 years of practice, a period that also may be seen as a test period. After that, the need for revisions will wear off, as do the reduction in number of accidents. Compared to the life-span of other sub-targets within the Vision Zero Initiative, that can be seen as durable enough.

**DISCUSSION**

It is important that road travelling can be conducted at a safe-enough level on all parts of the road network, both on surface roads and in tunnels. Present governing documents do not, however, offer any guidance on how safe is safe enough. Thereby, it is not possible to answer the question:

*How safe is it to travel through Swedish road tunnels?*

The above implies that the safety level in both existing tunnels and tunnels that are being planned and constructed is unknown. This exposes tunnel planning, design and construction to uncertainties that
may lead to tunnels being put into operation with insufficient knowledge of how safe they are. It also indicates that the possibilities to evaluate the utility cost for this unknown safety will be limited. The absence of explicit road tunnel considerations within the Vision Zero Initiative scope also may be problematic since it only takes one, unfortunate, tunnel accident to endanger the national safety target for one year.

Naturally, the comparison with surface road traffic safety may be criticised, primarily because of the analytical twist to equate the likelihood for an initiating event on one vehicle-kilometre of surface road traffic and one vehicle kilometre of road tunnel traffic. It, however, makes analytical sense even if it yet is to be proven and no solid data that points the other way has been found. Also, it may be argued that road tunnels are viewed as “holes in the ground”, i.e. stripped from safety measures separating them from surface roads as the safety target is constructed. However, since the target aims to enable road tunnel traffic to be as safe as surface road traffic, the need for safety measures only can be motivated if there is a need for them, identified by the result from a quantitative risk analysis which is compared to the safety target. Some tunnels, therefore, may need a more extensive palette of safety measures, whereas others only may need a minimum of standard measures.

The foremost danger to management by objectives is that the target and its achievement is isolated from the context and that the guiding purpose of the process is lost. A deep understanding of how the target may be met thereby is important, i.e. how the analytical work is being performed and what data and what knowledge it is based upon. Henceforth, decision-making in the future also will have to be based on an understanding of when data provide more or less certain answers and that it is important to take responsibility for both the short term and the long run, to be able to separate the reasonable from the unreasonable and the likely from the unlikely.

In the long run the absence of a quantitative safety target may be difficult to defend. Apart from being evasive of the critical question of how safe it is to travel in road tunnels, it also endangers the credibility of the traffic safety work as a whole. Thereby, it is proposed that the suggested safety target should be considered for national acceptance, following from certain adjustments. The alternative of not having a safety target can be seen as worse from all points of view, although periodical adjustments of the target strictness as traffic safety improves will have to be considered, as with other sub-targets within the Vision Zero Initiative. This can also be seen as a part of a natural knowledge development, as also present work within the Vision Zero Initiative can be characterized in terms of learning. Some allowance for preparatory training may also be seen as natural.

The foremost result from the implementation of the safety target and the analytical methodology will be improved expediency in the traffic safety work. This is due to the need for safety measures to be decided based upon their effect on safety and the actual need to achieve the target. Partly, the safety measures will be directed towards reducing the frequencies of single-vehicle accidents and collisions, fires and dangerous goods accidents. Partly they will be directed towards mitigating the consequences from fires and dangerous goods accidents in the cases where preventive action fail to meet the safety target. In addition, a systematic use of the analytical methodology can be expected to improve the quality in all related decisions. To perform a risk analysis can be seen as a part of what it takes to achieve the safety objective since it provides detailed knowledge regarding the risks of the analysed system. The risks in question therefore will be managed with a strategy that is tailor-made for the nature of the actual risks.

There are several reasons to why systematic risk analyses may be preferred compared to other, more informal or intuitive, ways of handling the extensive, but not complete, available knowledge [9]. Primarily it implies the use of risk analytical methodologies, involving systematic collection, organisation and compilation of available knowledge in a way that allows gaps in knowledge to be identified. This enables the prerequisites for the analyses to be tested, questioned and corrected by independent persons or agencies. The methodologies also imply assumptions and assessments that form the base for various estimations to be clarified in order to avoid misunderstandings. This enables
premises, simplifications and uncertainties stemming from data to be managed transparently and be supported by other approaches. All in all, this improves the quality of the related work.

CONCLUSIONS

It is obvious that without formulating a safety target and adopt a strategy that embraces the whole consequence potential for road tunnels compared to surface roads, the control of personal injury development in the traffic safety work as a whole may be endangered. This problem can be minimized by means of the suggested proposal.

Present governing documents prescribe the performance of risk analyses in various specific cases in order to assess what can be accepted. However, the same documents also fail to address what that is. This can undermine the safety culture and threaten the confidence for the analytical approach. To respond to that, it should be considered to prescribe the regular performance of risk analyses in planning and construction of road tunnels. The prescription of a safety target that quantifies what level of safety that can be accepted in tunnels also should be included in this, by example on a national level. In this paper, such a target is proposed.

The quantitative target for life safety in road tunnels improves the Vision Zero Initiative’s position to guide the assessment of safety in road tunnels. The target does not replace the Vision Zero Initiative but complements it, the same way other semi-targets within the Vision’s context. The target enables the identification of need for action when that is necessary, but the reverse when safety is adequate. The target also can be adjusted in line with changes in the general road safety. Other advantages are that the question of how safe it is to travel in Swedish road tunnels will be possible to answer, as well as the quality of road tunnel design and safety concepts will improve. This lays the foundation for a range of other improvement opportunities.

The increase in total risk in tunnels compared to surface roads must be compensated if equality in traffic safety is to be achieved. Since the increased risk in tunnels is founded on the view of the tunnel as a road through a “hole in the ground”, this compensation may be realized by means of a combination of accident prevention and mitigation measures which:

- Reduces the likelihood for single-vehicle accidents, collisions, fires and dangerous goods accidents.
- Reduces the likelihood for escalation of the accidents that do occur, with regard to single vehicle accidents, collisions, fires and dangerous goods accidents.

The road tunnel safety target enables the identification of the need for complementary safety measures when that is necessary and the opposite when safety is sufficient. The target also is designed to be adjusted in accordance to developments in road traffic safety in general. The safety target does not replace the Vision Zero Initiative, but rather complements its framework regarding road tunnels. Thereby, it can be viewed as any other of present sub-targets.

FURTHER WORK

The work for this paper has highlighted several opportunities for improvement that are considered important for the possibilities to achieve a better and clearer control of safety in road tunnels. It is proposed that:

- The issue of safety in tunnels is included within the scope of the present Swedish Vision Zero Initiative work.
- The Safety Indicators in use within the Vision Zero Initiative are extended with road tunnel accidents, vehicle fires and dangerous goods accidents in road traffic.
• Annual reports are compiled from the national accident database regarding road tunnel accidents, accident types, frequency and severity.
• Annual reports are compiled from the database of rescue services regarding response to vehicle fires and dangerous goods accidents in road traffic.

Knowledge of what the proposed safety objective means in practice is however insufficient at present. It is therefore proposed that:

• The safety level is evaluated for one or a few selected case study tunnels to test the methodology. This is proposed to include:
  · Calibration of the proposed safety target.
  · Assessment of the resulting safety level in tunnels if no safety measures at all are included and, also, evaluation of what level of safety present regulatory framework leads to.
  · Comparison with other countries' national safety targets.
  · Evaluation if the proposed safety level is affordable from a total cost perspective.

The next 15 years of road construction in Sweden will double the total road tunnel length compared to the present situation. Therefore this may be the moment to be proactive since road travellers will be increasingly exposed to road tunnel specific risks in the near future. Thereby, in order to be able to look forward towards a sustainable future regarding road traffic safety, it may be good advice to consider revision of the present risk management strategies regarding road tunnels.

REFERENCES

Evaluation of Road Tunnel Fire Safety and Risk

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ABSTRACT

The aim of this paper is to help a decision maker to decide whether a road tunnel is safe enough with respect to fire safety. Safety objectives as well as societal, ethical and political objectives are identified for the decision. It is argued that most uni-directional tunnels that comply with minimum EC requirements, with a longitudinal ventilation system along the traffic flow fails safely in the event of fire. Catastrophic fires should not be an issue, even for a risk averse decision maker. Considering the issue of fairness the tunnel is argued to be safe enough, and resources are either better used elsewhere or should be allocated so that the utility is maximized. For high-risk bi-directional tunnels, catastrophic fires could be an issue, in particular if there is no separate emergency pathway. Then a risk averse decision maker may take extra safety measures against such fires. A risk neutral decision maker would allocate resources so that the utility is maximized. Road tunnel regulation should set minimum requirements rather than cautionary requirements and allow for a probabilistic approach.

KEYWORD: Road tunnel fire safety, risk & safety evaluation, ethics, decision making.

INTRODUCTION

The aim of this paper is to help a decision-maker to evaluate road tunnel fire safety, not in relation to other transport alternatives, but in relation to whether a specific tunnel is safe enough. The reign paradigm and mean to evaluate safety within engineering and society at large is risk management with a particular focus on technical risk analysis [1, 2]. However, decisions concerning safety and risk are fundamentally ethical and political [3, 4]. Since ethical factors such as fairness or freedom are excluded in technical risk analysis, it is not a sufficient basis for evaluating whether a tunnel is safe enough. The World Road Association (PIARC) writes in a recent report on current practice for risk evaluation for road tunnels:

“When a risk analysis is performed it is important to realise that decision-making about risk is complex. Not only technical and mathematical aspects are important, but ethical, political, societal and other factors have an important role as well. Whereas risk analysis is a scientific process of assessment [...] risk evaluation is a socio-political process in which judgments are made about the acceptability of those risks” [2:16].

The aim in this paper is to explicitly analyse and include ethical factors for the evaluation of road tunnel fire safety risk. Political and societal factors with a bearing on safety and risk evaluation are derived from literature, regulation and policies.

The logic of decision-making is to choose the option that promises most of what you want. With the introduction of performance-based fire regulation it becomes possible to choose the option that promises most of what you want [5]. In an earlier article Gehandler [6] identified several deficits that could be traced to a poor fire safety decision making practice. Bjelland [7, 8] argues that the fire safety decision making process should be iterative and mathematical rigour should give way for other types of knowledge and discussions that allows for solutions to evolve as the problem and its objectives are reframed along the process. The paper will follow a general decision-making process consisting of the following five main stages [9]: #1 problem framing, #2 objectives, #3 development of alternatives, #4 consequence analysis, and #5 tradeoff between conflicting objectives.
#1 PROBLEM FRAMING

The way the problem is stated frames the decision and determines what can be regarded as solutions. Posing the right problem drives everything else. The context for the decision is that we have an existing or planned road tunnel for which a decision maker has to decide whether the tunnel is safe enough with respect to fire safety. An important moral factor concerns the desirability of the activity in question [10]. Large infrastructure projects are often highly debated, the cost is high and motorized traffic has several social and environmental limitations compared to bikes or metro. Nevertheless, for this article it will be assumed that the tunnel will be constructed or is already in operation and that it now is a question of providing enough safety. Consequently it is not an evaluation between transport alternatives.

#2 DECISION OBJECTIVES

Objectives specify the goal of the decision, and give the direction to strive for. In this article objectives are of two types. Safety objectives further specify what a safe tunnel is. Political, ethical and societal objectives are concerned with how safe is safe enough. Both are derived from literature including policies and regulation.

Safety objectives

The overall aim of a fire safe tunnel is by Gehandler et al. [11, 12] broken down into the following five objectives.

1. Limit the generation and spread of fire and smoke.
3. Provide means and safety for rescue operations.
4. Load-bearing capacity of the construction can be assumed in the event of fire.
5. Efficient management of operation, traffic, incidents, accidents and maintenance.

These key objectives were derived in a Swedish context but can be derived from the EU construction products directive (CPR) [13] and EC directive on minimum safety requirements for road tunnels [14].

Political, ethical and societal objectives

The Swedish Traffic Administration has the following goals from the Swedish government. Ensure an economically efficient and long-term sustainable provision of transportation, which benefits both industry and citizens throughout the country. Availability with regards to usability for all road users and tunnel vehicle capacity is a performance goal. Safety, the environment and health should be considered [15]. According to the Swedish Environmental Code that applies when tunnels are to be built, valuable natural or cultural environments should be protected. These goals are general and likely to be valid for most countries [16].

In 1997 the Swedish Parliament coined the concept ‘vision zero’ for traffic safety with the goal to one day reach zero deaths and zero serious injuries on the road network. Later other countries have followed or adopted similar goals [17]. Vision zero may initially seem to be a clearly deterministic and deontological vision. From a political perspective it may also signify a committed leadership towards safety. However, Elvik argues that vision zero calls for an efficient use of resources, which means resources should be allocated to the lowest net cost to save lives, in accordance with a utilitarian and probabilistic point of view [17]. In this sense vision zero coincide with the overall goal of cost efficiency, or the more fundamental objective to use resources wisely. This will be the interpretation used in this paper.

If risk is defined as a combination of likelihood and severity, the main difference for tunnels, compared to roads above ground, is that the rate of accidents in general is reduced, while the likelihood of severe fires is increased [18, 19]. Risk perception studies have found that societies have an aversion against large accidents [4, 20]. This is therefore an argument to avoid catastrophic road tunnel fires.
A fair distribution of risks and benefits is a central ethical risk issue to justify why someone is exposed to a risk [21, 22]. As children, young adults, and the elderly are disproportionately exposed to traffic risks – Nihlén-Fahlquist [23] argues that fairness rather than utility should be the overriding rule for resource allocation.

According to van Wee [24] perceived safety is an important transport safety indicator as the ethically important aspect *freedom of movement* is at stake. A Swedish survey showed that about one in three is at least sometimes anxious when driving in tunnels and 4% avoid driving in tunnels. It was further found that, through the use of driving simulations, safety was increased if the perceived safety, i.e. the feeling of being in control, was increased. This means that the indicator of perceived safety may be particularly important for road tunnels as they create more stress and avoidance cost than do roads above ground [24, 25].

To summarize, the following political, ethical and societal objectives are identified which means that a road tunnel decision maker should:

- use limited resources wisely,
- achieve a high availability,
- consider the environment,
- aim at vision zero,
- ensure a fair risk and benefit distribution,
- avoid catastrophic fires, and
- ensure that the perceived safety level is high.

##3 ALTERNATIVES

Alternatives are the different courses of action available to choose from. The decision can be no better than the best alternative. For a particular decision, alternative solutions will depend on several local factors, e.g. whether the tunnel pass through a mountain, under water or below a city, and what type of construction that is feasible. In order to derive a safe tunnel it is important to consider safety at an early stage in the decision process. Then inherent safe solutions are most likely to be achieved [26].

The amount of safety that is aimed at is strongly depending on the design approach that is chosen for the design. For example we would expect a deterministic design approach where the tunnel is designed for a worst-case fire to result in a more conservative solution (safer) than if a probabilistic approach is followed [10]. In any case we can expect that any solution must comply with minimum requirements from existing laws. This gives us a base case to start from.

### Minimal requirements (the base case or ‘do nothing’ alternative)

For tunnels longer than 500 m on the trans-European road network, minimum safety standards with respect to organisational, structural, technical and operational aspects are prescribed in EU legislation [14, 27]. Quantitative and/or qualitative risk analysis concerning health (safety) and environment are performed along the design process [16]. Often it is a debate whether the tunnel is safe enough, or how the risk analysis should be interpreted, is the tunnel safe enough or not? The answer partly depends on whether a deterministic or probabilistic design methodology is followed.

### Deterministic design

In the deterministic approach the tunnel is designed for a ‘plausible worst case’ or ‘worst case’ scenario [28]. A critical issue in deterministic design is the selection of reference scenario and design fire as the consideration of likelihood of occurrence is only implicitly considered. Should it be more of a ‘worst case’ or a ‘worst plausible case’? How large sacrifice is directed to treat incredible scenarios [28]? In this sense the possible consequences becomes the criterion on which decisions are justified, in accordance with a deontological position in moral philosophy. Deontology is a theory that is concerned solely with establishing the principles upon which actions can be considered to be right or wrong. A deterministic design rests on that individuals should not pose a risk to others. A strict
deontological designer is precautious and choses a design that has an impossibility to pose risk to others [10]. The cautionary principle is sometimes used in risk management and states that in face of uncertainties, caution should be the guiding principle [29]. A strict deontological approach may ultimately lead to the banning of all risky activities. Thus the deontologist may infringe on the same values she wishes to preserve which may cause more risks than it could possibly prevent [10, 30]. Nevertheless, deterministic approaches are common in fire safety, e.g. the use of design fire [7]. An advantage with the deterministic approach is that it is simple, it is clear what the tunnel is designed for and that high consequence scenarios can be designed for.

Probabilistic design
In the probabilistic approach the likelihood of occurrence is included in the analysis which makes it possible to argue that the utility with regards to the expected loss and the cost of prevention should be maximised, in accordance with a utilitarian position within moral philosophy. Utilitarianism stems from the idea that happiness is the only thing desirable as an end, all other things being only desirable as means to that end. The probabilistic designer will aim to choose the design with the highest probability-weighed sum of utilities. A critical issue for the probabilistic designer is to justify that very low probabilities justify accepting potentially very large consequences, i.e. that the probabilities are de minimis [10].

From a moral perspective an unjust societal arrangement could produce more utility than a just one, therefore other relevant factors, e.g. justice and fairness need to be acknowledged in the decision [22, 23]. Minorities with special needs are not visible in statistical estimates and are therefore “sacrificed” for the need of the majority. Probabilistic design is gaining ground in fire safety engineering and road tunnel design [2, 7, 31]. An example is the increasing use of probabilistic risk assessment, however, what is meant by probabilistic approach here is the utilitarian use where the risk is weighed against other objectives with the aim to maximize the utility.

The deterministic and probabilistic approaches are sometimes combined. One example is to require tunnels to be at least as safe as roads above ground (a deterministic and deontological criterion) by probabilistic means, e.g. QRA [32]. However, in essence this is still a deontological approach as this does not take the cost or utility into account. Another is the use of the As Low As Reasonable Practicable (ALARP) concept where the total risk is required to be below a tolerability level (deontological level) and CBA is used to ensure that reasonable and practicable safety measures are implemented for the residual risks below this level but above a lower level judged as acceptable, i.e. de minimis risk [33, 34]. This approach is in essence closer to a utilitarian approach.

#4 CONSEQUENCES
In this section the consequences each alternative would have for each objective are analysed.

Generation and spread of fire and smoke
The aim of this requirement is to offer protection against the origin, development, and spread of fire and smoke within the structure. The indicator most often used to express road safety is the number of fatalities per travelled vehicle km [24]. In this respect road tunnels are safer than roads above ground [35, 36]. This is also the measure most commonly used in risk analysis for road tunnels (sometimes also normalised per tunnel km) [2, 31, 32]. Such measures highlight the amount of vehicles and tunnel length, which also are identified as key measures for tunnel risk classification in the EC [14] requirements. Although these factors cover the risk exposure, these two factors alone do not fully grasp road tunnel fire safety. From an Austrian survey over their road tunnel fires in 2006-2012 it is clear that the length of the tunnel and the number of vehicle kilometres are poor indicators for the amount of fires in different tunnels. Instead the survey highlights tunnels with long and steep approaches causing overheated HGV engines or brakes [19]. Key factors identified for causing road tunnel fires are: tunnel inclination, tunnel curvature, the amount of HGVs, congestion, lighting conditions at tunnel portals and the area where the gradient goes from falling to rising [18, 19, 37]. Some of these factors can be evaluated in terms of perceived safety, see below. If road users experience the tunnel to be safe, they will cause fewer accidents [25]. The occurrence of fire can also
be reduced by organisational factors such as proper vehicle maintenance and cultural factors such as a safe driving culture. These are important pro-active factors that commonly offer a better pay-off than more reactive measures [6].

Due to the dynamics of tunnel fires, the smoke and heat follows the ventilation flow along the tunnel. This means that the fire separating function, to keep the fire in the tube of origin is relatively easily achieved [38]. More critical is the spread of fire within the same tunnel tube. For uni-directional tunnels the fire is not likely to spread as the vehicles downstream can be assumed to drive out of the tunnel, see below for a further discussion of this case. For bi-directional tunnels, the smoke flow can increase radiation towards vehicles downstream the fire, helping the fire to spread.

Means for safe self-evacuation
The aim of this requirement is to offer the users the possibility to reach a place of safety in the event of fire. As was demonstrated in the Mont Blanc tunnel fire, a rescue chamber is not a place of safety. Minimum requirements require separate emergency pathways or another tunnel tube leading to the surface for longer tunnels in accordance with the EC directive [27, 39, 40]. Evacuees should not be exposed to falling objects or physical obstructions, high temperature, high heat flux, high levels of toxic gases, or poor visibility. In tunnel fires, smoke is what cause fatalities. Life safety is therefore best achieved if evacuation through smoke can be avoided.

Depending on the tunnel and traffic situation this could for example be achieved in uni-directional tunnels by ensuring that the smoke travels with the traffic flow and that downstream traffic safely can continue driving, see Figure 1. Johnson [41] argued that queue was not an issue as the case of a cue downstream the fire being engulfed by smoke has never occurred. Clearly, designing a uni-directional tunnel for the scenario of stopped vehicles downstream the fire that needs to be evacuated is a worst-case scenario with very low probability of occurrence. However, collisions and poor vigilance or safety distance to vehicles in front are among the most common causes for road tunnel accidents which highlight the accident case of collision with stationary traffic in a uni-directional tunnel. Traffic management becomes an important pro-active measure to avoid these accident scenarios.

For bi-directional tunnels, people can be expected to be found downstream the fire. For the cases when evacuation has to be performed downstream a tunnel fire, tenable conditions for the evacuees needs to be ensured during the evacuation. As can be seen in Table 1, it is not a straight-forward task to evacuate all bi-directional tunnels on time. The distance between emergency doors is likely not as important as to convince the tunnel users to leave their vehicles and quickly initiate the evacuation, for this a communication system that reaches inside vehicles is needed [42]. Again the tunnel safety management system needs to operate it properly and fast with a clear message to exit the vehicles and to walk towards the closest emergency door [43, 44]. This means that a properly trained organisation is needed in order to deal with such events. A transversal ventilation system can improve the difficult situation, if designed and operated timely [45]. In practice this means life safety only concerns the tunnel users found in the exhaust zone. In the Tauern fire 1999 the transversal ventilation system is reported to have worked well [46]. Despite this, four people were killed by the fire, three that stayed in their cars and one who suffocated 100 m from the fire from smoke inhalation (Eight were assumed to have perished in the initial crash) [47].

Means and safety for rescue operations
The aim of this requirement is that the rescue service can undertake life-saving and fire extinguishing activities with satisfactorily safety for their personnel. Again uni-directional tunnels offers easy access to the fire as the unexposed tube can be used for the rescue vehicles and the emergency door upstream the fire used for accessing the fire scene, see Figure 1. For bi-directional tunnels rescue service vehicles are forced to use the tunnel portals to access the tube on fire. The ventilation system must be operated in such a way that they can approach the fire from a smoke free direction. One lesson from previous fires is that the operation of the ventilation system and the rescuers needs to be tuned, highlighting organisational aspects and the need for training. High-risk bi-directional tunnels with regards to fire occurrence, fire spread and evacuation set the highest demands on the rescue service
operation. For such tunnels the rescue service needs to arrive and to start the emergency operation fast, within 7 minutes, if they should be able to extinguish a HGV fire, and assist evacuees [48]. For some bi-directional tunnel fires not even a spotless rescue operation will suffice to keep the fire in control, e.g. Tauern fire. In this case only a FFFS could have put out the fire and kept the consequences under control [48].

![Figure 1 Safety concept for uni-directional road tunnels.](image)

**Load-bearing capacity of the construction**

The aim of this requirement is that the load-bearing capacity of the construction can be assumed in the event of fire. This requirement mainly concerns tunnels that are constructed in concrete. No tunnel is ever reported to have collapsed due to a fire. One reason is that, for rock tunnels the load bearing capacity is often not an issue [48]. The aim to reduce socio-economic costs from tunnel closure due to fire is slightly related to this although it is hard to imagine a tunnel that would be unaffected by a fire, surface lining and tunnel systems will be damaged by a larger fire and require tunnel closure and reparation (unless FFFS is installed, see Burnley fire in 2007 [46]). A tunnel collapse would likely require a longer tunnel closure as the tunnel would partly need to be rebuilt.

Often a deterministic criterion representing a worst-case fire is used as a design fire for the load-bearing capacity. Then structural members are classified according to standardized fire exposures. Three common exposure curves are the ISO 834, HC and RWS curve. The ISO curve (defined in ISO 834) is calibrated for enclosure fires. The HC curve (defined in EN 1363-2) is calibrated for hydrocarbon fires in open air. The RWS curve was developed in 1975 by the Ministry of Transport in the Netherlands and assumes an extreme petrol fire of 300 MW lasting for 120 minutes. A comparison of national design guidelines identified fire exposures between 90 and 240 minutes. NFPA prescribes a HC curve for 120 minutes fire duration [49].

In the Runehamar T1 tunnel fire experiment a HGV fire mock-up was set up. It resulted in the highest heat release rate ever measured from a tunnel fire test, 200 MW, which clearly represent a worst-case fire [50]. Comparing this fire with the curves mentioned above shows that the ISO 834 or HC curve for 60 minutes represent a similar exposure [51]. In order to achieve a longer fire, e.g. 120 min, fire spread is necessary to occur to other vehicles downstream the fire [38]. However, comparison with results from model scale experiments on fire spread to up to three targets indicate that the exposure on the reinforcement bars is only slightly affected [51]. This means that the HC curve for 60 minutes represent a rather conservative fire exposure curve.
Organisation and management
As part of the ever on-going systematic fire safety work, the tunnel manager should ensure necessary organisational, administrative and technical measures for safe operation within system boundaries. These concerns: proper maintenance and efficient traffic, incident and emergency management. For vulnerable tunnels, it should be ensured that the organisation that is created before, during and after crisis is fit to take appropriate response. Almost every system is dependent on maintenance and the correct training in order to function in the intended way when needed. This becomes more important the more systems are installed and the larger the organisation is. Organisation and management is largely pro-active which in general makes it very cost efficient and effective albeit it may be hard to quantitatively assess its utility [52, 53]. Therefore, this requirement deserves the highest priority and resource allocation must always be in proportion to other measures and the needs of daily operation and incident management. Scenario analysis and training, e.g. through table-top exercises or exercises have previously been identified to test the organisation [11, 52]. An indispensable complement is internal and external administrative control and a total quality management system [53, 54].

Using limited resources wisely
Different tunnels will have different utility and construction costs. Inherent safe solutions may come at the same or even lower price than others, if safety is regarded early in the planning process [26]. However, most safety measures come at a price and there is a long tradition within traffic safety to evaluate the economic efficiency of safety measures by the use of CBA. There are several ethical issues that a CBA ignores, e.g. fairness, see below, that needs to be considered in addition [55]. This objective obviously favours a probabilistic approach where the utility can be evaluated.

Availability
A high availability with regards to vehicle capacity will sometimes be in conflict with safety, e.g. authorities trying to reduce speed on roads with higher incidents against the will of local communities that obviously value time and availability higher than safety [6]. At other times availability is in favour of safety, e.g. FFSS causing a shorter tunnel downtime after fire. Another key parameter for the availability is the number of road lanes which is considered to lie outside the scope of this paper. A probabilistic approach using CBA can be used for tradeoffs between availability with regards to vehicle capacity. Availability with regards to usability for all road users is a critical issue as only motorized road users commonly are allowed in road tunnels, see section on fairness below, and due to fear of using road tunnels, see perceived safety below.

Consideration of the environment
Environmental concerns can conflict with safety objectives, e.g. if a ventilation shaft is to be situated in the habitat of an endangered species [56], or safety can favour environmental concerns, e.g. through reducing the amount of vehicle fires and its pollution to the environment [57]. Vehicle fires contaminate air, water and soil and mainly concern the tunnel during operation. The environmental impact from vehicle fires can be estimated from car fire emission measurements [57]. Protecting the natural and cultural environment mainly concerns the construction of the tunnel. The natural and cultural environment is valued by future generations, while road tunnel safety mainly concerns the current generation. In a probabilistic approach, environmental concern could be weighed against safety although it is questionable what value to place on e.g. an endangered species [58, 59] and why future values should be discounted [60]. To account for these factors, it is argued that the natural environment with regards to biodiversity should be protected for future generations, for example by turning it into a prima facie objective, an objective at a higher hierarchy than e.g. safety objectives [61]. Most likely safe enough solutions can be derived anyway.

Ensure a fair risk and benefit distribution (fairness)
Rule based ethics, e.g. Kantianism, emphasize that people should be used as ends in themselves, not merely as means. This highlights who the winners and losers are. Unfortunately it is almost impossible to do anything in the transport system without having losers, nevertheless, who the winners and losers are is an important factor that should be included in any evaluation [55]. It is the motorized road users who benefit from roads and road tunnels, sometimes on behalf of other groups in
society who benefit less, but share a higher risk from the road system. According to Rawls’ second principle, economic and social inequalities are only justified if they benefit all of society and in particular the least advantaged members [29]. The main reason why young and elderly are exposed to higher risks and ripe less benefit from roads is that they are pedestrians or cyclists. Non-motorized road users are in general not allowed in road tunnels. If tunnel safety is increased it will benefit motorized road users, non-motorized road users will not get any benefits, a probabilistic or deterministic design approach would typically not account for this [30, 55]. Therefore this is an argument for spending safety resources on young and elderly on roads above ground or on people with limited freedom of movement in society, rather than in tunnels, i.e. in support of minimum safety requirements.

To avoid catastrophic fires
The weight put on this requirement depends on the perceived dread associated with road tunnel fires and the severity of catastrophic fires, relative to other hazards that our society face today. Defining risk as the likelihood for fatalities and injuries, it is commonly known, that road traffic causes a great number of fatalities and serious injuries. The risks from road traffic are rather large, compared to other means of transportation, such as by airplane or train. Despite, risks from road traffic are more acceptable than many other risks in society. Some reasons for this are [17, 62]:

- the benefit is considered to be larger than the risk,
- most drivers perceive themselves to be in control,
- society has become accustomed to traffic accidents, and
- the accident type and its consequences are well known.

Fire and crash are argued to be similar from a risk perception perspective, since they are well known and society has become accustomed to them [63, 64]. Autonomy is an important moral value, and driving a car through a tunnel is a risky activity that many people choose to do despite the risk [65]. Another important moral factor is that the risk is voluntary for most road users (non-motorized road users can be argued to be involuntarily exposed to traffic risks, see section about fairness below). It appears that road tunnel fires should receive resources in proportion to traffic safety or fire safety in general, the only exception could be the risk for catastrophic tunnel fires.

The catastrophic potential that a risky activity has mainly relates to the following factors [4, 20, 66]:

- Dread towards the activity in question, e.g. nuclear power plants.
- Extent of direct damage with regards to fatalities, injuries and socioeconomic losses, e.g. explosion causing hundreds of fatalities.
- Reversibility: whether the situation can be restored to the state before the damage occurred, e.g. reforestation.
- Persistency with regards to the temporal extension of potential damage, e.g. persistent chemicals.

Fortunately road tunnels score low on all of these factors compared to other technological risks such as nuclear power plants, genetic engineering or chemical industries. The dread towards auto accidents and fires is neutral or low [66], there are no reported cases for when the tunnel could not be restored to the state before the fire accident, and fire does not cause persistent damage. Although road tunnels have very limited direct damage compared to accidents causing hundreds of victims and considerable material damage such as the petrochemical explosions in Texas city killing over 500 or the collapse of the great Teton dam destroying 100 000 acres of farmland [67], direct damage seems to be the main catastrophic potential for road tunnel fires. Based on Swedish traffic accidents with fatalities in the period 2003-2012 [32], it is argued that fire accidents in tunnels causing 7 or more fatalities are exceptionally large accidents and not of the type “normal” traffic accidents. As a comparison NFPA labels fires that result in five or more fire-related deaths as ‘catastrophic’ [68]. In Table 1 all road tunnel fires in Europe causing more than or equal to 7 fatalities are summarised [38, 46, 47].

Insurance companies first evaluate the maximum probable loss to make sure no loss is incurred that lead to bankruptcy [61]. Similarly Prwatiz [61] argues that it is rational to reject nuclear power plants since the potential loss is too large and probabilities are uncertain and not de minimis. For road
tunnels it is difficult to argue that the consequences are of such a magnitude that they should not be accepted. From a European perspective on traffic safety and safety in general, four road tunnel fires in all of Europe claiming 9, 11, 12 and 39 fatalities respectively in modern times cannot be regarded as very alarming or exceptional [38, 46, 47]. Further, tunnels without a separate emergency path (e.g. the Mont Blanc tunnel fire in 1999) are not allowed in the minimum requirements within EU since 2004 [14]. The community is further affected by a closed road tunnel, which will not be much worse than the situation before the tunnel. Most likely the tunnel will be re-opened within a few days or weeks time [38, 46]. It is argued that the likelihood for catastrophic fires in many cases is de minimis. Then a probabilistic or minimum requirements approach has more support than a cautionary deterministic approach designing against catastrophic fires.

Table 1 Severe road tunnel fire incidents causing 7 or more fatalities.

<table>
<thead>
<tr>
<th>Year and Tunnel</th>
<th>Tunnel length (m)</th>
<th>Bi/uni-directional</th>
<th>Cause of fire</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006, Viamala, Switzerland</td>
<td>740</td>
<td>Bi</td>
<td>Head-on collision between bus and two cars</td>
<td>9 dead 5 injured, Damage to lining</td>
</tr>
<tr>
<td>2001, St. Gotthard, Switzerland</td>
<td>16920 Bi (equipped with a parallel service tunnel)</td>
<td>Bi</td>
<td>Head-on collision between two HGVs</td>
<td>11 dead, Severe damage on 230 m, Closed for 2 months</td>
</tr>
<tr>
<td>1999, Tauern, Austria</td>
<td>6765</td>
<td>Bi</td>
<td>A HGV collided with stationary traffic killing 8 in the crash.</td>
<td>12 dead (8 from the initial crash), Severe Damage on 450 m, Closed for 3 months</td>
</tr>
<tr>
<td>1999, Mont Blanc, France-Italy</td>
<td>11600</td>
<td>Bi</td>
<td>HGV. Plausible diesel leakage on hot surface</td>
<td>39 dead, Severe damage on 900 m, Closed for 3 years</td>
</tr>
</tbody>
</table>

Ensure that the perceived safety level is high
According to Rawls’ first principle of justice everyone have equal basic rights and freedoms, e.g. freedom of movement, that can never be violated [55]. A high perceived safety level will increase the actual safety and the freedom of movement and reduces stress which are ethically important factors [24]. From the concept of duties it can be argued that society has a duty to provide a certain level of access to members of society [55]. A utilitarian approach is not well suited to account for issues of freedom [30, 55]. A deterministic approach is more suitable. The Perceived safety level can be evaluated with computer driving simulations and from operational driving experiences.

#5 TRADEOFFS AND CONCLUSIONS
The aim of this paper was to help a decision-maker to evaluate road tunnel fire safety, not in relation to other transport alternatives, but in relation to whether a specific tunnel is safe enough. Safety objectives as well as political, ethical and societal objectives were derived from literature, policies and regulation. Possible tunnel solutions need to comply with minimum requirements. Whether the tunnel is safe enough and what this means, largely depend on whether a deterministic or probabilistic design approach is adopted, and which ethical factors are emphasised.

Depending on the decision maker’s risk tolerance, he will prefer a smaller or larger residual risk. The risk tolerance is partly shown by the weight put on objectives, consequences and uncertainty. The
actual weight put on these factors depends on the values of the decision maker and her organisation. Often objectives conflict with one another, which is why trade-offs are inevitable.

Since several ethical factors support the perceived safety and since a high perceived safety level will improve safety, it is argued that a high perceived safety should be aimed at for all road tunnels. Although the consequences for catastrophic fires are uncertain, the relatively limited impact for catastrophic consequences, and its low likelihood of occurrence leads to that the weight put on this factor should be low for most road tunnels, in particular uni-directional road tunnels.

The five safety objectives defined in section #2 mainly depends on whether the tunnel is uni- or bi-directional, and on factors that affect the likelihood and consequences of fires, see Table 1. Among the objectives concerned with the level of safety, maximizing the utility with respect to the use of resources and availability, favours a probabilistic approach. In addition, issues of fairness need to be considered which means that enough safety is closer to minimum requirements than to a cautionary and deterministic approach.

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Engineering Analysis to Improve Safety of the Melocheville Tunnel as Recommended in the NFPA 502

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ABSTRACT

The 2014 edition of the NFPA 502 [1] “Standard for Road Tunnel, Bridges and Other Limited Access Highways” says that “regardless of the length of the facility, as a minimum, the following factors shall be fully considered as part of an engineering analysis of the fire protection and life safety requirements...”. In the spirit of the NFPA 502 [1] and best practices, an engineering analysis is required to determine the measures that needed to be implemented in order to ensure the safety of the users and the protection of the structure. The scope of the measures is defined by the characteristics of the traffic and the emergency response in case of fire.

The fire protection of any tunnel depends on the specific characteristics which allow establishing an overall fire scenario and then the means to improve the safety of the users in case of an incident. The level of improvement of an existing tunnel depends even more on such characteristics as the location of the fire brigade and the delay to arrive on the site.

In the case of the Melocheville Tunnel, an adapted worst case scenario has been established based on the traffic analysis and the probability and size of the fire which may occur in the tunnel according to the level of traffic before and after the construction of the nearby road; Highway A30. The response of the fire brigade and the access to the fire, were also evaluated to determine the effectiveness of the firefighting when compared with the development of the fire. The dangerous goods are presently not allowed in the tunnel.

This paper addresses the necessity and the benefits of an engineering analysis based on the actual characteristics compared to the previous characteristics. The changes to the traffic parameters have a direct effect on the results of the engineering analysis.

KEYWORDS: Specific tunnel characteristics, traffic analysis, risk analysis, fire protection, emergency response, fire scenario, firefighting, design fire.

ENGINEERING ANALYSIS of THE MELOCHEVILLE TUNNEL

The proper determination of the fire scenario and the resulting level of risk should be done through an engineering analysis and include relevant aspects of the traffic related to the case under consideration. This kind of evaluation has been done previously for some existing major highway tunnels and was recently conducted for the Melocheville Tunnel presented in the paper, an existing short tunnel passing under the St. Lawrence Seaway near Montreal. This tunnel has the characteristics of a tunnel of categories X or A according to the NFPA 502[1].

The initiative of the owner of the tunnel, the Jacques Cartier and Champlain Bridges Inc. (JCCBI) to include a life safety engineering analysis in the scope on the refurbishing of the Melocheville Tunnel, build in 1957, reflected the owners desire to evaluate the different factors affecting safety in case of a fire in the tunnel, based on a rational risk analysis and the safety performance of the tunnel facility in reference with the NFPA 502 [1] requirements. Risk assessment studies performed in the last years for two major tunnels in the Montréal region (one crossing the St. Lawrence River and the other under the city core) helped to develop an understanding of the wide range of topics related to the matter.
CHARACTERISTICS OF THE TUNNEL

The Melocheville Tunnel is 23.8 meters wide and 220 meters long, with two regional highway lanes (one per direction) plus an adjacent sidewalk in one direction. Three ventilation towers on each portal provide sanitary airflow in the tunnel. The main purpose of the tunnel is to cross under the St. Lawrence Seaway, which is a major passage for international maritime traffic into North America towards the Great Lakes. According to the 2013 Annual Report of The St. Lawrence Seaway Management Corporation [2], the fluvial traffic in the section Montréal - Ontario Lakes allows the passage of more than 28 million ton of cargo from about 2800 ships. The annual income from the seaway is about 29 million CAD during the 280 days the seaway is open to navigation.

Characteristics such as:
- the location of the structure and its environment,
- and the emergency response of the fire brigade in relation to accessibility,
were used in the implementation of an engineering analysis to determine how these parameters could help reduce the risk of a major fire and ultimately, reduce the needs for costly improvements in the Melocheville Tunnel.

Figure 1  The Melocheville Tunnel under the St. Lawrence Seaway.
EARLIER STUDIES

Earlier studies were done before the construction of the highway A30, while the tunnel still served for the transportation of dangerous goods and the circulation was higher. These studies covered the modernization of the tunnel automation systems [3] and the tunnel ventilation systems [4]. The recommendations from these studies, presented in Table 1, did not take into account the possibility of using natural ventilation as presented in article 11.1.1 of the NFPA 502 [1], but simply calculated the required air velocity as in appendix D of the NFPA 502 and analysed the existing ventilation system with regards to these requirements. The air velocity was calculated for a 150 MW fire.

The sanitary ventilation air flows recommendations in these studies were based on 1990 AIPCS emission values, which are about 10 times higher than present AIPCS values and for traffic levels that are higher than the present ones.

Table 1  Recommended measures from former studies.

<table>
<thead>
<tr>
<th>Recommended measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Increase the ventilation rate at all times.</td>
</tr>
<tr>
<td>2  Increase the ventilation rate to reach the desired air velocities and flows for a 150 MW fire.</td>
</tr>
<tr>
<td>3  Replace existing fans for 200°C rated fans.</td>
</tr>
<tr>
<td>4  Add warnings for air flow maintenance corridors/ventilation ducts beyond the accepted values according to AIPCS (2200 ft/min)</td>
</tr>
<tr>
<td>5  Protect tunnel structures from high temperatures.</td>
</tr>
</tbody>
</table>

However, the completion of Highway A30 in 2010 has changed the traffic situation considerably, as well as the transportation of dangerous goods was forbidden by decree in 2014 since there was now an alternative route. Therefore, a new evaluation of the traffic levels was done, as well as an analysis of the fire risk. An evaluation of the traffic analysis has been made, and the fire criteria were reviewed.
TRAFFIC ANALYSIS

As our goal is to underline the effect of traffic load on engineering analysis, we present the decrease in traffic after the Highway A30 commissioning in 2010. The annual average daily flow (AADF) before 2010 was around 12,000 vehicles. The AADF decreased to 4,500 vehicles after the commissioning. From those annual average daily flows, hourly flows per type of vehicles were calculated and they are presented in Table 2.

Table 2 AADF of Melocheville Tunnel before and after Highway A30 commissioning in 2010.

<table>
<thead>
<tr>
<th>AADF (Veh/day)</th>
<th>Before 2010</th>
<th>After 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 ways</td>
<td>12,000</td>
<td>4,500</td>
</tr>
<tr>
<td>1 way</td>
<td>6,000</td>
<td>2,250</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light vehicles</td>
<td>10,320</td>
<td>4,365</td>
</tr>
<tr>
<td>Heavy weight vehicles - bus</td>
<td>14% (1680)</td>
<td>3% (135)</td>
</tr>
</tbody>
</table>

RISK ANALYSIS OF INCIDENT IN THE “TUNNEL-LIKE” STRUCTURE

Before calculating the likelihood and the frequency of fires in the tunnel, it was decided to analyze the overall risks of incident. The West direction was found to present more risk than the East direction, because of:

- Two traffic lanes in operation;
- Higher speed;
- Sidewalk (pedestrians and bikes).

The analysis was based on the French concept. In North America, the statistics of accidents in tunnel are rare. In France, where we count hundreds of tunnels, the fires in tunnel are listed and statistics were established by the CETU [5] expressed in 100 million vehicles-kilometers. The rates are presented in Table 3 and correspond to road tunnels in non-urban and urban zones with low to strong slopes and curves. The CETU [6] also defines rates of occurrences of fires in a tunnel after a collision, as shown in Table 4. These values are used for the calculation of the frequency of fires in tunnels of this type.

Table 3 Rates of fires by 100 million vehicles-kilometers - CETU [6].

<table>
<thead>
<tr>
<th>Type of vehicles</th>
<th>Rate of fires by 100 million vehicles-kilometers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light vehicles</td>
<td>2</td>
</tr>
<tr>
<td>Heavy weight vehicles – Bus</td>
<td>from 1.5 to 4.5</td>
</tr>
</tbody>
</table>

Table 4 Rates of fires after collision by 100 million vehicles-kilometers – CETU [6].

<table>
<thead>
<tr>
<th>Type of vehicles</th>
<th>Rate of fires after collision by 100 million vehicles-kilometers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light vehicles</td>
<td>0.07</td>
</tr>
<tr>
<td>Heavy weight vehicles – Bus</td>
<td>0.05</td>
</tr>
</tbody>
</table>

According to the CETU [4], approximately every thirty fires are caused by collisions. The rates of occurrence are thus 30 times less than the global rates of the Table 4. The annual frequency of fires for a tunnel can be expressed by the following formula Eq. (1):

\[ F = \text{Rate} \times 10^{-8} \times (365 \times \text{AADF by way} \times \text{tunnel length}) \]  

The formula Eq. (1) represents the rate of occurrence by the number of kilometers traveled annually in the tunnel for a particular type of vehicle (cars and trucks). The calculation is similar for the annual frequencies of fires resulting from collisions shown in Table 5.
Table 5  Annual theoretical frequency of fires.

<table>
<thead>
<tr>
<th>Vehicles type</th>
<th>Before 2010</th>
<th>After collision</th>
<th>After 2010</th>
<th>After collision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global</td>
<td></td>
<td>Global</td>
<td></td>
</tr>
<tr>
<td>Light vehicles</td>
<td>0.0083 (1/120 yr)</td>
<td>0.0029 (1/345 yr)</td>
<td>0.0035 (1/285 yr)</td>
<td>0.00012(-95%) (1/8333 yr)</td>
</tr>
<tr>
<td>Heavy weight vehicles - bus</td>
<td>0.0017 (1/588 yr)</td>
<td>low</td>
<td>0.00012 (1/8333 yr)</td>
<td>low</td>
</tr>
<tr>
<td>Total</td>
<td>0.01 (1/100 yr)</td>
<td></td>
<td>0.0036 (1/276 yr)</td>
<td></td>
</tr>
</tbody>
</table>

Thus, by applying the rates of the CETU [6] to the traffic of the tunnel, an annual frequency of fires of 0.01 fire/year was estimated for any type of vehicle before 2010 and 0.0036 fire/year after 2010. Among these frequencies, 0.0017 fire/year implies a heavy weight vehicle or a bus before 2010 and 0.00012 fire/year after 2010. In other words, the global rate of 0.01 fire/year corresponds to one fire in every 100 years and the rate after 2010 of 0.0036 fire/year corresponds to one fire every 276 years.

Before 2010, the global probability of a fire is thus present (every 100 years), but the probability of a truck fire is very low (1/588 years). After 2010, the global probability decrease slightly to 0.0036 (1/276 years). The chances that a fire would occur is decreasing in the same ratio then the traffic level AADF (4 500/12 000 = 0.37).

Therefore, by applying the CETU rates to the Melocheville Tunnel, relatively low frequency rates for fires are obtained, no matter what type of vehicle. However, we observe a significant reduction following the opening of Highway A30, from 57 % to 95 % (see Table 4). Referring to Table 3, the reduction of the AADF is 62 % globally and 78 % for trucks and busses.

While the low calculated rates can be explained by the short length of the tunnel and its low rates of usage, the preceding analysis shows the impact of reduced traffic on the theoretical annual frequency of fires. As a guide, the same method, applied to similar tunnels in the Montréal metropolitan area, has given much higher yearly frequency rates of fires. In these three cases, the catastrophic scenario was based on a truck fire:

- The Ville-Marie Tunnel: Due to its length and intense usage, the theoretical annual frequency reached 0.71 for light vehicles and 0.07 for trucks, for an overall AADF rates of 48 000 and a heavy trucks traffic of 4 %;
- The Louis H-La Fontaine Tunnel: With an AADF of 65 500 and a high percentage (14 %) of heavy trucks traffic, the theoretical annual frequency reached 0.58 for light vehicles and 0.21 for trucks;
- A future short tunnel of 90 meters to be built as part of the Turcot Interchange Project: The theoretical annual frequencies are 0.055 for light vehicles and 0.008 for trucks for an AADF of 45 000 and a heavy trucks traffic of 7.2 %.

The global low probability of a fire in the Melocheville Tunnel could lead to question the needs for an eventual improvement according to the recommendations of the NFPA 502 [1]. It was therefore necessary to evaluate the effectiveness of the emergency response.

**EMERGENCY RESPONSE**

One of the main factors bound to the emergency response is the proximity of fire stations. The firemen are moreover the first responders in the emergency situation. In our case, two fire stations are close to the tunnel as shown in Table 6.
The nearest fire station, station n° 17, is located approximately at 5 kilometers from the tunnel, on the Beauharnois side. Figures 2 and 3 shows the location of the station and a proposed intervention route for the tunnel via the East and West entries.

Intervention times were estimated as 8 minutes to arrive to the East side of the tunnel. For the West side, if the suggested access is blocked, 11 minutes are requires, or 3 minutes more. This is possible due to the availability of Highway A30 that allows quick transit over large distances.

<table>
<thead>
<tr>
<th>Beaurnois fire station (#17)</th>
<th>Rough distance (travel time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>From East</td>
<td>5 km (8 min)</td>
</tr>
<tr>
<td>From Ouest (via A-30)</td>
<td>15 km (11 min)</td>
</tr>
</tbody>
</table>

Table 6 Distance and time of response of fire stations nearby.

TRAFFIC ANALYSIS HIGHLIGHTS

The main highlights of the traffic analysis are:
- The annual frequency of fires before 2010 of the tunnel was 0.01 fire/year for all vehicle types (every 100 years);
- The annual frequency of fires after 2010 of the tunnel is 0.0036 fire/year for all vehicle types (every 276 years) which reflect the lower traffic;
- Since 2014, no hazardous material goods are allowed in the tunnel;
- As a major passage for international maritime traffic, the seaway can be affected by a major fire in the tunnel;
- The response of firefighters would be relatively fast and within 8 or 11 minutes from the event identification;
- Heavy weight vehicles traffic decreases significantly (from 14 % to 3 % of AADF) after 2010 which reduce, in proportion, the level of annual theoretical frequency of fires.

Mitigation measures

According to the NFPA 502 [1], the mitigation measures to improve emergency response and safety, should be as follows:
- 24/24 cameras of video surveillance with incident detection;
- Fire hydrant in tunnel with chemical extinguisher.

At the time, no mitigation measure was analysed or planned at the Melocheville Tunnel to reduce the response time in case of incident and potential fire.

ADAPTED SPECIFIC HAZARD INVESTIGATION

A worst case scenario is a suite of plausible events leading to a fire which would occur in the tunnel considered in the study. The worst case scenario was developed to see the impact of such an event on the infrastructure and the users, in particular. Ideally, the scenario implies different players: road users, operators of the tunnel, road supervisors, emergency services, etc.
An elaboration of the worst case scenario involves professionals from different domains such as traffic, ventilation, structure, etc. The multidisciplinary approach allows juxtaposing in a most objective way, in a “space-time” graph, all relevant events creating an easy to read picture of the scenario. This procedure is strongly recommended by the PIARC [8]:

- One of the objectives is to visualize the interrelations;
- Another is to identify the mitigation measures which can reduce the potential risk factors.

To follow an approach inspired by the CETU [6] it is thus advisable to:

- Choose a design fire;
- Propose an adapted worst case scenario;
- Analyze the temperatures and smoke generated by the fire;
- Represent the adapted worst case scenario in the “space-time” graph.

PARAMETERS RELATED TO THE FIRE

The fire scenario was established based on the traffic analysis and the probability and size of the fire which may occur in the tunnel. The response of the fire brigade and the access to the fire were then evaluated to determine the efficiency of the firefighting, when compared with the development of the fire. The effect of the existing ventilation system was taken into consideration.

Determination of the Fire Scenario

The analysis of the traffic data and the determination of the probability and potential of the fire were done based on the “Guide to Road Tunnel, Safety documentation - Specific Hazard Investigations” issued by CETU [7]. The existing data for the traffic were incorporated into the analysis. The geometry of the tunnel was considered in parallel with the fire size to choose the curve representing the condition within the tunnel. The efficiency of the firefighting was applied to the growth of the fire curve and then used as a parameter in the analytical simulation to determine the two scenarios.

Design Fire Sizing

On the basis of the analysis done in the fire scenario, an 8 MW fire was chosen for the simulation. This corresponds to a light vehicle fire, the most likely to happen in the tunnel.

A second simulation was also conducted on the basis of a 30 MW fire for a heavy truck in order to establish if the structure was at risk due to the heat from an unlikely, but possible, larger fire.

Finally, for the purpose of comparing with the situation existing before 2010, a fire simulation was done for a 50 MW fire, considering that there were effective mitigation measures existing at the time, specifically a special procedure that was activated for safety during the transportation of dangerous goods, making a regular large truck fire the most likely dangerous event. The CETU does not provide a curve for such a 50 MW, only a more intense 100 MW event, so development rates similar to those for a 30 MW fire were used.

Calculation of the actual performance

Based on the fire curve established via the fire scenario, the FDS (Fire Dynamics Simulator) models were created to represent the facility system and an analysis was performed to determine the temperature at the surface of the structural elements as well as the smoke distribution. As a first step in the analysis, the critical velocity, as described in Annex D of the standard NFPA 502 [1], was determined by calculation for the 8 MW and the 30 MW fire. The existing ventilation system was unable to provide the required velocity in both cases, and the simulations were done with this system out of operation as a worst case scenario.
The 8 MW FDS simulation was then done to evaluate the smoke level in the tunnel in a natural ventilation scenario. The simulation showed that the smoke was evacuated in an adequate way from the tunnel ends and that user safety would be adequate in the case of such a fire.

The second simulation, with the 30 MW fire, was then conducted over the entire 90 minutes burn of an uncontrolled fire. The air temperature at the ceiling reached a maximum value of 335 °C. This is insufficient to damage the concrete. Therefore the structural safety is not compromised by a 30 MW fire.

The results are compatible with the recommendations of the NFPA for tunnels of less than 300 meters and CETU for less than 1 000 meters in non-urban, low traffic areas, where natural ventilation is deemed sufficient.
The third simulation was done for a 50 MW fire for the conditions existing before 2010. It can be seen that the surface temperature is considerably higher, reaching 1 000 °C just over the fire.

**Discussion regarding the surfaces temperatures for the concrete roof**

The surface temperature at the concrete is a function of convection and radiation from the fire, as well as the conductivity of concrete. A large part of the fire’s radiation is absorbed by the roof and the air. As far as the surface temperature is concerned, it is largely a factor of the convective heat transfer at the air concrete interface, balanced by the heat transfer rate of the concrete. The models showed surface temperatures of 115 °C for an 8 MW car fire and of 335 °C for a 30 MW light truck fire.

Supposing, very conservatively, that the surface concrete temperature is almost equal to the air temperature, it is clear that damage to the concrete is unlikely at these temperatures.

However, for the larger 50 MW fire, the surface temperatures were considerably higher and reached 1 000 °C, particularly because this simulation was done with the fire much closer to the roof, simulating a heavily loaded truck. It might be possible that damages would results from a prolonged fire in such a case, however the detailed structural evaluations were not carried out in the scope of this study.

**Discussion on firefighter intervention**

The intervention of firefighters in a similar situation for a 50 MW fire was evaluated in a previous study [10]. This study concluded that it was such a fire, that fire fighters would be capable of approaching the fire sufficiently to intervene with fire hoses and reduce the impact of the fire.

**Gap analysis with the NFPA 502**

A gap analysis was conducted in regards to the NFPA 502 to establish the differences between the actual and the desired situation and evaluate the actions required after the engineering analysis. Table 7 shows the results of the analysis:
Table 7   Recommended measures from former studies after engineering analysis.

<table>
<thead>
<tr>
<th>Recommended measures from studies</th>
<th>Recommended measures from engineering analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Increase the ventilation rate at all times.</td>
<td>Not required according to analysis</td>
</tr>
<tr>
<td>2. Increase the ventilation rate to reach the desired air velocities and flows for a 150 MW fire.</td>
<td>Design fire about 8MW, no improvement needed</td>
</tr>
<tr>
<td>3. Replace existing fans for 200°C rated fans.</td>
<td></td>
</tr>
<tr>
<td>4. Add warnings for air flow in maintenance corridors (beyond accepted values according to AIPCS) (2200 ft/min)</td>
<td>Actual rate is 10 time the need so too high for safety need</td>
</tr>
<tr>
<td>5. Protect tunnel structures for high temperatures.</td>
<td>High temperature can occur in case of major fire with low probability. Emergency response should be less than 10 minutes</td>
</tr>
</tbody>
</table>

DISCUSSION

The engineering evaluation performed for the Melocheville Tunnel discussed in this paper allowed for the inclusion of all parameters relevant for the calculation of the actual performance and for the evaluation of the required improvement which could be put in place. The main goal being to insure the safety of the users and improve the emergency response plan in case of a major fire.

The transition from a tunnel with dangerous goods to a tunnel without dangerous goods reduced the level of risk, as well as the reduction in traffic density. Finite element modeling simulations show that the operation of the ventilation system in the case of the probable fire scenario was not required to ensure user safety and the structural integrity of the tunnel. Fire curve analysis from previous studies shows that fastest fire brigade intervention would reduce the risks. The addition of cameras as a fire detection system would help to ensure this fastest intervention.

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Developing a Practical Guideline for Smoke Dispersion Analysis (SDA) for Development in the Vicinity of Underground Transit’s Tunnel Ventilation System (TVS) Shafts

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ABSTRACT
To protect the safety of passengers and patrons, sub-surface transportation infrastructure (SSTI), such as subways, require mechanical ventilation due to their inherently limited air circulation and emergency egress opportunities. The applicable legislations and standards, in particular NFPA 130 (Standard for Fixed Guideway Transit and Passenger Rail Systems), provide a framework for assessing the ventilation requirements, which in turn drive the selection of the ventilation solution. In case of a fire emergency scenario within the SSTI, mechanical ventilation system would be activated, blowing smoke out of the vent shafts at surface. Fresh air would be pulled into the SSTI to replace the exhausted contaminated air. This fresh air flows into the system normally through station entrances and openings such as supply air shafts and the tunnels. The smoke with higher temperature being exhausted can be expected to move upward (creating a plume). However, wind and the surrounding buildings will cause the plume to deflect and potentially disperse. Depending on the wind direction and arrangement of the surrounding buildings, the deflected plume could result in a portion of the smoke mixing with the fresh air which gets recirculated back into the SSTI through an entrance. There is also a potential for ingress of the mix into the adjacent buildings through the buildings’ HVAC systems or through operable doors and windows.

To confirm that there will be minimal risk to the SSTI and adjacent buildings occupants’ health and to minimize property damage, the effects of the exhausted smoke are studied using Computational Fluid Dynamic (CFD) analysis. This is known, in the industry, as a Smoke Dispersion Analysis (SDA). In this paper, to establish proper SDA methodologies and criteria a combination of research on the existing and published material together with sample SDA analysis and simulations to provide some insight are presented.

KEYWORDS: Tunnel Ventilation, Ventilation Shafts, Smoke Dispersion, CFD analyses
INTRODUCTION
Sub-surface transportation infrastructure (SSTI) requires ventilation due to their inherently limited air circulation and emergency egress opportunities. The applicable legislations and standards, in particular NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems (2014), provide a framework for assessing the ventilation requirements, which in turn drive the selection of the ventilation solution.

The functional requirements of a transit system’s mechanical tunnel ventilation system (TVS) are:

- During normal conditions: to supply breathable air for the tunnel and station occupants and to maintain tunnel and station ambient temperatures within specified criteria.
- During an emergency (fire) event in the tunnels or stations: to maintain tenable conditions along the egress route for the specified egress period.

Figure 1 below shows TVS facilities and equipment at a typical transit station under emergency operation scenario.

![Figure 1: Typical TVS Facilities at a Transit Station](image)

NFPA 130 requires the design of the TVS to be supported by comprehensive engineering analysis. The analysis involves dynamic, time dependent computational modeling of the aerodynamic and thermodynamic behaviour of the surrounding environment for a number of scenarios and design conditions.

In an emergency case, when smoke is exhausted via the TVS exhaust shaft and discharged from the grates at street level, the momentum of the discharge, the buoyancy of smoke and the turbulence of the wind around the buildings, causes mixing of the products of combustion with outdoor air. There is a potential for ingress of the mix into the SSTI or the adjacent buildings through their HVAC systems or through operable doors and windows. As a result, and to confirm that there will be no/minimal risk to the adjacent buildings, SSTI, and their occupants, it is necessary to study the effects of the exhausted smoke on the surrounding buildings using a Computational Fluid Dynamics (CFD) analysis to produce a Smoke Dispersion Analysis (SDA).

The necessity of performing an SDA is sometime disputed with the argument that there could also be a burning truck on the road and no particular studies are made for all scenarios of such fires. It is important to establish the differences of a truck/car fire versus an incident in an SSTI, and establish the need for an SDA. A truck/car fire in the street and a fire in an SSTI are fundamentally different because of three major reasons categorised as follows:

- **Statistical**: When dealing with SSTIs, with regard to fire/emergency cases, there is fixed equipment installed in certain locations, with certain capacities and defined fire scenarios which in turn will be translated into calculated risks, which need to be dealt with. However when dealing with a truck/car fire in a street the statistical chances of a fire in a certain location combined with a specific wind direction and a certain fire scenario will be close to zero.
- **Psychological**: In case of a truck/vehicle fire in the street, the open flames at the street level are visible and will trigger reactions from people in the vicinity of the fire; even the presence of an emergency vehicle at the area will trigger a sense of emergency in people around the danger zone. However unlike an open flame, in the case of a fire at a SSTI, the ventilation shafts will only exhaust smoke, which may not trigger the same sense of urgency in people. In case of such an event happens during the dark hours, people may not even notice the
exhausted smoke until it is too late. In addition, in case of fire in SSTIs, the emergency vehicles may approach and provide services to an area far from the smoke extraction shaft locations (for instance station entrances, which may be 50m-100m away from TVSs) and as a result an emergency situation regarding the exhausted smoke from those shafts may not be triggered.

- **Owner’s/Operator’s liability:** When installing permanent facilities in urban environments, the owners and operators of those systems are required to safeguard the public safety. Not performing an SDA to analyse and assess the risks associated with the SSTIs’ fire/emergency scenario may, not only, result in possible preventable loss of life and/or property, but it may also result in further complications (such as law suits).

**THE ISSUE**
Requirements, acceptable criteria and guidance on how to develop an SDA analysis for areas in the vicinity of the SSTIs’ ventilation shafts are vague. There is no published guideline to perform this work. In this paper, a step by step practical guideline for SDA analyses is established and explained. The approach uses recent SDA analyses for new residential development and transit projects in Ontario, Canada

**MAJOR PARAMETERS AFFECTING SMOKE DISPERSION ANALYSIS**

**Sensitive Receptors**
Sensitive Receptors (SRs) are features within the street environment, such as entrances and HVAC intakes, which are considered to be particularly sensitive to smoke entrainment. For instance, the presence of smoke of a certain concentration at station entrances has the potential to impede passenger evacuation and hamper Fire Department access. There is also potential for smoke to be re-entrained back into the SSTIs through the entrances or nearby HVAC/Make-up air intakes. Re-entrainment through HVAC intakes is mitigated, however, by smoke detectors within the intake ductwork which will shut down the HVAC system, or put it into recirculation mode, upon detection of smoke in the airstream. Although the presence of smoke in the vicinity of adjacent building entrances is undesirable, the buildings and their occupants are not at direct risk from the fire itself and there is no need for evacuation. As a result, occupants may remain within the buildings in a place of safety until such time as conditions on the street allow them to leave. Alternatively, it is expected that occupants might evacuate the adjacent buildings through secondary means of exit, such as doorways leading to the back of the buildings. It is also possible that discharged smoke could be drawn into a building’s fresh air intakes; however, any centralized HVAC serving a significant occupancy would likely have an automatic shut-down sequence to guard against smoke entrainment.

Before performing any SDA analysis, it is of crucial importance to clarify and understand the extent of sensitive receptors as set by the project. For instance, in a recent project the following was specifically mentioned:

“*A smoke dispersion analysis for emergency ventilation systems shall be undertaken to demonstrate the following:*

- **Smoke discharged from emergency ventilation shafts is not drawn into the Station entrances or other Station air intakes; and**
- **Smoke discharged from emergency ventilation shafts is not drawn into entrances or air intake shafts of adjacent buildings.”*

Before performing any SDA analysis it is of crucial importance to clarify and understand the extent of sensitive receptors as set in the project. With such a clear statement, it is very easy to identify the sensitive receptors and provide measureable results.

As such the first step to a successful SDA is proper identification of sensitive receptors by a thorough investigation of the TVS ventilation shafts adjacent areas. Figure 2 depicts the sensitive receptors identified in a recent project.
Properties of Exhausted Smoke
The most significant parameters affecting the SDA are related to the properties of exhausted smoke, the main parameters in this category are:

- Concentration of Smoke: the flow coming out the ventilation shafts are a combination of fresh air and the smoke. The smoke is generated due to a vehicle fire, and as such the amount of smoke can be calculated using the vehicle fire properties and ventilation fan capacities. Appendix A of this paper provides a sample calculation procedure to determine the smoke concentration. In general for a typical vehicle fire load ranging between 5MW to 15 MW, resultant smoke concentration levels of 5% to 20% are expected.

- Flow rates and velocities: Although the flow rate and velocity of air and smoke mixture coming out of the ventilation shafts are also important factors, it is relatively easy to establish these, as they are a linear function of ventilation fan capacities and ventilation shafts sizes. These properties are in general, much less disputed between parties.

Wind Speed and Direction
Wind speed and direction are probably the most disputed parameters in performing an SDA, partly due to their randomness and statistical nature. Based on NFPA92 recommendations, a wind speed (WS) of 1% probability of exceedance is recommended to be used for SDA simulations. Reference 5 of this paper provides a detailed insight on the effects of wind on smoke control. Figure 3 depicts the effect of wind speed on the outcome of an SDA simulation. As shown in this example, while the results of the SDA due to the 1% wind velocity shows signs of possible issues (Yellow and Red colour), the lower wind speed shows significant improvement with no sign of a possible issue.
Wind direction cases in SDA are one of the most disputed parameters. This is mainly due to the fact that the wind direction has a major impact on the outcome of SDA. Figure 4 shows the effect of the wind direction on the outcome of a sample SDA for a high rise condo in downtown Toronto. As depicted in this figure, the wind direction can have a major and defining effect on the outcome of SDA, and this is why it is crucial to be defined carefully. In case there is no specific requirement from the owners/client it is recommended to consider the following major wind directions as a conservative assumption:

- Most prevalent wind direction based on annual wind statistical data
- Two additional wind directions, 90° and 270° from the above
- Second most prevalent wind direction based on annual wind statistical data
- Two additional wind directions, 90° and 270° from the above
- Wind direction(s) blowing directly over the ventilations shafts’ grating and towards the sensitive receptor under investigation

It is also of importance to note that the wind speeds through downtown cores will normally vary from airports due to the increased surface roughness around cities and the height of the buildings. ASHRAE describes the method (equation 4) to convert wind speed measured at an airport to areas of different terrain categories.

Figure 4: Effect of wind Direction on SDA Outcome (Right: West Wind Direction, Left: East Wind Direction)
SDA ACCEPTANCE CRITERIA
The ultimate goal of the SDA is to confirm the safety of the occupants of the sensitive receptor(s) under investigation. To provide the safety of the occupants and residents, the buildings under investigation shall at least maintain a tenable environment at all times, or a proper smoke management and/or evacuation procedure shall be in place. Four main parameters are used to define the tenability of spaces, they are:
• Visibility
• Temperature
• Toxin levels (in a fire case, CO levels)
• Air Velocities

Study results shows that in case of an SDA scenario, Air Velocities and Temperatures are not a concern, and the only parameters that need to be considered are Visibility and CO concentration levels.

Based on the guideline provided in the ASHRAE Handbook, Chapter 53 and previous experiments documented in ASHRAE transaction 2009, to achieve a tenable environment a dilution ratio of 1% (equivalent to a level of smoke contamination of 10,000ppm) when compared to the immediate fire area concentration will satisfy both visibility and CO concentration requirements.

Considering the fact that SDAs, and smoke movement in general, are inherently subject to uncertainties, it is recommended to use a dilution ratio of 1%, when compared to the concentration of the smoke at the SSTI’s ventilation shaft gratings.

DEVELOPING AN EFFECTIVE SMOKE MANAGEMENT SYSTEM WHEN THE SDA ACCEPTANCE CRITERIA ARE NOT SATISFIED
In reality due to proximity of major underground subways and transportation projects to the commercial and residential buildings, especially where those projects are executed in the downtown cores of major cities, it proved impossible to satisfy the SDA criteria requirements at all times. As a result and as stated previously, to protect the safety of public, an effective smoke management system/procedure needs to be in place. In the following example, from a real SDA case in downtown Toronto, a sample smoke management system to protect the safety of the residents in the vicinity of SSTI’s ventilation shafts is described.

Case Description
Figure 5 below shows the location of a proposed development in downtown Toronto. The development involves the demolition of the existing 1 and 2 storey retail/commercial buildings on the site and building of a mixed-use residential complex. The development will consist of a 5 and 3 storey connective podium and two towers. The south tower will have the height of 164.0m, (52 storeys) and the north tower 74.0m, (23 storeys) respectively.

Figure 5: Location of the Proposed Development
This development is in very close proximity to an existing SSTI ventilation shaft. This proximity to a potential smoke source necessitated an SDA, to ensure the safety of the public is observed at all times. Figure 6, shows the proximity of the Building to the SSTI’s ventilation shafts.

Figure 6: Proximity of the Proposed Development to the Ventilation Shaft Locations

Figure 7 shows the results of the SDA due to a Western Wind direction, the dark red colour indicates high levels of contamination. The exhausted contaminants diffuse into the air and are pushed into the building. The planned canopy on the back of the building can partially contain the smoke, however, the smoke moves upwards along the building façade due to the wind and the local air flows. As shown, the residential units of the south tower up to the 13th floor may be affected in this case. As established in the study, the residential units are equipped with individual HVAC units and air intake and as such there is a possibility of smoke ingress into the building in an emergency case. As a result and to protect the safety of the residents, the HVAC equipment of each residential unit at the south tower, up to 13th floor, was designed to be equipped with smoke sensors and motorized dampers. In addition, all operable doors and windows of those units are equipped with sensors to monitor open/close statues. Also, smoke detectors will be installed in the SSTI’s exhaust shafts as well. If the smoke detector at the unit is activated due to presence of smoke, the HVAC unit will shut down and the motorized damper will close automatically. As an additional safety level, if the smoke detector at the ventilation exhaust shafts is activated, the building fire alarm system will send a signal to the designated units with an open door/window to alert the occupants by way of a local alarm.
CONCLUSIONS
To protect the safety of the public, the study of smoke dispersion in the vicinity of underground infrastructure system’s ventilation shafts are highly recommended and is required by law in some jurisdictions. It is of utmost important to realize that these studies are inherently full of uncertainties. As discussed in this paper, major parameters such as wind speed and direction, fire source, and concentration of smoke in the exhaust contain uncertainties and need to be established and agreed upon before such a study is undertaken. Based on multiple studies and sensitivity analyses performed, this paper provides suggested values and direction on how to set these parameters, at least as a first or preliminary choice. In addition, this paper provides an insight on how to provide an effective smoke management system, when, in some cases, the SDA criteria cannot be achieved. Finally the Authors hope that this paper inspires and encourages more technical and in-depth research in this area, which may result in the development of required codes and guidelines for this subject.

REFERENCES
APPENDIX A- A SAMPLE CALCULATION PROCEDURE TO DETERMINE THE SMOKE CONCENTRATION

There are two parameters involved in calculating the fire smoke release rate, $\dot{m}$, in the event of a fire from a train. These are the fire heat release rate for a fully developed train, $Q$, and the heat of combustion, $\Delta H_c$, which represents the energy release under complete combustion. These values are shown below and are selected based on CFD Design Criteria [CFD-DC] (Table 8).

The fire smoke release rate is calculated by dividing the fire heat release rate for the train by the heat of combustion as follows:

$$Q = 13.1 \text{ MW}$$
$$\Delta H_c = 18 \text{ MJ/kg}$$

Air to Fuel ration (AFR) = 14

$$\dot{m} = \frac{Q}{\Delta H_c}$$

$$\dot{m} = \frac{13.1 \text{ MW}}{18 \text{ MJ/kg}}$$

$$\dot{m} = 0.728 \text{ kg/s}$$

Assuming the density of air and smoke are the same and given that the Air to Fuel Ratio (AFR) is 14, the quantity of smoke can now be determined as follows:

$$\dot{m}_{\text{smoke}} = \dot{m} + \text{AFR} \times \dot{m}$$

$$\dot{m}_{\text{smoke}} = 0.728 + 14 \times 0.728 \text{ kg/s}$$

$$\dot{m}_{\text{smoke}} = 10.91 \text{ kg/s}$$

Therefore the smoke generated in a train fire would produce **10.91 kg/s** in the event of a fully developed train fire based on the design parameters stated above.

Density of Air is 1.127 kg/m$^3$ @40°C, which means, the amount of contaminated air coming out of vent shaft will be:

$$10.91 \text{ kg/s} \div 1.127 \text{ kg/m}^3 = 9.68 \text{ m}^3/\text{s}$$

The resultant smoke concentration discharged at the grate from a train fire at the station is based on the assumption that all of the smoke generated at the platform is extracted by two fans at that end of the station, and it is split equally between the two vent shafts:

$$200(\text{m}^3/\text{s}) \times 1.127 = 225.4 \text{ kg/s}$$

The percentage of the smoke will be **4.8%**, which, for the purpose of this study, will be conservatively estimated as a **10%** smoke contamination and will be used in further calculations and simulations.
ABSTRACT

The Alaskan Way SR99 Tunnel is currently under construction and the world’s largest soft ground bored tunnel. This design-build project is located in Seattle and consists of a single bore tunnel that is 9,200 feet long. The roadways are stacked with an egress corridor with utility spaces and smoke extraction duct positioned at the sides along with a drainage utilidor in interstitial space below the bottom roadway and tunnel liner.

Roadway drainage inlets are positioned along the length of the tunnel to allow safe and effective drainage of fire suppression water flows along with tunnel wash operations activities. Fixtures designed for differential movement are incorporated in drainage network to accommodate thermal expansion created by construction process and seasonal temperature changes. System design incorporates surge chamber, detection and ventilation systems to mitigate fire hazards present for liquid fuel spills in tunnel.

Gravity drainage conveyed to the tunnel midpoint at lowest elevation is treated and discharged into force main transit pipe to convey drainage flows out of tunnel to local storm water surface collection network. Dry sump pump station includes oil water separator, settling basin and innovative surcharge reservoir configuration to utilize tunnel invert volume.

KEYWORD: liquid fuel, fire hazard, tunnel drainage, fire suppression, hydrocarbon detection, surge chamber, dry sump pump chamber

INTRODUCTION

Tunnel accident involving fire incident is a low frequency event. However, its consequence is serious if tunnel safety systems are not designed for robust and reliable operations. Systems such as ventilation and overhead fixed fire sprinklers provide direct response to fire hazards. However, tunnel drainage systems provide crucial secondary support for limiting fire size and mitigating flooding hazards within the tunnel. Agency design criteria and performance parameters of Washington State Department of Transportation (WSDOT) are incorporated into the design or must be incorporated into design to maintain facility operations custody from the design team to the facility operators. The following provides a description of the major components:

- New enclosed drainage systems will be installed in the South Portal area for the depressed roadways leading into the South Portal of the tunnel. The depressed roadways will be far enough below ground level that it will not be feasible to convey the tunnel discharge to the local combined sewer system using only gravity lines. The enclosed drainage systems in the depressed roadways will collect and convey runoff to a South Stormwater Pump Station (SSWPS) located in the tunnel cut-and-cover section. The stormwater will be pumped from the SSWPS to a manhole on the surface, where it will gravity drain through a new storm drain pipe and discharge to the combined sewer.

- The WSDOT Alaskan Way Viaduct Replacement Program has a stormwater code flow control exception for the south portal drainage basins. Therefore, no detention will be provided for the south roadway and South Operations Building site runoff. Stormwater
quality treatment is not required for stormwater discharging to the combined sewer system. Flow control and runoff treatment facilities will not be provided for the south portal area.

- The basic components of the tunnel and cut-and-cover drainage collection system consist of gutters and grated inlets in the roadway, which collect runoff from fire suppression during a fire event. The inlets connect to a main collection header pipe through six-inch diameter lateral pipes. The header pipe conveys tunnel runoff to the low point pump station (LPPS) via gravity. Runoff is then pumped from the LPPS to the SSWPS through an intermediate Mid-Point Pump Station (MPPS). The SSWPS discharges the runoff from the low point, the headhouse roof, the South Operations Building roof, and the south depressed roadways in a single combined force main pipe to a storm drainage manhole.

- After completion of the SR 99 Tunnel Project, new depressed roadways and new enclosed drainage systems will be constructed by a separate project. The depressed roadways will be far enough below ground level that it will not be feasible to convey the tunnel discharge to the local combined sewer system using only gravity lines. Drainage systems from future project will collect and convey runoff to a North Stormwater Pump Station (NSWPS) located in the tunnel cut-and-cover section in the vicinity of the North Operations Building. The stormwater will be pumped from the NSWPS to a storm drainage manhole.

METHODOLOGY

Tunnel drainage system design required holistic approach of addressing multiple drainage functions within a single system. The following key issues are required to be incorporated into the design;

- Tunnel portal configuration of impervious surfaces and drainage structures is evaluated to determine extent of rainwater flows that will be captured by tunnel portals
- Fire incident sprinkler flows are evaluated to determine water based suppression system generation of roadway drainage flow quantities that would need to be accommodated by pump lift stations.
- Maintenance tunnel cleaning operations are evaluated for generated flow rates and cleaning materials that must be treated before drainage to acceptable surface water discharge sites.
- Roadway grade and super elevation are configured to optimize cross road surface drainage flows and drainage inlet placements to minimize the amount of water (or liquid fuel) pooling area on roadway.
- Drain inlet bodies and drain outlet locations are designed to minimize tunnel air circulation access to surface area of liquids in drainage system.
- Hydrodynamic calculations are completed to size storm drainage lift pump equipment and associated electric motors required to convey tunnel drainage out of tunnel.
- Confined atmospheres within drainage vaults, dry and wet well pump rooms are evaluated for minimum ventilation flows to limit risk for flammable/explosive atmospheres

Figure 1 provides an overview of the system with interconnecting piping routing indicated. Note pump station elevations were established to facilitate cost effective pump equipment selections.

PERFORMANCE CRITERIA, STRUCTURAL CONSTRAINTS AND PUMPING SCHEME

Bored tunnel and cut-and-cover drainage sections

Currently there are no existing specific design guidelines or criteria established for roadway drainage collection and conveyance systems within tunnels. The WSDOT Hydraulics Manual only provides guidance for the design of drainage systems for stormwater runoff resulting from precipitation. As precipitation will not fall directly on the pavement surfaces within the tunnel and cut-and-cover sections, many of the Hydraulics Manual guidelines are not applicable.
Therefore, the following project-specific drainage design criteria were developed and approved:
Drainage collection systems are typically spaced to minimize the buildup of water on the roadway to reduce the potential for vehicle hydroplaning. The roadway drainage systems have been designed assuming that the tunnel will be closed to the public during tunnel washdown and fire protection systems testing, and that tunnel users will be required to evacuate their vehicles during a fire event. Therefore, it was determined the inlet spacing in the tunnel would be based on a maximum flow depth in lieu of a flow event. As a result, the flow spread width, velocity, bypass flow and cross flow of water flowing on the tunnel roadway surface (at superelevation transitions), which are typically minimized due to concerns with hydroplaning were not accounted for in the inlet spacing design because vehicles will be stopped or travelling at reduced speed.

The flow depths at the barrier face were checked for the fire flow event to facilitate access to the egress passage. The design uses a maximum flow depth of five inches at the barrier face throughout the tunnel sections to minimize the amount of water that could flow through the egress doors and potentially enter the electrical rooms. This flow depth is also less than the height of a standard six inch curb found on a typical roadway, and was determined to be reasonable. There will be one location at the Northbound North Portal that will have a flow depth of six inches. This location is on the east side of the tunnel at the 2-foot shoulder area, on the opposite side of the tunnel from the egress doors. It was determined that a six inch ponding depth would be acceptable at this location because the flow depth at this location will not affect the egress doors or electrical rooms. The fire event flow depths at the barrier face at typical locations in the tunnel sections vary, and the maximum flow depth at each section is summarized in Table 1 below:

<table>
<thead>
<tr>
<th>Location</th>
<th>Maximum Flow Depth (ft)</th>
<th>Maximum Flow Depth (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Portal, NB Roadway</td>
<td>0.49</td>
<td>5.9</td>
</tr>
<tr>
<td>North Portal, SB Roadway</td>
<td>0.34</td>
<td>4.1</td>
</tr>
<tr>
<td>South Portal, NB Roadway</td>
<td>0.36</td>
<td>4.3</td>
</tr>
<tr>
<td>South Portal, SB Roadway</td>
<td>0.23</td>
<td>2.8</td>
</tr>
<tr>
<td>4.00% Longitudinal Slope Areas</td>
<td>0.24</td>
<td>2.9</td>
</tr>
<tr>
<td>3.60% Longitudinal Slope Areas</td>
<td>0.24</td>
<td>2.9</td>
</tr>
<tr>
<td>1.60% Longitudinal Slope Areas</td>
<td>0.28</td>
<td>3.4</td>
</tr>
<tr>
<td>Sag Points</td>
<td>0.36</td>
<td>4.3</td>
</tr>
<tr>
<td>S-NBON Ramp</td>
<td>0.42</td>
<td>5.0</td>
</tr>
</tbody>
</table>

1 The 5-6 inch maximum flow depths at the NB North Portal and at the S-NBON Ramp are on the east side of the tunnel at the 2-foot shoulder area. The flow depths will not affect the egress doors or electrical rooms.

Tunnel and cut-and-cover section drainage inlet spacing is based on the fire zone length. The inlets are centered over the boundaries between adjacent fire zones. In the tunnel sections, the fire zone is 108.33-feet in length and 33.25-feet in width (the width of the roadway). The fire zone dimensions in the cut-and-cover sections vary as the roadway widths are transitioning into and out of the stacked configuration in these areas. The sprinkler deluge zones have been designed to have a maximum deluge sprinkler water discharge in any two adjacent deluge zones that does not exceed 2,500 GPM.

Inlets are located on the low side of the super elevated roadway. Tunnel transverse section in Figure 2 shows where the flow depth must be minimized at locations where the superelevation low point is on the side of the egress passageway and electrical rooms. The flow not caught by an inlet will be allowed to flow downstream to the next inlet until all the flow is collected by the system. The number of inlets in the sag (low point) has been
determined for the fire flow event using analysis methods included in the WSDOT *Hydraulics Manual*.

Figure 2  SR-99 Tunnel Transverse Cross Section.

- The tunnel drainage main collection header pipe is routed along the west side of the tunnel in the Invert Utilidor level. The header pipe capacity is sized for the maximum drainage requirement of 4,000 GPM. If there is a fire event in the tunnel sections, the fire suppression system will activate two adjacent deluge zones for the single fire event.

- The main collection header pipe and pump stations are located on the west side of the tunnel. The Invert Utilidor maintenance access manholes are located on the wider west shoulder of the northbound roadway, allowing for access to these systems from above.

**Tunnel pump stations**

The tunnel pump stations include the following systems:

- The basic components of the LPPS consist of a flow splitter, pre-settling basin, oil water separator, wet well, pumps, discharge piping, and controls and alarms. The LPPS will receive the drainage in a pre-settling cell where settleable solids are settled out prior to pumping. The pre-settling basin will normally be full, and as additional water enters, the existing water will be displaced over a baffle and flows into the oil water separator. The oil water separator allows for the oil particles to rise to the surface and be contained behind vertical baffles. The separated water then flows through a downturn elbow (orifice) which controls the flow into the wet well. Water is then pumped from the LPPS to the SSWPS through the intermediate MPPS. The SSWPS discharges the runoff from the low point, the headhouse roof, the South Operations Building roof, and the south depressed roadways in a single combined force main pipe to a manhole adjacent to south portal.
• The MPPS is a booster pump station. The MPPS consists of a wet well where the water pumped up from the LPPS is discharged and then pumped to the SSWPS, and a dry well where the pumps are housed.

• The basic components of the SSWPS consist of a pre-settling cell, trash rack, wet well, pumps, discharge piping, and controls and alarms. The SSWPS will receive stormwater flowing into the South cut-and-cover portals in a pre-settling cell where settleable solids are settled out prior to pumping. The runoff will flow through an opening with a trash rack into the wet well where the stormwater will be pumped through a discharge line to the force main discharge manhole at Alaskan Way South and South King Street. A manual bypass pump in the pre-settling cell will allow the maintenance tunnel wash down water (industrial process water) to flow down to a LPPS for treatment prior to discharge to the combined sewer system.

• The basic components of the NSWPS consist of a pre-settling cell, trash rack, wet well, pumps, discharge piping, and controls and alarms. The NSWPS will receive stormwater flowing into the North cut-and-cover portals in a pre-settling cell where settleable solids are settled out prior to pumping. The runoff will flow through an opening with a trash rack into the wet well where the stormwater will be pumped through a discharge line to the force main discharge manhole at 6th Avenue North and Harrison Street. A manual valve system bypass in the pre-settling cell will allow the maintenance tunnel wash-down water (industrial process water) to flow down to a LPPS for treatment prior to discharge to the combined sewer system.

North and south roadway drainage and U-sections

Drainage collection and conveyance systems for roadways subject to rainfall events that are to be owned, operated or maintained by WSDOT (located within WSDOT Limited Access) meet the requirements of the WSDOT Hydraulics Manual. The Rational Method was used to analyze stormwater runoff flows used in the drainage of impervious surfaces and storm drain design calculations. Rainfall coefficients (m and n) for Seattle were used to calculate the rainfall intensities in accordance with Figure 2-5.4A of the WSDOT June 2010 Hydraulics Manual.

Portal rain water interception system shall be configured to process drainage flows separately from the rest of the tunnel drainage system.

DETAILED PUMP STATION DESIGN AND HYDRAULIC ANALYSIS

Hydro evaluation of peak rain flows are utilized to determine storm flows generated by impervious roadway and portal surfaces at portal. Roadway drainage flows must be conveyed longitudinally down the tunnel to storm lift stations.

Pump station overview

The SR 99 Tunnel Project includes four pump stations in the cut-and-cover and tunnel sections, including the SSWPS, the NSWPS, the MPPS, and the LPPS. The pump stations will remove water that collects in the tunnel from storm events, tunnel cleaning and sprinkler testing, seepage, and fire suppression events.

South stormwater pump station description

The basic components of the SSWPS consist of a pre-settling cell, trash rack, wet well, pumps, discharge piping, and controls and alarms. The primary use of the SSWPS is to pump stormwater collected in the depressed sections of the roadway, the South Operations Building roof, the headhouse roof, and seepage water collected in the south cut-and-cover section out of the tunnel. The SSWPS will receive water from the south cut-and-cover header pipe in the pre-settling cell, where settleable solids are settled out prior to pumping. The water will flow through an opening with a trash rack into the wet well and is pumped through a discharge line to the force main discharge.
manhole at Alaskan Way South and South King Street. An overflow header pipe is included in the wet well as an emergency overflow to the LPPS to bypass flow events larger than the 25-year storm event. Additionally, the water pumped from the LPPS is also discharged into the SSWPS wet well and pumped to the discharge manhole at Alaskan Way South and South King Street.

A manual bypass pump in the pre-settling cell allows the maintenance tunnel wash down and fire suppression testing water (industrial process water) to flow to the LPPS for treatment prior to discharge to the combined sewer system. The bypass pump discharges into the tunnel main header collection pipe downstream of the SSWPS. The process water is treated in the LPPS in accordance with King County Industrial Waste permit requirements.

North stormwater pump station description

The basic components of the NSWPS consist of a pre-settling cell, trash rack, wet well, pumps, discharge piping, and controls and alarms. The primary use of the NSWPS is to pump stormwater collected from the North Access Project’s roadways and seepage water collected in the north cut-and-cover section out of the tunnel. The NSWPS will receive stormwater flowing into the north cut-and-cover portals in a pre-settling cell where settleable solids are settled out prior to pumping. The runoff will flow through an opening with a trash rack into the wet well where the stormwater will be pumped through a discharge line to the force main discharge manhole at 6th Avenue North and Harrison Street. A manual valve system bypass allows the maintenance tunnel wash down and fire suppression testing water (industrial process water) to flow to the LPPS for treatment prior to discharge to the combined sewer system. The bypass system discharges into the tunnel main header collection pipe downstream of the NSWPS. The process water is treated in the LPPS in accordance with King County Industrial Waste permit requirements.

Low point pump station and mid-point pump station

The LPPS is both a water treatment center and a pump station, consisting of four wet cells and one dry cell. The basic components of the LPPS consist of a flow splitter, pre-settling basin, oil water separator, wet well, pumps, discharge piping, and controls and alarms. The LPPS is designed to store and treat process water collected in the low point of the tunnel. This includes the 300 GPM normal tunnel flows from sprinkler testing, tunnel wash down operations, and seepage.

Normal tunnel flows (300 GPM) from the tunnel header pipes outfall into the flow splitter cell and flow over a baffle into the second pre-settling cell, where settleable solids are settled out. The pre-settling basin will normally be full, and as additional water enters, the existing water will be displaced over a baffle and flow into the oil water separator. The oil water separator allows for the oil particles to rise to the surface and be contained behind vertical baffles. The separated water then flows through a downturn elbow (orifice) which controls the flow into the wet well where the water will be pumped to the SSWPS wet well via the MPPS. The fifth dry cell houses the pumping equipment. The pre-settlement cell was designed to have a 10-minute retention time for the removal of settleable solids. The oil water separator was sized to allow for 45 minutes of retention time as required by King County.

The orifice between the oil/water separator and the wet well controls the flow rate into the pump cell to convey the normal tunnel flow of 300 GPM into the wet well using the sizing method outlined in Chapter 3.2.4 of the Washington State Department of Ecology’s 2005 Stormwater Management Manual for Western Washington: Volume III. The orifice is equipped with a downturn elbow to keep oils from entering the wet well.

An emergency overflow weir in the flow splitter cell bypasses flows in excess of 300 GPM to the Invert Utilidor for storage. The emergency overflow weir was designed in accordance with Section 5 of the WSDOT 2008 Highway Runoff Manual. The maximum drainage requirement is 4,000 GPM for the duration of two hours for firefighting. Approximately 480,000 gallons (64,170 cubic feet) of water could be discharged to the tunnel Invert Utilidor during this maximum fire event. The tunnel has approximately 733,090 gallons (98,000 cubic feet) of storage volume available below the bottom of the north bound roadway deck, which is ten times larger than needed to contain the maximum fire...
The MPPS is a booster pump station. The MPPS consists of a wet well where the water pumped up from the LPPS is discharged and then pumped to the SSWPS, and a dry well where the pumps are housed. The MPPS does not include a pre-settling cell because the settleable solids were removed in the pre-settling cell of the LPPS.

**Low point sump pumps**

The Low Point Sump pumps are small maintenance pumps designed to pump seepage water collected in the tunnel Invert Utilidor that is not collected elsewhere at the low point into the main collection header. The floor of the tunnel is built up to create a channel on the west side of the Invert Utilidor that serves as the wet well for the pumps.

**Design criteria**

**Pumps**

The tunnel and cut-and-cover pumps were designed according to the general criteria derived from the Hydraulic Engineering Circular No. 24, *Highway Stormwater Pump Station Design*.

**Number of pumps:**

The SSWPS was designed to pump the 25-year storm from the south depressed roadways and the South Operations Building roof based on the StormShed analysis. Additional capacity was added to handle the discharge from the LPPS. The pump station consists of 3-1000 GPM pumps each individually able to pump the design flow. A single manual bypass pump is also included in the pre-settling cell of the SSWPS. This pump will only be used during tunnel maintenance to bypass process water to the LPPS for treatment. The pump is sized for 300GPM, which accommodates the expected normal tunnel design flows from tunnel wash down, sprinkler testing, and seepage rates. The NSWPS pump station flows were designed based on the StormShed Analysis. The NSWPS consists of 3 – 90 GPM pumps, each with the capacity to pump the 100 year storm event to the outfall. The LPPS and the MPPS have both been designed to contain a 300 GPM pump sized to match the 300 GPM flow rate of the processes water treatment center at the low point of the tunnel. The process water treatment center was designed to handle a flow equal to tunnel maintenance events which consists of tunnel wash down, sprinkler testing, and seepage rates. A redundant pump is provided at each pump station with equal flow rate. The two tunnel low point sump pumps include a primary and a backup pump designed to handle water not collected in the primary collection system. This water is primarily seepage into the Invert Utilidor and is expected to be less than 22 GPM.

**Wet wells**

Pump station wet wells were designed to provide acceptable pump intake conditions, adequate volume to prevent excessive pump cycling, and sufficient depth for pump control while minimizing solids deposition. The pumps have been designed assuming constant speed operating conditions and a minimum 5 minute pump run time. For constant speed pumps, the minimum volume between pump on and off levels can be calculated using the following general formula:

\[ V = \frac{t \times Q}{4}, \text{ where} \]

- \( V \) = minimum volume (gallons)
- \( t \) = minimum time between pump start and top (minutes)
- \( Q \) = pump capacity (gallons/minute)
**Force mains**

**Size and velocity**
The force Mains have been designed to exceed the recommended minimum 4-inch diameter discharge line and maintain minimum self-scouring velocities. The minimum self-scour velocity for pump force mains is 2 feet per second and the maximum velocity of 8 feet per second. The SSWPS and NSWPS will pump through a force main to manholes located at the surface street level. At the manhole, the line will transition from a force main system to a gravity system. The LPPS discharges into the MPPS wet well. The MPPS then pumps the water to the SSWPS where it is discharged into the wet well. A downturn elbow is used at the discharge point to reduce surface turbulence at wet wells.

**Air relief valves**
Air relief valves will not be required for the pump systems because the termination of the force main is into a vented manhole or wet well set at the high point so that air cannot be trapped within the pipe.

**Blow-offs**
Blow-valves will not be necessary because the force main pipes will not have any low points other than at the pump. Check valves, and shut-off valves will be installed above the pump for servicing.

**Pumping strategy**
The three main pump stations in the tunnel are designed to handle four different design events: storm events, fire events, normal tunnel flows (includes tunnel wash down, seepage, and fire suppression testing), and hydrocarbon detection.

**South stormwater pump station**
The SSWPS cycles through the three 1000 GPM pumps for normal flow from tunnel seepage and storm events. During tunnel maintenance events, process water will flow into the pre-settling cell. The 300 GPM bypass pump will engage and pump the process water to the header collection pipe for bypass to the LPPS for treatment. During this event, the 1000 GPM pumps in the wet well will be used to discharge the treated process water from the LPPS. During a fire event in the south cut-and-cover sections, all pumps shut down. Water from the fire suppression flow will overflow through the emergency header pipe located in the wet well and bypass via gravity to the LPPS. In the event hydrocarbons are sensed in the pump station, the pumps will immediately shut off, the SCADA system will receive an alarm, and the ventilation fan will engage. Water will remain in the sump until it is inspected by maintenance crews and disposed of appropriately.

**North stormwater pump station**
The NSWPS cycles through the three 90 GPM pumps for normal flow from tunnel seepage and storm events. During tunnel maintenance activities, the pump flow will be diverted to the overflow header to the LPPS for treatment and discharge. After maintenance activities have finished the shear gate between the pre-settling cell and the wet well will be opened. This will allow the pumps to empty all the process water from the north cut-and-cover section of the tunnel to bypass to the LPPS. During a fire event, the pumps will be shut off and flows will bypass the pump station by gravity via the emergency overflow header pipe to the LPPS. In the event hydrocarbons are sensed in the pump station, the pumps will immediately shut off and the ventilation fan will engage. Water will remain in the sump until it is inspected by maintenance crews.

**Low point and midpoint pump stations**
The LPPS and MPPS work together to remove water collected in the invert of the tunnel. The LPPS removes water from the low point treatment center and the MPPS acts as booster pump station to carry the water to the discharge at the SSWPS. The pumps work the same under normal operations.
and tunnel maintenance activates in full operation. During a fire event the pumps will be shut off. An emergency overflow weir in the low point treatment center will outfall water into the Invert Utilidor where it will be stored until inspected. A sluice gate between the wet well and the floor of the Invert Utilidor will allow the LPPS pumps to remove the water stored in the Invert Utilidor after a fire event. In the event hydrocarbons are sensed in the pump station, the pumps will immediately shut off, the SCADA system will receive an alarm, and the ventilation fan will engage. Water will remain in the sump until it is inspected by maintenance crews and disposed of appropriately.

**Tunnel sump pump**

The Tunnel Sump pumps will be automatic under all conditions except for the fire event, where they will shut off until Invert Utilidor is pumped clear of fire suppression water.

**Pump station emergency system**

Each pump station has sensing units to monitor pump activity and water level sensing. Data is fed to the Supervisory Control and Data Acquisition System (SCADA) that is monitored 24 hours a day. Should any problems occur, information will be sent to the operator.

**UNIQUE DESIGN CONSIDERATIONS**

Drainage system that is located away from tunnel portal rainwater interception system has design flow conditions established by sprinkler flows. This design condition introduces an opportunity to incorporate a drainage flow surge chamber into the design that is sized to accept sprinkler flow duration that will allow more cost effective sizing of roadway surface flow treatment for surface water discharge. Hydrocarbon exhaust fans (HCEF) are configured to limit the concentration of flammable gases in the drainage collection sumps (and connected drainage pipework). Discharge for the HCEF equipment is directed into the tunnel exhaust duct with bubble tight dampers to isolate drainage sumps from emergency exhaust systems when emergency exhaust is activated. Some considerations for creating flammable/explosive atmosphere in exhaust duct during normal operations are mitigated by makeup air dilution with tunnel ventilation system operating at low flow conditions.

**CONCLUSIONS**

Space proofing for drainage systems is key for establishing adequate installation, maintenance and equipment access space for drainage lift pumps. Wet well sizing and design configuration are essential to establishing a reliable system design to maximize equipment reliability while minimizing pump equipment energy consumption. Accommodating water based fire suppression flows requires innovative strategies for pump station design. System must incorporate water treatment requirements for oil separation on road surface run off.

**REFERENCES**

Emergency Ventilation Design for Chicago Union Station
North and South Tracks and Platforms

Ana M. Ruiz-Jimenez\textsuperscript{1}, S. Torralba\textsuperscript{1}, D.Silván\textsuperscript{1}, J. Grella\textsuperscript{2}, J. McCarron\textsuperscript{2}
\textsuperscript{1}TD&T LLC, Chicago, USA
\textsuperscript{2}AMTRAK, Philadelphia, USA

ABSTRACT
Union Station is a major railroad station that opened in 1925 in Chicago (CUS), replacing an earlier station built in 1881. It is now the only intercity rail terminal in Chicago, as well as being the city’s primary terminal for commuter trains. There is a need for establishing the emergency ventilation system at the platforms. The existing ventilation systems in the overbuild buildings over Chicago Union Station were designed to exhaust the diesel exhaust from locomotives. They are not designed to exhaust the high temperature and volume of gases that will result from a train fire. A new ventilation system independent of the existing is required. The proposed emergency ventilation system comprises multiple rows of jet fans mounted on stands that are completely separated from the structures of the overbuilds. Jet fan selection and sizing account for physical constraints in the tunnels and environmental conditions such as prevailing wind at the portals. The jet fans will push the hot gases and smoke out of the north or south portals of the platform tunnels. Makeup air will be supplied from sections of existing openings to Chicago River near the Station at 222 South Riverside Plaza. The remaining sections of existing openings along Chicago River not being used for makeup air intake will need to be closed off to prevent short-circuiting of airflow. Two of the existing fans in 222 Riverside Plaza which separates the north and south platforms have been converted to supplying makeup air to the platforms. However, the fans in 222 Riverside Plaza are not used to supplement the supply of makeup air in this study. CFD has been used to validate concept.

KEYWORD: CFD, Chicago Union Station, platform, emergency ventilation, fire, diesel.

INTRODUCTION
The main objectives are:

- Develop a concept and basis of design for a ventilation system to remove heat and products of combustion (smoke) from a fully involved 50 megawatt coach fire. Jet-fans ventilation system has been adopted.
- Provide calculations determining the required air (Jet-fans number calculated) to be exhausted for a 50 megawatt coach fire.
- Perform a computational fluid Dynamics (CFD) analysis to validate emergency ventilation concept, for a 50 megawatt coach fire.
- Develop a concept and basis of design for a ventilation system to remove diesel exhaust. The diesel exhaust system may be integrated into the fire and life safety exhaust system.

DESCRIPTION
The station stands on the west side of the Chicago River between West Adams Street and West Jackson Boulevard, just outside the Chicago Loop. Including approach and storage tracks, it is about nine and a half city blocks in size. Its facilities are mostly underground, buried beneath streets and skyscrapers. Chicago Union Station is the third-busiest rail terminal in the United States, after Grand Central Terminal and Penn Station, both in New York City. It is also Amtrak’s overall fourth-busiest
station. It handles approximately 120,000 passengers on an average weekday and is one of Chicago’s most iconic structures, reflecting the city’s strong architectural heritage and historic achievements.

**Emergency ventilation design (Jet Fans) calculations**

The next formulae are presented for designing the emergency ventilation system using jet-fans. Equation for the balance of pressure differences is given:

\[ n_j \Delta p_j = \Delta p_{veh} + \Delta p_{tw} + \Delta p_{MT} + \Delta p_{fire} + \Delta p_{th} \]  

(1)

With:

- \( n_j \) = number of jet fans.
- \( \Delta p_j \) = pressure rise by one jet fan.
- \( \Delta p_{veh} \) = pressure drop caused by stationary traffic in the tunnel.
- \( \Delta p_{tw} \) = pressure drop from entrance and exit losses and wall friction.
- \( \Delta p_{MT} \) = pressure drop (or rise) because of meteorological influences.
- \( \Delta p_{fire} \) = pressure drop caused by the fire.
- \( \Delta p_{th} \) = pressure drop (or rise) caused by thermostatic effects.

With this formula, the emergency ventilation system, i.e., the number and type of Jet Fans has been calculated, both in North and South platforms of Chicago Union Station. Jet Fans included in the design have the following features:

<table>
<thead>
<tr>
<th>Jet Type1</th>
<th>Jet Type2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter = 1 m.</td>
<td>Diameter = 0.7 m.</td>
</tr>
<tr>
<td>Air flow = 32.185 m³/s.</td>
<td>Air flow = 15.4 m³/s.</td>
</tr>
<tr>
<td>Jet velocity = 41 m/s.</td>
<td>Jet velocity = 40 m/s.</td>
</tr>
<tr>
<td>Theoretical thrust = 1583.57 N.</td>
<td>Theoretical thrust = 740 N.</td>
</tr>
</tbody>
</table>

**Acceptable Visibility**

According to tenability criteria, (NFPA-130) smoke opacity levels should maintain below an illuminated sign should be distinguishable at 30m, when illuminated with 80 luxes. Walls and doors should be visible at 10m.

According to tenability conditions, maximum smoke concentration for 10 m. visibility, for non-illuminated objects, using worst conditions has been calculated.

**CFD Simulations**

CFD simulations have been achieved in order to validate the emergency ventilation concept. 3D CATIA models have been built for North and South platforms. There exist windows closed and open, at the riverside, near to the connection between the North and South platforms. In order to model the station as if it were a tunnel, all openings have been considered to be closed (this could be achieved at the station, by installing fire curtains, whose operation should be integrated when the fire alarm is received, and emergency ventilation is started).

There are three regions at the CATIA model, RiverWindow 1, RiverWindow 2 and RiverWindow 3 (every one including two real openings), at the riverside, in the proximity of Building 222 (where the concourse of both platforms is located). According to this configuration, for platform North and South, the 3D model has included:

- 4 trains.
- Fire at second coach of a train located at one track, among two other trains in consecutive tracks.
- Connection from North to South platform (air coming from the other side of the station has been measured at 1 m/s).
- Openings (air coming from the river, at 1 m/s) to the river for North platform:
  - Case 1: 4 openings.
Case 2: 6 openings.

- Openings (Air coming from the river, at 1 m/s) to the river for South platform:
  - Case 1: 6 openings (according to North platform results).
- 4 Jet-fans at the first row, close to the fire site, which will not be switched on in the models, because they will not be operational, because of possible fire burning.

![North platform](image1.png) ![South platform](image2.png)

Figure 1 North platform  Figure 2 South platform

Given the actual structure of the platforms at the station, we have considered to use smaller Jet-fans (Diametre = 2.3 ft) at the pedestrians area, and the bigger Jet-fans (Diametre = 3.2 ft) at the tunnel area where there is a need of bigger flow rate and thrust, even if there might be less number of rows.

Wind coming into the tunnel (from the North) at an speed of 7 m/s, has been considered for final calculation of Jet-fans total number. Those are included in the model, according to the calculated emergency ventilation concept design.

**CFD NORTH PLATFORM SIMULATIONS**

The geometry of the model was constructed using the software “Catia” while the actual CFD analisys was performed using “Ansys-CFX”. The dominium of calculus has been generated as 3D solids. The mesh obtained includes 10669833 tetrahedra, with 2140228 nodes. CFX results give temperatures, smoke concentration contours and velocities. The results are shown in cross section planes and isosurfaces.

![North platform model](image3.png)

Figure 3 North platform model

**Ventilation design**

The configuration of the ventilation system is:

- 4 rows of 9 Jet-fans Type 2: Platforms.
- 2 rows of 7 and 9 (respectively) Jet-fans Type 1: Close to tunnel exit.

![Ventilation system North platform](image4.png)

Figure 4 Ventilation system North platform
CFD model corresponds to North of Chicago Union Station, with 4 trains stopped. In the model, the fire source is located at second coach close to 222 building. Train in fire happens between two trains. A comparison of results of cases 1 and 2 is given below:

**Table 1  Isosurface soot Mass concentration North platform**

<table>
<thead>
<tr>
<th>Results – Isosurface Soot Mass Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Platforms CUS with 4 openings</td>
</tr>
<tr>
<td>420 seconds</td>
</tr>
<tr>
<td>720 seconds</td>
</tr>
</tbody>
</table>

**Table 2  Temperature 1m over North platform**

<table>
<thead>
<tr>
<th>Results – Plane of temperature XY, 1 meter over platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Platforms CUS with 4 openings</td>
</tr>
<tr>
<td>420 seconds</td>
</tr>
<tr>
<td>720 seconds</td>
</tr>
</tbody>
</table>
Table 3  Streamlines (Air velocity) North platform

<table>
<thead>
<tr>
<th>Results - Streamlines (Air velocity)</th>
<th>North Platforms CUS with 4 openings</th>
<th>North Platforms CUS with 6 openings</th>
</tr>
</thead>
<tbody>
<tr>
<td>420 seconds</td>
<td><img src="image" alt="Streamlines 4 openings" /></td>
<td><img src="image" alt="Streamlines 6 openings" /></td>
</tr>
<tr>
<td>720 seconds</td>
<td><img src="image" alt="Streamlines 4 openings" /></td>
<td><img src="image" alt="Streamlines 6 openings" /></td>
</tr>
</tbody>
</table>

From the results above, it has been concluded that CUS North platforms model (6 openings) works better:

- Temperatures in platforms are considerably lower (around 50 ºC) than in the previous model, with 4 openings.
- Movement of smoke is much faster than previous model, with 4 openings. At 420 s, smoke layer has over passed the existing accesses at the right side of the platforms. In the previous model smoke layer is barely reaching them.
- Smoke concentration is much lower because of higher dilution, than in previous model.

As a summary, we can conclude that there is more flowrate in Case 2 with 6 openings, which is the reason for lower temperatures, higher dilution and higher speed of smoke layer, faster streamlines, with a better performance of ventilation system behavior.

For case 2 (6 openings) it can be observed:

- Smoke concentration
  - From 180 to 420 s, full operation of Jet-fans makes smoke move towards the right side, and the tunnel portal. At 420 seconds, pictures show the correct movement of smoke.
  - At 720 s, smoke layer arrives to the narrower side of the station. There is a bottleneck for the smoke to leave towards portal.
  - At 1020 s, there is no backlayering, the smoke exhausts towards the tunnel portal.

- Temperature
  - At 120 seconds, at platforms far from the fire site temperatures are under 60ºC. The ceiling is under 180 ºC.
  - At 420 seconds, at platforms, far from the fire site temperatures are under 60ºC and ceiling maximum temperature is 270 ºC.
  - At 720 seconds, ceiling maximum temperature is 400 ºC.
  - At 1020 s, at platforms far to the fire site temperatures are under 60ºC. Ceiling maximum temperature is 530 ºC.

- Streamlines
Conclusions

- Jet-fans concept for fire ventilation at CUS North platform is adequate, allowing for smoke exhaust and individuals egress.
- It is necessary to leave 6 openings at the riverside, allowing higher flow rate to come into the platforms.
- Fire curtains shall be installed in Chicago river openings that need to be closed, located far from the necessary openings for ventilation.

CFD SOUTH PLATFORM SIMULATIONS

After CFD simulations for North platforms, a decision was made to use just six openings for South platform CFD simulation. The dominium of calculus has been generated as 3D solids. The mesh obtained includes 9799722 tetrahedra, with 1869392 nodes.

**Figure 5 South platform model**

Ventilation design

The configuration of the ventilation system is:

- 5 rows (of 15, 15, 18, 17 and 15 Jet-fans respectively) Type 2: Platforms.
- 3 rows (of 9, 8 and 8 Jet-fans respectively) Type 1: Close to tunnel exit.

**Figure 6 Ventilation system South platform.**

CFD model corresponds to South platform of Chicago Union Station, with 4 trains stopped. The model has the fire source situated at second coach close to 222 building. Train in fire is located between two trains, at consecutive tracks.
Table 4  
**Isosurface Soot Mass concentration South platform**

<table>
<thead>
<tr>
<th>Results – Isosurface Soot Mass Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>420 seconds</td>
</tr>
</tbody>
</table>

Table 5  
**Temperature at plane located 1 meter over South platform.**

<table>
<thead>
<tr>
<th>Results – Plane of temperature XY, 1 meter over platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>420 seconds</td>
</tr>
</tbody>
</table>

Table 6  
**Streamlines (Air velocity) at South platform.**

<table>
<thead>
<tr>
<th>Results – Streamlines (Air velocity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>420 seconds</td>
</tr>
</tbody>
</table>

- Smoke concentration
  - At 420 s, smoke moves towards the tunnel portal. A small part of smoke arrives to platforms at the opposite side of the river. This effect is caused by streamlines entering perpendicularly to the station.
  - At 720 s, smoke layer arrives to the narrower side of the station, where there is an abrupt change of section and an eddy is formed in the corner. The eddy is formed due to streamlines coming out from the jet-fans of the fifth row that are directed against the wall. Streamlines collide and bounce back, arriving to jet-fans row again.
  - The effect of the eddy, produces that smoke layer does not accumulate in the abrupt
change of section. The smoke avoids passing through this area and moves towards the portal.

- **Temperatures**
  - At 120 seconds, at platforms near the fire site, temperatures are under 180ºC, at platforms far from the fire site, 60ºC, and at the ceiling, under 180 ºC.
  - At 420 seconds, at platforms near the fire site, temperatures are 180ºC, at platforms far from the fire site are 60ºC, and at the ceiling is 270 ºC.
  - At 720 seconds, the ceiling maximum temperature is 300 ºC.
  - At 1020 s, at platforms close to the fire site, temperatures are 230º C, at platforms close to the river site are under 60ºC and at the ceiling is 370 ºC.

- **Streamlines**
  - The effect of the eddy, produces that smoke layer does not accumulate in the abrupt change of section. The smoke avoids passing through this area and moves towards the portal.

**Conclusions and recommendations**

- Jet-fans concept for fire ventilation at CUS South platform is adequate, allowing for smoke exhaust and individuals egress.
- It is necessary to leave 6 openings at the riverside, allowing higher flow rate to come into the platforms.
- Fire curtains shall be installed in Chicago river openings that need to be closed, located far from the necessary openings for ventilation.
APPENDIX A: 150N RIVERSIDE OVERBUILD MODEL

INTRODUCTION

The previous paper shows the emergency ventilation design system for CUS, that is going to be provided by AMTRAK, in a short future. However, the architects for the 150N Riverside Overbuild, new building above CUS, that is being designed and built by 2014, had the need to design diesel exhaust system, according to AMTRAK regulations. So, the present appendix shows the particular Diesel exhaust design done for this building (located at platform North), in particular. Designers need to anticipate locomotive operation during the design phase of Chicago Union Station, particularly when estimating source strength on published locomotive emissions data. Some important parameters include the number of operating locomotives and the location, duration, and throttle position at which they operate. Design for Diesel emissions criteria was taken of the ASHRAE HVAC Applications.

DESCRIPTION

The general concept for track ventilation of 150N Riverside Building includes fan assisted ventilation in a transverse direction to the rail lines. The system arrangement and design parameters are:

- Exhaust fans mounted within the building structure on the east edge of the site ducted to louver bands facing the river.
- These fans will be ducted in a method to capture air along the west edge of the building structure bordering the east side of the tracks.
- Make-up air will be obtained from the west side of the site through ventilation openings extending up through the plaza above.
- The exhaust system is sized to produce 12 air changes per hour of the total overbuilt track area. The total calculated air flow is 234,000 CFM distributed between 3 fans.
- The fan operation will be time clock base for normal operative hours. During off-time hours, NOx sensors will be used to activate the fans as a result of passing trains. Once activated, the fans will remain on until the proper NOx levels are maintained. During intermittent periods, the NOx sensors will reduce the exhaust airflow to maintain acceptable NOx levels. All fans will have variable airflow control.

METHODOLOGY

Regulations: criteria for NOx emissions

According to AMTRAK REGULATIONS for OVERBUILDS, those are applicable and were taken into account, as described below:

- The design criteria shall be 5ppm of Nitrogen Dioxide at an elevation of 14 feet above the top of rail.
- The ventilation systems shall be energized when the NOx concentration at this elevation reaches 3ppm.
• In the event of normal operations train idling is no greater than ten train-minutes per hour, no analysis needs to be made.
• It shall be assumed that the emergency ventilation systems can be operated in such a manner as to purge diesel emissions from the station or built-over tunnel when the 3ppm concentration is reached.

According to ASHRAE HVAC Applications Handbook, NO\textsubscript{x} emission has been taken, from the Four Stroke Cycle, With Head End Power (HEP), when the Locomotive is in Standby mode.
• NO\textsubscript{x} emission = 118g/min

Also, this emission includes only a combined NO\textsubscript{x} emission value. Field measurements in locomotive facilities, found that about 13% of ambient NO\textsubscript{x} could be attributed to NO\textsubscript{2}. This factor can be used to estimate NO\textsubscript{2} source emissions from available data.
• 38.46 ppm of NO\textsubscript{x} \rightarrow 5ppm of NO\textsubscript{2}(13%).
• 23.00 ppm of NO\textsubscript{x} \rightarrow 3ppm of NO\textsubscript{2}(13%).

**CFD simulations**

A determination and design of fan type and capacities required to remove the Diesel Emissions for a train stopped for 20 minutes (1200 seconds), so a set of different iterations according to different ventilation options have been modelled before the final design:
• 2 main grates at the two extremes of the park, at lower fan speed of 500ft/min the park, with 3 intermediate jet fans located at the wall openings with a speed of 3937ft/min
• 3 main grates at the extremes and center of the park at fan speed of 1000ft/min and exhaust at 1000ft/min with 3 intermediate jet fans located at the wall openings with a speed of 3937ft/min
• Final design has been considered with continuous grates at the park at air delivery speed of 2000ft/min and exhaust at 2000ft/min with 3 intermediate jet fans located at the wall openings with a speed of 4906ft/min.

**Simulation results**

The ventilation is energized, when NO concentration reaches 3ppm concentration at 14 feet. This concentration is reached at 25s, of CFD simulation run without any ventilation system activated.

<table>
<thead>
<tr>
<th>Table 7</th>
<th>Isosurface 3ppm of NO\textsubscript{2}</th>
<th>Isosurface 5ppm of NO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results – NO\textsubscript{2} Isosurface profiles 8 min</td>
<td>Exhaust to the river</td>
<td>Exhaust to the river</td>
</tr>
<tr>
<td>3ppm at 25s</td>
<td>3 ppm</td>
<td>5ppm</td>
</tr>
</tbody>
</table>
Table 8  Isosurface 3ppm of NO$_2$ and Streamlines (Air velocity).

<table>
<thead>
<tr>
<th>NO$_2$ Top 3ppm</th>
<th>Exhaust Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Study has been performed:
- Ventilation system has been energized at the 25s time, when the 3ppm concentration is reached, in CFD simulation.
- NO$_2$ layer gets totally exhausted, in a straight line, through the exhaust at the building structure on the east edge of the site ducted to louverbands facing the river.
- There is no spreading of NO$_2$ layer, around the stack exhaust of the train or backwards (to the grate side).
- With 5ppm concentration layer, the views show that the layer is staying over 14ft.

Conclusions and recommendations
- Design of exhaust ventilation system for NO is working properly.
- NO$_2$ detectors shall be used, and fans have been energized when reaching 3ppm NO$_2$ concentration, which is the minimum acceptable level.
- The control system is a stand-alone on NO$_2$ sensing and then tied to the DMS for fan control.

REFERENCES
1. PIARC (Technical Committee on Road Tunnel Operation), *Fire and Smoke Control in Road Tunnels*, 2004.
2. PIARC (Technical Committee on Road Tunnel Operation), *Systems and equipment for fire and smoke control in road tunnels*, 2006.
Impact of AFFF to the Performance of Fixed Fire Fighting Systems in Tunnels

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ABSTRACT

Fixed fire fighting systems (FFFS) have become a common fire safety method in tunnels over the last 10 years. FFFS have been noticed to be very effective in limiting and suppressing fires resulting in a safer environment for users to be evacuated, improved safety for rescue services and protecting the tunnel structure. In the context of FFFS many discussions were held about which fire loads and different potential risks would be representative for road tunnels. Especially the performance of FFFS in Dangerous Goods Vehicles (DGV) fires has been discussed intensively, including the possible improvement of the performance of FFFS by the use of Aqueous Film Forming Foam (AFFF) additives. This paper discusses results of full scale fire tests with FFFS and flammable liquid fires for both cases, FFFS with and without the adding of 1% AFFF. Their performances are evaluated and compared. For the referenced tests a newly developed fine water sprays system generating a fine droplets was selected. As expected, the presence and absence of AFFF led to different test results. These differences are to a lesser extent found in the overall firefighting performance and more noticeable in extinguishing times. Furthermore, the commonly used test arrangements for pool fires with their uncovered surface and deep fuel layers is critically being evaluated in regard of its representativeness for actual fire scenarios in tunnels. Also environmental and health aspects are discussed. Balancing the additional technical requirements when foreseeing the use of AFFF in terms of safety, commercial and environmental aspects the authors see little arguments in favour of changing from the commonly used FFFS applying pure water to such FFFS adding AFFF. This conclusion is drawn even when considering DGV fires and spill fires. The present “state of the art” test set up with pool fires is found to be not representative for actual fire scenarios with relatively thin layers of fuel.

KEYWORD: Fixed fire fighting systems (FFFS), Aqueous Film Forming Foam (AFFF), Class A fire, Class B fire, full scale tunnel fire tests, water mist system, water spray system.

INTRODUCTION

Fixed fire fighting systems (FFFS) have become a common fire safety method for tunnels during the last 10 years. One of the main drivers behind this development are the European research projects, which have shown on hand that fires with heavy good vehicles (HGV) can lead to much higher heat release rates (HRR) than previously used as design fires. The design fires for over 25-50 tons HGVs are typically considered between 70-100MW nowadays [1]. Some standards e.g. NFPA502 specifies 150MW design HRR for HGV’s [2]. Such fires are challenging to ensure life safety or safety of emergency forces only with “conventional” safety systems like relying purely to the ventilation. FFFS have shown to be very effective in limiting and suppressing fires leading to a safer environment for evacuation and rescuing. There has been a lot of discussion about the fire loads and different potential risks, especially related to dangerous goods. Flammable liquid fires are a common discussion topic when dangerous goods are considered as additional fire hazard. Using AFFF as an enhancement of
FFFS has been a topic in this context. In some recent installations the adding of AFFF has been foreseen, e.g. in several tunnels in Austria. Also some tunnels in the U.S. have been equipped with the deluge/foam systems using AFFF [2]. Adding AFFF increases the complexity and the costs especially in regard of maintenance of the FFFS, environmental considerations are required. These drawbacks have to be balanced with a potential gain in the fire fighting performance and the risk analysis of each individual tunnel.

**FIXED FIRE FIGHTING SYSTEMS (FFFS) AND AQUEOUS FILM FORMING FOAM (AFFF)**

In the recent years an increasing number of Fixed fire fighting systems (FFFS) have been installed to tunnels. The technology and its benefits are more often recognized compared to the past. The main reason is the extensive experimental testing that has proven the efficiency of FFFS in full scale fire tests. Nowadays this technology probably has been tested more intensively than any other active safety means for tunnels. Research is however still ongoing making the technology even better understood with more extraordinary fire risks.

![Figure 1](image)

**Figure 1** Spray test with deluge and water mist type FFFS [3][4].

Two main streams FFFS technologies are applied in tunnels. Low-pressure deluge systems (often called “sprinklers”) and water mist systems (normally applying high-pressure). Low-pressure deluge systems have been applied since longer time e.g. in Japan, USA and Australia. The background of deluge systems is coming from standard sprinkler applications. Pipes, connecting methods, nozzles and valves are normally the same or very similar to the ones used in buildings [5]. Water mist systems are primarily used in European tunnels and have been developed as a result of research work form projects like UPTUN and SOLIT [6][7][8]. The technology used has been developed specifically for tunnels. Especially water mist type FFFS have been tested very extensively, but there have been some rare fire tests with deluge FFFS during the recent years. The following is a comprehensive list of different fire test programs carried out within the last 15 years. The fire tests programs that included larger flammable liquid fires are marked with the letter “B” in the list below.

**Water mist fire testing:**
- Paris A86 tunnel fire tests 2003 [9]
- UPTUN fire tests, B, Virgolo tunnel, 2005 [6]
- M30 tunnel fire tests 2006 [10]
- Madrid Fire Service fire tests, B, 2006 [10]
- Marioff fire tests 2006 [12]
- SOLIT research project, B, 2006 [7]
- Rikswaterstaat A73 tests, B, 2008 [13]
- SINTEF tests (low pressure water mist) manufacturer 2009 [14]
- Eurotunnel fire tests 2010 [15]
- Dartford tunnel tests by Highways Agency 2010 [16]
• SOLIT2 research project, B, 2011 [7]
• Tunnel Mont Blanc 2012, comparison fire tests high-pressure water mist, low-pressure water mist and deluge systems [17]
• FOGTEC tests with/without AFFF, B, 2012

Deluge type FFFS fire tests:
• FOGTEC Fire Protection, comparison tests of deluge and water mist systems, 2011 [18]
• Tunnel Mont Blanc, comparison fire tests high-pressure water mist, low-pressure water mist and deluge systems 2012 [17]
• FOGTEC Fire Protection, fine water spray system tests with/without AFFF, B, 2012
• Land Transport Authority (LTA), deluge system fire tests 2013 [19]
• SP of Sweden and Swedish Road Administration, deluge system tests 2013 [20]

It is noticeable that tests with AFFF are very limited, especially considering that it has been used in a number of tunnels already. The Memorial tunnel fire test program in 1996 is the best known one utilizing AFFF with deluge systems [2]. These tests were carried out with conventional deluge system with application rates between 2.4mm/min…3.8mm/min and 3% AFFF concentration. The test reports claimed that the deluge system would have extinguished a 100MW pool fire within 30 seconds. There is not much information available about these deluge tests, but presumably the fuel layer was very thin, probably several millimetres, which might make the results not comparable to today’s tests making use of so called pool fires with much deeper fuel pools. The HRR was presumable also not measured during the tests. The Rijkswaterstaat fire test program in 2008 is another test series were AFFF was applied. This was done in combination with a high-pressure water mist system and a 1% AFFF concentration. The main purpose of these tests was assessing the risk of preventing a BLEVE [13][21]. Very positive results suggested that water mist with an application rate of approx. 4mm/min (no volumetric value was reported) was able to extinguish a pool fire with a potential HRR of 200MW within 80 seconds. However, the HRR was not measured or reported, and it was estimated that the HRR was minimum 150MW. Taking into account the small tunnel cross-section and the extinguishing time, it is very likely that the steam production has suffocated the oxygen access and enhanced the performance in the given scenario.

AFFF AND FIRE FIGHTING
AFFF is known for many fire risks to be an efficient type of fire suppression agent especially when fighting flammable liquid fires. AFFFs are water-based; they mostly contain additives (suffacants) that increase their ability to spread over the surface of hydrocarbon-based liquids. The low surface tension of the water-foam solution enables the aqueous film, although heavier than the burning liquid, to float on top of the liquid surface. There are various makes and types of AFFF foams available. They are typically used in concentration rates of 1%...6%. As FFFS generally have high flow rates an AFFF dosing of 1% shall is favourable.

AFFF is known to generate its benefits in fire fighting in tunnel environments predominantly with Class B (flammable liquid) fires. When Class B fires are used in testing, they are typically arranged by using open pools. This maximizes the benefit of using AFFF. It has been shown that if the pools are covered, the access of AFFF concentrate to the fuel surface is hindered and the foam is not as effective.

Fire testing with Class A (solid fires) tunnel fires on the other hand, e.g. by the authors of the 2006 SOLIT research project, showed that the benefits of applying AFFF were minor compared to Class B fires, whereby solid fires are generally considered as the more demanding design fires. This is e.g. addressed by e.g. SOLIT2 – Annex 7. Design fires based purely on flammable liquids are more producing a constant HRR and often used only for calibration purposes. Moreover, previous work e.g. by Swedish SP [23][24] have shown that flammable liquid spillages are limited in the burning area as well as the depth of the liquid film. Therefore large deep pool fires, like tested in most Class B full scale fire tests, are not necessarily representative cases.

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Combining FFFS with AFFF requires technical arrangements that will increase the costs of the systems significantly. A separate AFFF supply and distribution pipe is required throughout the tunnel to enable an adding of AFFF instantly after fire detection. If instead the AFFF is mixed into the water in the pump room, the water and AFFF mixture normally only reaches the respective firefighting zone after a considerable time. As AFFF additives are very corrosive, it causes additional costs for the technical equipment. AFFF, depending on the type, is normally considered as hazardous even when mixed into water. It therefore has to be collected by the tunnel sumps and disposed in a correct way. There are different guidelines that show how such waste water shall be disposed [25].

Some AFFFs are also noticed to be very hazardous for the health and their usage is limited. Especially AFFFs having perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) have been implicated with a variety of cancers and toxic health effects in humans that have had long term exposure to products containing PFOS/PFOA. This has led to a total ban of certain AFFF products [26].

**FIRE TESTS**

In the following a fire test series with a FFFS with and without applying AFFF is discussed.

**Test tunnel and measurement instruments**

The fire tests were executed in the Spanish test facility “Tunnel Safety Testing” (TST) in San Pedro de Anes. The test tunnel has a total length of 600 m and is slightly S-shaped with an incline of 2%. The tunnel cross-section was reduced using a false ceiling installed at a height of 5.0m. The tunnel cross-section is shown in the following figure.

![Cross section of the test tunnel and measurement setup](image)

The measurement system that was used in fire tests was extensive. In total approx. 260 different sensors were installed in the test tunnel recording the fire tests. These included the following devices:

- Temperatures, 77 pcs
- Heat radiation, 45 pcs
- Air velocity, 58 pcs
- Gas concentration (O2, CO2 and CO), 26 pcs
- Air humidity, 10 pcs
- Video cameras, 8 pcs
- Infrared cameras, 2 pcs
- Pressure sensors, 2 pcs

The measurement equipment was distributed throughout the tunnel and was connected with IFAB’s redundant BUS network over the entire tunnel. The measurement equipment was specifically developed by IFAB and used already in several similar test programs previously.
Fire load
The range of fire load included among others 8 individual pools with a dimension of 2.5m (w) x 1.6m (l) x 0.4m (h) each. The pools were arranged next to each other longitudinally forming a total surface area of 2.5m x 12.8m. The total surface area was 32 m² which corresponds approximately to 60MW HRR when the whole surface was burning. Each pool was filled with a water layer and a diesel fuel layer on top. Approximately 100 litres of diesel was filled into each pool, corresponding to a layer depth of 50mm. Each pool was ignited with approximately 2 litres of gasoline. The pools were not covered, which maximised the effect of AFFF.

Fixed fire fighting systems
The FFFS type used was a newly developed fine water spray system operating at low pressures. High pressure watermist systems are known to be very effective in fighting class B fires due to application of very small droplets; thus the expectation for the firefighting capability of the tested fine water spray system, using still small but in comparison slightly larger droplets, was somewhat lower. The performance of the same type fine water spray nozzle was studied for Class A fires in full scale fire tests earlier and found to be effective, although more water was required than for a common high pressure system [22]. The nozzle structure contains a reflector breaking the solid water streams into smaller droplets. A minimum operating pressure of 10bar is applied, which is slightly higher than for
e.g. conventional deluge systems. The nozzle head is made of stainless steel to withstand the expected heat exposure during the pre-burn stage and corrosion.

The technical specs and the figure of the nozzle are shown below.

1. Fine water spray system (deluge)
   - Operating pressure ~10bar
   - Application rate ~10lpm/m²
   - Installation length ~30m
   - Total flow rate 2850lpm
   - AFFF dosing 1% (AFFF total flow rate for the pool area is 320lpm)

Figure 5 Tested fine water spray nozzle (FOGTEC).

**Fire test results with fine water spray system**

The following figures present some key results of the fire tests. HRR, air velocity and temperatures are presented. Temperature measurements in N10 (Figure 8.) are located 4 meters behind the pools on the downstream side. The measurements in N00 (Figure 9.) shows the temperatures in the centre of the fire load. Thermocouples show different installations heights of 1, 3 and 5 meters. Additionally thermocouple measurements from both pool edges are shown and marked as FL.

Figure 6 HRR measurement using the fine water spray system with and without AFFF.
DISCUSSION

Fire suppression
The HRR measurement gives a good idea about the suppression effect of the FFFS. The maximum value measured was about 50MW during the pre-burn stage. This is lower than the theoretical value of the pool surface, but this can be explained with the HRR measurement tolerance. The FFFS was able to suppress the fire size and the produced heat shortly after activation. The immediate suppression effect can be seen from the HRR measurement. The ventilation speed was reduced after
the activation of the FFFS, which caused some additional delay for the HRR measurement as the measurement point was located in a distance of over 100m from the fire load. It was therefore more practical to check the final extinguishment points using video / thermal recordings as shown in the following sequence.

![Figure 9](image)

**Figure 9** Temperature measurements in N00 using the fine water sprays system with and without AFFF.

![Figure 10](image)

**Figure 10** Screenshots from video / thermal recordings using the fine water sprays system without AFFF (images on the left side) and with AFFF (images on the right side).

The final extinguishment was achieved about 1min 55s with AFFF and 8min 30s without AFFF. Although the full extinguishment happened clearly faster with AFFF, the fine water spray system (without AFFF) was able to suppress the fire very rapidly and only very small flames were left soon after its activation. The screenshots in figure 10 show that the pool fire was almost extinguished within 3min after activation as only some small flames could be noticed close to the pool’s walls. Compared to supressed Class A fires the remaining flames had been considerably smaller after the same activation time.
Temperatures
The fine water spray system was able to suppress the fire very effectively as shown in the previous chapter. Consequently the temperatures dropped very quickly as the heat decreased.

Directly behind the pool (location N10) the temperatures dropped immediately after activation. The number of small droplets produced by the fine water spray system in combination with the high flow rate was actually able to cool the surrounding temperatures faster compared to the reduction of the HRR. It was found that the fine water spray system was able to achieve thermal control and rapidly cooled the fumes.

A similar behaviour of temperatures was also measured with the thermocouples that were located in the pool area. Temperatures dropped very quickly after activation of the FFFS. The differences in all measured values between AFFF and pure water were negligible except in the pool edges where higher temperatures were measured over longer time for the tests without AFFF. This is due to the small flames as described in the previous chapter.

CONCLUSIONS
Class B fires are sometimes considered as design fire scenarios although the likeliness of their occurrence is very low. There is some debate within the industry whether very large Class B fires can occur in tunnels due to the expected maximum spillage and available drainage systems. There is lot of test data available with FFFS, but these are more related to Class A than to Class B fires. Test data of full scale fire tests with FFFS and AFFF is very limited but interesting, as AFFF is known to be effective for water based fire fighting against Class B fires.

The tested fine water spray system presents a new technology working with flow rates similar to conventional deluge systems; the pressure is slightly higher than with conventional systems to produce smaller droplets achieving similar effects like water mist systems. The tested nozzles have proven their effectiveness for Class A fires in previous full scale fire tests. The described test series has shown that the same system is also effective in fighting large pool fires. The test results showed that the fine water spray system was able to suppress a 32m² pool fire very rapidly already without AFFF. However, the final extinguishing took longer without AFFF; the question is whether this is problematic or not? The fire was suppressed to a very small fire without AFFF in 2-3 minutes and only smaller flames were noticed afterwards. The flames could not be recognized by the HRR measurements nor by the temperature measurements as the water spray system was cooling the fire zone effectively. With AFFF all flames were extinguished within 2 minutes.

AFFF has some severe drawbacks related to the FFFS’ complexity, its maintenance, material requirements, corrosion protection and environmental aspects. When comparing the benefits of AFFF and the fire fighting performance, it is questionable whether the additional costs and the above described drawbacks justify the use of AFFF. This should be considered very carefully when designing a FFFS especially when taking environmental aspects into account.

REFERENCES
3. IFAB archives (Tests in Mount Bakery tunnel) 
4. SOLIT research program archives, 2006.
Energy Budget in Tunnel Fires – Consideration of Fixed Fire Fighting Systems and Passive Fire Protection

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ABSTRACT

The effects of a fixed fire fighting system (FFFS) and passive fire protection on the energy budget and critical velocity for a tunnel fire were investigated using Fire Dynamics Simulator Version 6 (FDS 6). Two types of tunnel and fire geometries were modeled, and cases with and without a FFFS operating were analyzed and compared to existing equations for critical velocity. When using the NFPA 502 equation, the critical velocity was under predicted (relative to the FDS 6 result) at fire heat release rates (FHRRs) of 10 MW and 30 MW, but the conclusions were not consistent at 100 MW. When a FFFS was modeled, the critical/confinement velocity was reduced by only 0.25 m/s, with the water absorbing 35% to 60% of the FHRR. Passive fire protection did not substantially impact energy budgets, but did cause slightly increased temperatures downstream of the fire.

KEYWORDS: tunnel fire, critical velocity, energy budget

INTRODUCTION

Fires for tunnel ventilation design are defined in terms of the fire heat release rate (FHRR), and the FHRR is a critical input parameter to the critical velocity calculation for a longitudinal ventilation system. When the energy budget is considered, it is typical to allow only 70% of the FHRR as convective energy that the ventilation system must overcome, the remainder being radiation energy that is absorbed into the tunnel walls. The value of around 30% radiation FHRR has been observed in full scale tunnel fire tests [1].

Fixed fire fighting systems (FFFSs) and passive fire protection (a protective board on the tunnel wall) could alter the energy budget of a tunnel fire, and perhaps in turn affect the ventilation. The evaporation of water from a FFFS, for instance, will remove a substantial amount of heat, thereby decreasing the energy that the ventilation system must overcome. On the other hand, a passive board could decrease the heat transfer to the walls of the tunnel and cause an increase in the energy that the ventilation must control.

The impact of a FFFS on the critical velocity for smoke control has been studied previously using computational fluid dynamics (CFD). A reduction in the critical velocity was observed due to the cooling effect of the water for a 100 MW FHRR: from 3.35 m/s with no FFFS, to 2.75 m/s with a FFFS operating at 8 mm/min [2]. This analysis had no reduction in the FHRR modelled due to FFFS application. A reduction in the thrust required from jet fans (for a longitudinally ventilated tunnel) was also determined based on the lower gas temperatures downstream.

CFD models have been used to record the energy balance in a scale model tunnel with no FFFS operating [3]. The CFD model (based on Fire Dynamics Simulator (FDS) Version 5) was first validated by comparison of temperature results to tests performed in a scale tunnel. CFD models were then used to study the energy budget. It was found that heat lost to the walls by radiation was 52% of the overall FHRR when backlayering occurred, and it was reduced to 42% when the velocity was large enough to prevent backlayering. Considering convective heat flux to walls, it was concluded
that 67% of the FHRR is transferred to the walls when velocity is less than critical, and around 50% is transferred to the walls when the velocity is greater than the critical value [3].

The energy budget with a FFFS operating has also been studied using CFD models with validation carried out on a scale model tunnel [4]. A longitudinal velocity was applied and the FFFS was a mist system. The energy budget was considered in terms of energy going to the tunnel walls (24% of the FHRR), convection out of the tunnel exit (33% of the FHRR), and absorption by water mist (50% of the FHRR). The water application rate was such that the fire was suppressed but not extinguished, thus allowing the energy budget to be studied. It was found that 47% of the water applied to the tunnel space did not contribute to cooling (i.e. the process was 53% efficient, based on the energy carried out by water mist divided by the total energy carrying potential of the water injected).

The energy budget has been studied experimentally in tunnel fires with a configuration allowing fire suppression [5]. The following energy budget contributions were found in small-scale tests: 15% to 25% (average 20%) of the FHRR was absorbed by water evaporation; and around 25% to 55% (average 38%) of the FHRR was absorbed by heating of liquid water. Convective heat transfer was estimated to account for around 25% to 51% (average 43%) of the total FHRR. The authors comment on the impact of a FFFS for full-scale fires, noting that the FHRR might be reduced from 100 MW to 30 MW with a properly designed system. Furthermore, the authors state that it might be possible to reduce the convective FHRR (used to determine the critical velocity for ventilation) from 30 MW to 15 MW, based on their observations from tests. Such a reduction of the FHRR could have an impact on the ventilation design, however, it is noted that this result was not directly correlated from the tests reported.

While the results from experiments have been useful, there is an inherent difficulty in measuring all terms in an energy budget equation with an experiment. CFD models have enabled direct computation of the energy budget [3, 4]. In this present work, CFD models are used to study the energy budgets for situations with FFFS and passive fire protection. Parameters such as water evaporation efficiency are examined, as well as impact on the velocity required to control smoke. A range of input parameters, including water application rates and FHRRs, are considered on a full-scale tunnel configuration.

VERIFICATION AND VALIDATION

CFD simulations were conducted using FDS 6. The software is validated for many different types of scenarios, including tunnel fire scenarios [6]. In this paper the FFFS is modelled in a manner that allows the water to evaporate and cool surroundings, but fire suppression is not modelled. FDS has been used this way previously with Version 5 [3], however, the present work was conducted with FDS 6. Therefore, a model to verify FDS 6 was developed in accordance with the main parameters given in the previous work [4]:

- Scenario: Scale model tunnel 43 m long, 2.6 m wide and 2.0 m high, blockages added to make the area approximately 4 m², with a heptane burner placed part-way along the tunnel. Ventilation at 3 m/s applied at the tunnel exit. The FHRR and also temperature downstream of the fire were measured.
- FFFS: A total of six nozzles were modeled with a flow rate of 5.5 L/min/nozzle, positioned on the tunnel centerline approximately 1.5 m apart. The nozzles were activated 300 s into the simulation. Average particle diameter was set to 40 microns (Roslin-Rammler distribution, using the FDS defaults), velocity at the nozzle was 30 m/s, with a spray angle set to 45 degrees from the nozzle axis and an offset from the nozzle of 1 mm.
- Grid: Grid size was 0.1 m in the longitudinal direction, 0.05 m in the width and vertical directions. Arched tunnel configuration as per the test geometry.
- Fire: FHRR set to vary with time based on the profile used in the original work, nominal heat release rate per unit area was 4000 kW/m², surface area of the heptane pool was 0.5 m².
Selected results from the verification runs are provided in Figure 1 (CFD results fluctuate as they are not time averaged). The results show generally excellent agreement after the FFFS is activated at 300 seconds. The points of variation, particularly at 0.3 m above the floor before the FFFS is activated, were seen in the work conducted previously [4] but the CFD in this work predicts a larger temperature, at least near the floor level. Once the FFFS is activated, the results tend to be in good agreement. Results at other locations showed similar outcomes. As a result of this effort it is concluded that FDS 6 is capable of capturing the main physics associated with the energy budget when the FFFS is activated but does not suppress the fire.

![Figure 1](image_url)  
*Figure 1  Selected validation results at different elevations, 12 m downstream of the fire*

**APPROACH**

Two types of tunnel geometry and fire configuration were considered. The first configuration corresponded to the Memorial Tunnel Fire Ventilation Test Program (MTFVTP) [7] (arched tunnel, fire based on pans of diesel oil burning), and the other configuration was modelled to represent a typical two lane road tunnel with a flat ceiling. For the simulations of the two lane road tunnel, the fire was based on a heavy goods vehicle (HGV) geometry. Figure 2 shows the main geometric features of each model.
For the road tunnel configurations with the FFFS (right image in Figure 2), open head sprinkler (deluge) nozzles were placed over each lane. The wall and roadway material were specified as concrete, and the fuel reactant was modelled as GM21 (a typical polymer). Airflow came from the tunnel entrance. The fuel load was modelled as four layers of wooden pallets and one layer of plastic pallets shielded by the roof of the HGV trailer on top, with the HGV cab at the downstream end. The pallets were approximated as solid rectangles in order to lessen the modelling and computational load (i.e. to model the finer pallet geometry would have required a prohibitively fine grid resolution). The FHRR was a constant value in order to obtain steady state values for the backlayering distance. While this does not model a realistic fire (since there is no extinguishment modelled, or growth and decay period), it was necessary to have the fire at its peak value for an extended period of time to see the steady state backlayering distance. The input parameters for the simulations are given in Table 1.

Temperature, heat flow, mass flow rate, and mass fractions of the combustion products were measured at the inlet and exit of the tunnel. Simulations were run for 600 seconds.

### Table 1 Model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MTFVTP</th>
<th>Typical road tunnel simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid size</td>
<td>0.2 m in each direction (x, y, z)</td>
<td>0.2 m in each direction (x, y, z)</td>
</tr>
<tr>
<td>Tunnel dimensions</td>
<td>8.8 m wide at the base, 8 m high at the crown, model was 150 m long, area 61 m².</td>
<td>8 m wide, 6 m high with wall thickness of 1 m, model was 150 m long, area 48 m².</td>
</tr>
<tr>
<td>Fire geometry</td>
<td>Several pans of fuel: 3 m by 1.6 m with each pan providing approximately 10 MW.</td>
<td>Heavy goods vehicle: 12 m long, 2.8 m wide, 4.6 m high. Fuel pallets: 60 pallets, each 1.2 m long, 1.2 m wide, 0.2 m high.</td>
</tr>
<tr>
<td>Critical velocity calculation geometry (NFPA 502 [8] equation)</td>
<td>Area = 61 m², tunnel height at fire = 7 m, tunnel perimeter = 33.6 m, grade = -3.2%.</td>
<td>Area = 48 m², tunnel height at fire = 4.6 m (6 m for equation), tunnel perimeter = 28 m, grade = 0% (note annular area 37.4 m²)</td>
</tr>
<tr>
<td>Fuel</td>
<td>A fuel HRRPUA of 2083.33 kW/m² was modeled. Radiative fraction of 0.3, soot yield of 0.131 kg/kg. The radiative fraction is used to calculate the heat source term in the radiation transport equation. It is possible in the model for energy to be transferred between convection and radiation.</td>
<td>A fuel HRRPUA of 130.2 kW/m² to yield a 30 MW fire (scaled for 10 MW and 100 MW cases). Radiative fraction of 0.3, soot yield of 0.131 kg/kg.</td>
</tr>
<tr>
<td>Fixed fire fighting system (FFFS)</td>
<td>Not included.</td>
<td>40 nozzles in 2 rows, spaced every 3 m. Water application area of 480 m². Deluge average droplet size of 1000 μm</td>
</tr>
</tbody>
</table>
CRITICAL VELOCITY CALCULATION

Four different methods of calculating critical velocity were compared to the FDS simulation output. The first method is from NFPA 502, which predicts critical velocity for tunnels without a FFFS by iterating on the following equations [8]:

\[ V = K_1 K_g \left( \frac{gHQ}{\rho C_p A T_f} \right)^{1/3} \]  
\[ T_f = \left( \frac{Q}{\rho A C_p A V} \right) + T_A \]

In these equations, \( H \) is the distance between the seat of the fire and the tunnel ceiling, \( A \) is the annular area of the tunnel at the fire site, \( T \) represents temperature in Kelvin, and \( Q \) is the FHRR in Watts. For a road tunnel situation or pan test, where the fire geometry does not block the entire cross section, the tunnel height and total area are used.

The second method, derived by Ko [9], is applicable for a FFFS inclusion. Ko uses Wu and Bakar’s equations [10, 11] (equations 3, 4, and 5) for the dimensionless heat release rate and critical velocity without FFFS, and then scales the critical velocity to account for the FFFS (equation 6). Ko used a set of experiments in a full-scale tunnel with a sprinkler system installed to determine a relationship between critical velocity, FHRR, and water application rate. In this equation critical velocity is defined as the airflow velocity when backlayering is prevented [9, 10, 11]:

\[ Q'' = \frac{Q}{\rho A T_A C_p g^{1/2} H^{5/2}} \]

\[ V'' = \begin{cases} 
0.40 (0.20)^{-1/3} Q''^{1/3} & Q'' \leq 0.20 \\
0.40 & Q'' > 0.20 
\end{cases} \]

\[ V'' = \frac{V}{\sqrt{gH}} \]

\[ \omega \left( \frac{V_{FFFS}}{V} \right)^2 \geq 9 \]

The parameter \( H \) is the hydraulic diameter of the tunnel, and \( \omega \) is the water application rate in mm/min. Other parameters are the same as the NFPA 502 equations.

The final method, developed by Li and Ingason, also uses the dimensionless FHRR, and is valid for cases without FFFS [12] (in the equations below \( H \) is the tunnel height):

\[ Q'' = \frac{Q}{\rho A T_A C_p g^{1/2} H^{5/2}} \]

\[ V'' = \begin{cases} 
0.81 Q''^{1/3} & Q'' \leq 0.15 \\
0.43 & Q'' > 0.15 
\end{cases} \]

\[ V'' = \frac{V}{\sqrt{gH}} \]
CRITICAL/CONFINEMENT VELOCITY – NO FFFS OPERATING

Smoke movement was observed on the tunnel centreline and if backlayering was kept at 10 m or less, this was deemed to be the confinement velocity for that case. The confinement velocity was computed by altering the upstream velocity in increments of 0.25 m/s. A smaller velocity increment and hence a critical velocity (0 m backlayering) was not pursued because the increment of 0.25 m/s is considered to be at the limits of practical application in a real tunnel, and a finer resolution of velocity change is pushing toward the accuracy limits of a CFD model.

Comparisons are made with equations for critical velocity. This is considered acceptable since in most cases the backlayering extent was much less than 10 m and a further increase of 0.25 m/s would have likely resulted in 0 m of backlayering, and by extension a prediction of the likely critical velocity. Further investigation to determine the exact critical velocity could be of interest in future work. However, within the accuracy of the models and results observed, a variation of 0.25 m/s does not appear to impact the conclusions made herein.

FHRRs of 8.5 MW (car fire), 25.5 (bus fire), 50 MW (truck fire) and 100 MW (truck fire) were investigated. For the MTFVTP, cases the resulting confinement velocities are plotted in Figure 3, along with the other equations considered (NPFA 502, Wu and Bakar, Li and Ingason). For the MTFVTP tests there were blockages around the fire that caused an increase in the velocity to the fire; those blockages were not modelled here but the velocity of the test results presented was adjusted to quote the local air velocity at the fire. Observations from the results are as follows:

- The NFPA 502 equations appear to under estimate critical velocity at low FHRRs (less than 100 MW) based on test results and CFD models. At 100 MW the performance of the equations is not consistent between the different geometry tested.
- Although it is industry practice to deduct 30% of the FHRR for the radiative portion, it is noted that the MTFVTP validation exercise did not appear to do this when plotting against the NFPA 502 equation [7]. In line with industry practice, results from the models and tests were plotted against a critical velocity equation that used 30% of the FHRR as an input (as were the CFD results herein). The results here do not provide enough data to make a conclusion on whether or not 30% of the FHRR should be deducted. Figure 3 shows results that do support the deduction, but Figure 4 shows the opposite.
- Test results from the MTFVTP are also plotted. It is noted that these test results were not tuned to achieve a critical velocity in the way the CFD models were. A case either controlled backlayering or it did not, but there was no effort to locate an intermediate velocity where backlayering was just controlled. It is noted that the NFPA 502 equation for critical velocity at FHRRs less than 20 MW tends to fit the MTFVTP where backlayering was observed (i.e. the equation may in fact under predict critical velocity at low FHRRs). However, it is also noted that at higher FHRRs (i.e. 50 MW to 100 MW) the alternative equations to NFPA 502 tend to predict a greater value of the critical velocity.

The results from the MTFVTP cases show that there could be a situation where the NFPA 502 equations are under predicting the critical velocity at low FHRRs (less than 100 MW). However, it is noted that there could also be some geometric effects to be considered. Results for the tunnel with a 6 m high flat ceiling configuration (i.e. the typical road tunnel with a ventilation duct) are provided in Figure 4 and it is seen that the NFPA 502 equation makes a closer prediction of the critical velocity within the 0.25 m/s velocity increment margin noted.
Global computational domain energy budgets for the cases where confinement velocity was achieved are provided in Table 2. For all MTFVTP cases the radiation proportion was around 30%, while for the cases with a flat ceiling the radiation proportion was much larger, at around 40% to 50%. The reason for this isn’t known at present, but the significance of this finding is that the flat ceiling cases tend to have a lower confinement velocity, suggesting that if enough heat is lost by radiative heat transfer that there is some reduction of confinement velocity. The reason could be the lower ceiling height or the different geometry with respect to the fire and the tunnel walls’ view factor. Further investigation is needed to understand the phenomena responsible for this result.

Previous work on the energy budget quoted a balance of around 42% of energy lost to the walls by radiation when the velocity was large enough to prevent backlayering, and 50% when convective energy transfer to the walls is also considered (conductive transfer in this case) [3]. The results here show that the energy budget is sensitive to tunnel and fire geometry, and that the results do not follow this in any manner that can be used to extract a trend, except that the case with a more realistic fire geometry (i.e. the truck mock-up) tended to have a larger radiative percentage.
Table 2  Energy budget for cases where confinement velocity is achieved

<table>
<thead>
<tr>
<th>Case</th>
<th>MTFVTP</th>
<th>Flat ceiling cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>FHRR (MW)</td>
<td>8.5</td>
<td>25.5</td>
</tr>
<tr>
<td>Vcfd (m/s)</td>
<td>2.75</td>
<td>3.50</td>
</tr>
<tr>
<td>Vc (%)</td>
<td>+64%</td>
<td>+52%</td>
</tr>
<tr>
<td>Texit (deg C)</td>
<td>45</td>
<td>84</td>
</tr>
<tr>
<td>Convection</td>
<td>0.65</td>
<td>0.70</td>
</tr>
<tr>
<td>Conduction</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.30</td>
<td>0.26</td>
</tr>
</tbody>
</table>

The row Vc (%) quotes the percentage difference of the CFD model to the NFPA 502 prediction.

CRITICAL/CONFINEMENT VELOCITY – FFFS OPERATING

Cases with FFFS operating were conducted on the typical road tunnel and fuel geometry (i.e., a typical truck). The same methodology as discussed above for cases without a FFFS was used to determine the confinement velocity. The water droplet size was 1000 μm and the water application rate was varied. The confinement velocities for the various cases are plotted against NFPA 502 [8], Wu and Bakar [10, 11], Li and Ingason [12], and Ko’s [9] equations in Figure 5. Ko’s equations are valid for FHRRs up to 30 MW [9]. Note that Ko’s equation is the only one meant for use in FFFS cases; the others are plotted for reference.

Figure 5  Critical/confinement velocity results with a FFFS operating

At 10 MW and 6 mm/min, Ko’s equation and CFD are in close agreement, however, the equation overestimates the velocity at 30 MW. At 30 MW, the 12 mm/min equation and CFD are in good agreement for the 3 mm/min, 6 mm/min and 12 mm/min CFD cases. Interestingly, at 30 MW the model showed no noticeable reduction in confinement velocity between 3 mm/min and 6 mm/min. By inspection, to account for a FFFS, the NFPA 502 critical velocity prediction can be reduced by 0.25 m/s (as a rule-of-thumb and further work is needed to better bound this). When compared to the CFD cases with no FFFS, the critical velocity equation could be lowered by 0.25 m/s to 0.5 m/s. Note that this assessment is based on a maximum backlayering distance of 10 m. If a larger distance in the order of 20 m to 30 m was allowed there may be an increased reduction in the confinement velocity reported.
Energy budget and evaporation efficiency

The energy budget for cases with a FFFS was calculated and compared to cases without a FFFS, shown in Table 3. At 10 MW, with no FFFS, 52% of the FHRR was in the form of convection. When the FFFS was turned on at 6 mm/min, the convective fraction dropped to 12% and the confinement velocity lowered by 0.5 m/s. Similarly, at 30 MW, the FFFS lowered the convective portion significantly. Both the conductive and radiative fractions also decreased slightly when suppression was added as well.

The efficiency of the FFFS was also investigated and quantified in two different ways. First, the efficiency was calculated as the amount of heat absorbed by the water divided by the FHRR. This method shows efficiency as the reduction in FHRR. Efficiency was also calculated as the amount of energy absorbed by the FFFS divided by the total amount of heat that could potentially be absorbed by the water. For example, at 3 mm/min, the evaporating water could absorb approximately 60 MW. This second method measures how much water input was actually used. These efficiencies are listed in Table 4, and those for the 30 MW fire are plotted in Figure 6.

Table 3 Effect of FFFS on energy budget

<table>
<thead>
<tr>
<th>Case ID</th>
<th>FHRR (MW)</th>
<th>Water application rate (mm/min)</th>
<th>CFD velocity (m/s)</th>
<th>Convective fraction</th>
<th>Conductive fraction</th>
<th>Radiative fraction</th>
<th>Absorbed by FFFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>10</td>
<td>0</td>
<td>2.00</td>
<td>0.52</td>
<td>0.10</td>
<td>0.38</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>6</td>
<td>1.50</td>
<td>0.12</td>
<td>0.11</td>
<td>0.28</td>
<td>0.51</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>0</td>
<td>2.25</td>
<td>0.43</td>
<td>0.10</td>
<td>0.48</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>6</td>
<td>2.00</td>
<td>0.14</td>
<td>0.07</td>
<td>0.34</td>
<td>0.46</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>6</td>
<td>2.00</td>
<td>0.20</td>
<td>0.08</td>
<td>0.37</td>
<td>0.36</td>
</tr>
<tr>
<td>11</td>
<td>30</td>
<td>12</td>
<td>1.75</td>
<td>0.06</td>
<td>0.06</td>
<td>0.31</td>
<td>0.58</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>0</td>
<td>2.50</td>
<td>0.41</td>
<td>0.04</td>
<td>0.55</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>100</td>
<td>6</td>
<td>2.25</td>
<td>0.21</td>
<td>0.04</td>
<td>0.36</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Table 4 Evaporation efficiency of FFFS

<table>
<thead>
<tr>
<th>Case ID</th>
<th>FHRR (MW)</th>
<th>Water application rate (mm/min)</th>
<th>Evaporation efficiency as % of FHRR absorbed by FFFS</th>
<th>Evaporation efficiency as % of heat potentially absorbed by FFFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>10</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>6</td>
<td>51%</td>
<td>4%</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>6</td>
<td>46%</td>
<td>11%</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>3</td>
<td>36%</td>
<td>18%</td>
</tr>
<tr>
<td>11</td>
<td>30</td>
<td>12</td>
<td>58%</td>
<td>7%</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>100</td>
<td>6</td>
<td>42%</td>
<td>33%</td>
</tr>
</tbody>
</table>

The efficiencies show that while the FFFS absorbed 36% to 58% of the FHRR for the 30 MW fire, that at best, only 18% of the water actually absorbed heat. These results are for a deluge FFFS; higher efficiencies could possibly be achieved using a mist FFFS.
The effects of the FFFS on tunnel exit temperature (in the simulations, 70 m downstream of the fire) were also investigated. A lowering of downstream temperatures can mean an increase in available safe egress time and improved ventilation performance. Tunnel exit temperature as a function of FFFS application rate is plotted in Figure 7.

The addition of suppression at 6 mm/min lowered the exit temperature by 25°C for a 10 MW fire and 42°C for a 30 MW fire. There is an 8°C drop between 3 mm/min and 6 mm/min for the 30 MW fire, and only an 11°C drop between 6 mm/min and 12 mm/min. At 100 MW, the exit temperature is almost halved from 205°C to 112°C.

Discussion and significance
The results have varying levels of agreement with Ko’s equations for critical velocity where the FFFS is factored in. At 10 MW and 6 mm/min, the CFD results agree with Ko’s equation, however, at 30 MW and 6 mm/min, the CFD suggests a lower confinement velocity by over 0.5 m/s. This is at the upper limit of Ko’s equation validity (30 MW), so multiple methods of determining
critical/confinement velocity should be considered instead of relying on one equation. Over a wide range of FHRRs, none of the equations investigated consistently agreed with the CFD. However, informed estimations of critical/confinement velocity could be made from looking at the FDS results combined with NFPA 502 and other applicable equations.

These cases showed that adding FFFS reduces the NFPA predicted velocity by 0.25 m/s (as a rule of thumb). This reduction is smaller than expected, and interestingly, applies for all of the FHRRs and application rates tested. The benefit of FFFS is better seen in the reduced air temperature downstream of the fire, which could lessen the damage downstream and improve ventilation system performance.

PASSIVE FIRE PROTECTION

Scenarios were investigated for the case of a passive fire protection layer employed. Cases with longitudinal ventilation were considered. The model parameters are similar to the typical road tunnel described in Table 1, except for the application of a material properties corresponding to a passive fire board on the walls and ceiling (density 870 kg/m³, conductivity 0.175 kW/m², heat capacity 1550 J/kg/K).

Model parameters and results are provided in Table 5. The parameters of the passive board were adjusted to accelerate the rate of heat transfer thereby enabling an equivalent 2 hour duration to be considered. This was important to take into account because a passive fire board will initially absorb heat at a similar rate to concrete.

The results here show that passive protection generally has a minor impact at a 30 MW and 100 MW FHRR. There is some increase in exit temperature, but is relatively minor, as is the redistribution of the energy budget. There is no significant impact on backlayering. From a design perspective the results show that the impact of passive fire protection on ventilation performance is most likely minor, provided that appropriate accounting is made for impact of increased temperatures on ventilation equipment and required fan thrusts or exhaust rates at higher temperatures.

Table 5 Passive fire protection results – typical road tunnel geometry

<table>
<thead>
<tr>
<th>Case ID</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Note</td>
<td>Concrete</td>
<td>Insulated</td>
<td>Concrete</td>
<td>Insulated</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>2.25</td>
<td>2.25</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>FHRR</td>
<td>30</td>
<td>30</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Convection</td>
<td>0.53</td>
<td>0.61</td>
<td>0.57</td>
<td>0.62</td>
</tr>
<tr>
<td>Conduction</td>
<td>&lt;0.05</td>
<td>&lt;0.03</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.42</td>
<td>0.38</td>
<td>0.43</td>
<td>0.38</td>
</tr>
<tr>
<td>Average exit T (deg C)</td>
<td>118</td>
<td>139</td>
<td>307</td>
<td>335</td>
</tr>
<tr>
<td>Backlayer (m)</td>
<td>10</td>
<td>12</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

CONCLUDING STATEMENTS

CFD models have been used to examine the energy budget and critical/confinement velocity for a tunnel fire situation. The CFD models herein have been developed based on the authors’ best knowledge using a consistent approach. A model verification exercise has been conducted to confirm appropriate implementation, however, as with any CFD model the conclusions here must be taken using some caution because the model accuracy is not universal, especially when considering a FFFS. The following concluding statements are made based on the model results:

- The NFPA 502 equations appear to under estimate critical velocity at low FHRRs (less than
100 MW) based on test results and CFD models. At 100 MW the performance of the equations is not consistent between the different geometry tested.

- Energy budget and critical/confineement velocity are affected by tunnel geometry and ceiling height. It was found that when the geometry had an arched ceiling and increased ceiling height, as opposed to a flat ceiling, less energy was apportioned to radiation heat transfer (around 30% with the arched ceiling and 50% with the flat ceiling). As a result, the critical/confineement velocity tended to be larger for a curved ceiling.

- When a FFFS is included, there is a reduction in the critical/confineement velocity, but it is not substantial, typically only 0.25 m/s. This could be a function of what was used to define backlayering being controlled. In this work a smoke movement of no more than 10 m upstream was allowed, and the change in velocity may be greater if more backlayering was allowed.

- With a FFFS application rate of 6 mm/min added, the convective fraction of heat transfer was reduced significantly; one quarter to one half of the value without a FFFS.

- The FFFS water absorbs between 35% and 60% of the FHRR energy for the range of FHRRs investigated.

- Passive fire protection did not substantially impact energy budgets, but it did have a minor impact on downstream temperatures.

REFERENCES

The Implementation of FFFS in the Existing Road Tunnel Safety Environment

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ABSTRACT

In the framework of this research project both the effectiveness of fixed firefighting systems (FFFS) as well as their integration into the overall safety system of a road tunnel was evaluated. For this purpose FFFS were implemented in a CFD simulation environment, thus studying the interaction of FFFS and different ventilation systems and their modes of operation with respect to consequences on life safety. A variation of relevant parameters regarding tunnel system, tunnel equipment and traffic was performed and the effects on life safety were evaluated. In addition to technical aspects, also possible influences on human behavior of road users were evaluated. In order to study these aspects virtual reality tests in a 5-sided Cave Automatic Virtual Environment (CAVE) were carried out, studying the reactions of up to 50 probands in a simulated tunnel environment with and without FFFS while driving and evacuating afoot.

The study demonstrated that with respect to the effects of FFFS on fire life safety of tunnel users a lot of parameters interact in a very complex manner, especially the interaction of FFFS and ventilation systems raise a lot of complex questions. Hence, general conclusions are difficult. Nevertheless, the results of the study showed that under specific circumstances FFFS has a high potential for increasing life safety and compensation of other safety measures.

The tests in virtual reality showed that for a given experimental setup, the evacuation behavior of the subjects is not significantly changed by the activation of a FFFS. The results are valid under the restriction that the haptic effects of FFFS, such as cold or wet conditions, could not be modeled.

KEYWORD: research project, fixed fire fighting systems, FFFS, road tunnel safety, behaviour of tunnel users, risk analysis; CFD simulations

BACKGROUND AND OBJECTIVES

Motivation and objectives of the study

Since the implementation of the EC-Directive 2004/54/EC a lot of investments have been made improving safety in European road tunnels. With respect to fire safety the focus so far was on providing fair self-rescue opportunities by providing emergency exits at regular distances in combination with smoke management by the ventilation system. The implementation of fixed firefighting systems (FFFS) is no standard safety measure – neither in Germany nor in other European countries – but provides new opportunities. Against this background the German Highway Research Institute BASt launched a research project focussing on the interaction effects of the implementation of FFFS in the existing tunnel safety environment of road tunnels in Germany.

The study is focussing on the subsequent objectives:

- Providing fair opportunities for self-rescue is one key objective in Europe road tunnels. There were concerns that the activation of FFFS in the pre-evacuation and evacuation phase could
derogate the efficiency of the self-rescue system, thus counteracting the positive impacts of FFFS on fire. Hence it shall be studied, how and to what extent an activation of FFFS may influence the experiences and behaviour of people involved in a fire incident in a road tunnel. These aspects are in particular relevant for the decision, when and how FFFS shall be activated.

- Further it shall be studied how the activation of FFFS interacts with other safety system, in particular tunnel ventilation, from the point of safety of people present in the affected zone.
- For this purpose, it shall be demonstrated how FFFS can be implemented in an integrated quantitative risk model.
- Based on this model, a quantitative risk assessment study shall be performed to investigate the influence of key traffic, tunnel, and ventilation parameters together with their interaction with FFFS on tunnel risk.

In general the study should cover three different types of FFFS – water spray systems, water mist systems, and compressed air foam systems – by discussing the different characteristics of the individual system in general. However the main parts of the study – the virtual reality tests with probands and the risk assessment approach – were based on water mist systems only. In this respect it is important to mention, that neither a detailed study of parameters of a specific FFFS type nor an in depth comparison of different FFFS types were in the focus of the study. Taking recent research results and the result of large scale testing as a starting point, a typical model type of FFFS was defined and taken as a basis for the study.

The integrated approach
Modern tunnel safety concept are based on an integrated approach [1] postulating a smooth interaction of tunnel users, tunnel operators, and emergency services in case of a tunnel incident. The action of these groups of people are embedded in an environment of an optimised integrated interaction of structural conditions, the operation and control of technical tunnel equipment, and the organisational concepts for emergencies.

Since the publication of the EC-Directive 2004/54/EC on minimum safety requirements for road tunnels in 2004 [2] an optimized safety strategy focussing on self-rescue has been established for fire incidents and was laid down in numerous national guidelines (like for instance RABT in Germany or RVS in Austria). The implementation of an innovative system like FFFS, which acts already at an early stage in a fire scenario, requires a careful analysis of the interaction with other already established safety systems.

The subsequent interaction effects are addressed in the study:

Interaction effects relevant for tunnel users
- During driving: activation of FFFS causes an unexpected, sudden, and heavy derogation of sight conditions in a tunnel, which impairs driving safety. This effect depends on FFFS type, the activation strategy and to a certain extent also on the specific layout of the system installed.
- Behaviour of people in the activated zone: additionally to positive effects on fire development the side effects of an activated FFFS – like heavy sight limitation, noise, chilliness, and wetness may influence human behaviour, in particular with respect to self-rescue-action (more details see clause 0).

Interaction effects relevant for tunnel operators and emergency management
- Activation strategy: must consider the interaction effects with tunnel users – both during driving as well as evacuating – and hence requires a certain procedure, which is based on information (like detection of a fire, status of traffic) which must be made available to the operator.
- Information strategy: visual and / or acoustical information is crucial for the initiation of self-rescue – both can be impaired by FFFS.
- Supervision and control of a fire incident: the impaired visibility impedes the visual tunnel
supervision (e.g. by video) – however, a similar but increased effect is caused by the fire itself.

- Interaction with tunnel ventilation: the activation of FFFS has positive effects by reducing fire size, but also influences smoke distribution inside the tunnel (more details see clause 0).
- Persistent functioning of safety relevant tunnel systems: heat is the main cause for collapse of tunnel systems in a tunnel fire. FFFS acts positively on the heat release rate of a fire and is in particular effective in cooling the tunnel atmosphere; hence there is a clear positive effect on the persistent functioning of tunnel safety systems.
- Furthermore, the implementation of FFFS determines some design requirements for a tunnel, in particular with respect to the water supply and dewatering systems.

Interaction effects on emergency response
- The specific conditions in a tunnel set clear limits to the ability to fight larger tunnel fires, exposing fire fighters to a high risk. The retarding effect on fire development and the efficient reduction of heat (both gas temperature as well as radiated heat flux). This eases and accelerates the interaction and makes it more effective with respect to assistance to people needing help.
- Positive effects may also arise with respect to personal resources, equipment, and intervention strategy.

INTERACTION OF FFFS WITH THE BEHAVIOR OF TUNNEL USERS

User behavior in tunnel fires
From heavy disasters, as the Mont-Blanc tunnel fire (1999), we know that tunnel users often show dysfunctional behaviour during a road tunnel fire. During the Mont-Blanc tunnel fire 27 from 39 fatalities were still sitting in their vehicles at the time of death [3]. Similar observations were made during the Burley tunnel fire in Melbourne in 2009 (Dix 2011 [4]). Dix reports behaviour as walking back to their cars after initial evacuation, or approach to the accident to take pictures. To our knowledge information on the behaviour of tunnel users in the area of direct exposition to a fixed fire fighting system (FFFS) have not been reported for real events.

Perception as a prerequisite for behaviour: Vision and Hearing
Form a theoretical perspective, different psychic processes will influence the behaviour of tunnel users in case of an emergency. We would only like to mention models on behaviour during stress (see Proulx93 [5]), but describe models focusing on evacuation behaviour in more detail (see below). Moreover, due to the activation of an FFFS, especially processes of perception are concerned. For humans the most important channels of perceptions are the visual and the acoustic system that should briefly be addressed.

The eye is the primary sensory organ of the human, and most perceptual input is processed in the visual system. Many security relevant signs in a road tunnel are presented visually (e.g., signs for emergency exits, emergency routes). The information derived from the system is very much dependent from physical properties of the environment (e.g., light intensity, smoke) and properties of the visual objects (e.g., reflection, luminance). Regarding tunnel drives, it is important that the visual system has to adapt to different lighting conditions (i.e., dark adaption), that takes up to 20 minutes, and can impair vision during tunnel drives. Furthermore, colour vision is dependent on a minimum brightness of the environment. Up to now, there are no systematic studies investigated the impact of activated FFFS systems on the visual processing.

Some studies that might help to derive conclusions regarding the effect of a FFFS on the human behaviour focus on the behaviour during heavy smoke in the tunnel. They show that the tunnel wall is an important point of orientation and people move along the wall during such conditions [6]. Other studies found that people avoid walking through smoky areas on their way to emergency exits and reduce velocity while walking in smoke because of the reduced sight [7]. Beside the visual perception the auditory system is the second major perceptual channel for humans. Related to emergency situations in tunnel acoustic information are often the first which give hints on
the actual emergency, e.g., noise of the crash, acoustic warning signals or instructions from the control centre. Most people orient their behaviour on the instructions given from authorities, e.g., instructions from the control centre [8]. Better adherence to instructions, in a situation were a larger group should evacuate, has been found when it was presented in a loud and clear voice [9].

It is obvious that an activated FFFS has an impact on the visual perception due to the water mist or foam in the air and on the car. Furthermore, an activated FFFS has an effect on the auditory system due to the sounds generated by the system and the water/foam dropping on the car or due to absorption effects (e.g., distraction, impaired comprehensibility of announcements). Therefore, we assume that visual and auditory perception is changed while a FFFS is activated, and thus, potential influences of these effects on the behaviour of the tunnel users have to be considered.

**Behaviour: Models on evacuation behaviour**

Generally, most models divide the flight behaviour during emergencies in several stages. Most prominent, a pre-evacuation and an evacuation phase are distinguished. In the pre-evacuation phase, all events before the actual flight starts are included. The phase ends with the decision to start the evacuation now. Relevant parameters for this phase are the duration and which factors have influenced the decision for the evacuation and the time point for initiating the evacuation.

The subsequent evacuation phase can be differentiated in the pre-movement-phase and the movement phase. During the pre-movement phase people search for information helping decide to take a specific flight route. The following movement phase includes all behaviour that is executed by the tunnel user until reaching the flight destination.

Such an approach has also been published by Kuligowski (2009). The model comprises four phases (see Figure 1). The first two correspond to the pre-evacuation phase, the third the pre-movement phase and the fourth the movement phase [10].

![Figure 1 Phases of evacuation in the model of Kuligowski [10].](image)

An activated FFFS system might affect all the different stages of the evacuation behaviour.

**Questions for FFFS**

Based on these models and actual evidence, we can formulate a few hypotheses for the impact of FFFS on tunnel users that are directly exposed to the water, water mist or foam in an activated segment after an accident. Regarding perception, we can assume that the vision is impaired while sitting in a car as well as while walking through the water or foam. Furthermore, the additional noise by the system and the water or foam might reduce comprehensibility of announcements. Regarding flight behaviour, the hypotheses are more speculative. For pre-evacuation, time to start might be enlarged, and the probability of taking action might be reduced due to creating a more ambivalent situation and reducing information by hindering perceptual input. Furthermore, regarding the movement phase, the activated FFFS system might influence walking speed or evacuation routes. Such effects might counteract the positive impact of the FFFS on the fire. However, there are up to date no reliable data available that gives hints of the influence of FFFS on the behaviour of tunnel users.
Expert interviews on impact of FFFS on tunnel users

One approach of the project was to evaluate the knowledge of the experts (operators and producers) regarding behaviour of users. The interviews were conducted in 2012. Interestingly, they were able to provide some data on the perception, but not on the influence on the behaviour. Regarding perception, the experts report a clear impact on sight for water mist (lower than 5 m), water (between 5-20 m) but not so much for foam (more than 20m) FFFS systems. Regarding acoustic, water mist might produce loud noise with levels about 105 dB(a), while foam systems also produce noise, but on an lower level with about 60 dB(a).

Personal experiences of a water mist FFFS

One major approach to understand a situation more fully is to get the personal experience of it. For that reason, FFFS tests in the Mona Lisa Tunnel near Linz, Austria, were attended and the influence of the water mist on perception and behaviour was investigated during a self-test. The following impressions were confirmed:

- Vision: While sitting in the car: The sight was largely reduced up to less than 5 m and it was nearly impossible to move the car in a responsible way (maximal velocity 10 km/h). Self-lighting signs were not visible at about 10 m distance. Sight through the side window in direction to the tunnel wall was better than through the front window. While walking through the water mist: The sight largely depends on the position within the tunnel. Sight at the tunnel wall is much better than in the middle of the tunnel. In the middle of the tunnel security signs at the tunnel walls (emergency exit, emergency phones) are not visible.

- Hearing: The water mist FFFS develops loud, however not painful noise. Conversation is still possible within the car and outside of the car. Measures result in 90 to 100 dB(a) in a distance of about 10 m from the activated area, and 75 to 80 dB(a) in the car within the activated area. Most important in this tunnel, the comprehensibility of announcements was largely impaired in the car in the activated area.

- Tactile: While walking in the activated area, clothes soak very fast. Water mist intrudes through small spaces within clothes, and the water feels awkward cold, but this might turn as our experience is that it feels positive cold during fire tests.

These perceptual information were used to create the visual and acoustic properties of a virtual scenario that was used in the simulation tasks.

Self-reports after experiencing a virtual water mist FFFS

There are different possibilities to derive answers for the questions how people experience emergencies and how they will behave in specific situations. All of the possibilities have specific limitations. Fortunately real events are rare, and could not include experimental variations. Field tests are logistically complex and expensive. Virtual reality simulation is a relatively new tool allowing experimental designs in an affordable fashion. For a discussion of pros and cons on the different paradigms see Kinateder und colleges [11].

Participants were acquired by announcements at regional online platforms. The total sample was 50 participants, from which 25 were in the group with activated FFFS. Only these participants were analysed in this paper. Thirteen of the participants were woman. The average age was 23.5 years (SD = 2.9). They acquired there driving license over 5 years ago (M = 5.2, SD = 2.5), and drive about 10 thousand kilometre per year (M = 24.6, SD = 29.9).

The simulation device for the simulation of the scenario was the 3D multisensoric lab situated at the department of psychology at the University of Würzburg. CS-Research 5.6 (VTplus, Würzburg, Germany; see www.cybersession.info for detailed information) was used to establish experimental control. Rendering was completed by Source Engine 2007 (Valve, Bellevue, Washington, USA). Visual stimuli were presented in a 5-sided Cave Automatic Virtual Environment (CAVE, 4 walls and floor). During driving, participants were within a simulated Golf V and were able to steer the car by steering wheel and pedals (Playseat). After leaving the car participants could walk in the virtual tunnel using a gamepad (for more information see [12]).

After completing informed consent and filling in some questionnaires, participants had the
opportunity to familiarize with the virtual environment and the navigation devises. During the 
following virtual reality scenario, participants drove a car (VW golf V) in a virtual bidirectional road 
tunnel. Participants had to stop the car behind several other cars already queuing behind an accident 
with a heavy good vehicle. At the accident fire and smoke were developing (the smoke propagation 
implemented in the model was determined by a 3D CFD model based on FDS for a 30MW fire 
developing under similar circumstances). About 15 s after stopping the car, announcements to 
evacuate the tunnel were given. After the first announcement, the FFFS (water mist) was activated. 
The impact of the FFFS was simulated only for the visual and acoustic modi (see Figure 2) for the 
visual modus).

Figure 2 View out of the virtual car before (left) and after activation of the FFFS (right)

The task for the participants was to behave as in a real situation. If participants decided to leave the 
car, a short break was introduced, the driving simulation setup was removed and participants 
completed their evacuation. After completion of the total task, participants were asked about their 
experiences. Within this paper, only their responses on these questionnaires were reported, behaviour 
during the task as well as comparisons between the group and a control group will be reported 
elsewhere.

The following results were generated by self-report of 25 participants that experienced a virtual water 
mist FFFS after a simulated incident including heavy smoke development in a CAVE system. The 
questions focus on the experience of the activated FFFS system, the impact on visual perception 
during the scenario, the knowledge about commonness of FFFS in road tunnel in Germany, and their 
atitude towards an integration of FFFS in road tunnel.

To get an impression of the acceptance of FFFS by tunnel users, we asked participants whether they 
experienced the water mist as danger and whether they were surprised by the activation of the FFFS. 
More than half of the participants (52%) rated the FFFS as potential danger (13 “somehow”), while 
only 16% (4) experienced the FFFS as not dangerous (“no” and “hardly”) and only 32% (8) as 
dangerous (“quite” and “very much”). On the question whether they were surprised 80% of 
participants (n=20) answered with “quite” and “very much”.

To get an impression of the impact of the activation of the FFFS on the behaviour of the participants 
we asked whether they had the impression that the FFFS influenced their decision to leave the car. 
Interestingly, a small majority declined such influences (56%), while nearly half stated that they were 
influenced (44%). Interestingly, some participants who reported to have been influenced by the 
avivated FFFS, stated that they have left the car because sight within the car was so heavily reduced. 
Others who were also influenced by the FFFS stated that they had been “irritated” because they lost 
overview due to the water mist. Participants who stated that their decision to leave the car was not 
influenced by the FFFS pointed out that they had the intention to leave the car in any case, because 
they experienced the developing of the fire and the smoke as dangerous. Overall, these statements 
hint at a positive influence on the decision to evacuate. Particularly the interpretation of the FFFS as a 
danger may have the positive effect of enhancing the probability of activation.

The results on the actual behaviour of the participants during the tasks will be published elsewhere. 
Overall, results did not reveal significant differences in the probability to evacuate or in its latency, 
while mean time to evacuate was somehow larger when the FFFS was activated. 
Sight conditions were derogated for the situation of sitting in the car and evacuation outside of the car.
Participants rated the impact of the FFFS inside the car as larger than outside the car. Inside the car, 80% of participants rated the impact high (“quite” und “very much”, see Figure 3), while outside the car only half of the participants (52%) rated the impact as high (“quite” und “very much”, see Figure 4).

![Figure 3: Experienced impact on sight due to FFFS while being in the car](image)

![Figure 4: Experienced impact on sight due to FFFS while being outside of the car](image)

ASSESSMENT OF INTERACTION OF FFFS WITH OTHER TUNNEL SAFETY SYSTEMS

Protection goals for FFFS in road tunnels
Based on the results of literature studies (focussed on real smoke fire testing and real incidents) and interviews with FFFS manufacturers a set of protection goals for the installation of FFFS in a road tunnel were defined and their effect on life-safety of tunnel users as well as on asset protection were analysed (see Table 1).

<table>
<thead>
<tr>
<th>Protection goals for FFFS</th>
<th>Effects on life-safety</th>
<th>Effects on tunnel structure &amp; equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction of fire growth</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Limitation of fire spread</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Facilitation of fire fighting</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Serving acceptable and stable conditions for self-rescue</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Monitoring stable operating conditions for other safety systems</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

As the focus of the study was on life safety of tunnel users, the goals were defined from the perspective of this specific target group and goals irrelevant for this group were not addressed in more detail.

Approach for the quantitative assessment
The approach for the quantitative assessment of the effectiveness of FFFS on the risk of tunnel users consists of several steps:
- Definition of 2 model tunnels – one unidirectional and one bidirectional – with variation of several safety relevant parameters regarding tunnel design and equipment.
- Definition of a fixed fire-fighting system for this model tunnel (type water mist).
- Establishing a risk model for the model tunnels.
- Implementing FFFS in the risk model.
- Performing risk calculations with and without activation of FFFS, including a variation of relevant other parameters in order to study interaction effects.

As the main focus of the study was on the investigation of interaction effects of FFFS with other tunnel safety measures, the model tunnel was defined in such a way, that key safety parameters can be varied like
• traffic mode
• emergency exit distance
• ventilation systems and ventilation design fire size
• traffic load (including congestion)

As model tunnel a 1.200m long tunnel with two lanes was chosen, because according to the German guidelines RABT for this tunnel type both – a longitudinal ventilation system as well as a smoke extraction system – are admissible. Distinction was made between unidirectional and bidirectional traffic. The relevant tunnel parameters and their variations are displayed in the subsequent table:

<table>
<thead>
<tr>
<th></th>
<th>Type 1 bidirectional traffic</th>
<th>Type 2 unidirectional traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1.200m</td>
<td></td>
</tr>
<tr>
<td>Emergency exist distance</td>
<td>200m / 300m / 400m</td>
<td></td>
</tr>
<tr>
<td>Longitudinal inclination</td>
<td>3.0% (to one side)</td>
<td></td>
</tr>
<tr>
<td>Ventilation system</td>
<td>Smoke extraction</td>
<td>Longitudinal ventilation</td>
</tr>
<tr>
<td>Ventilation layout</td>
<td>For 30MW fire (according to RABT)</td>
<td>For 100MW fire (according to RABT)</td>
</tr>
<tr>
<td>Traffic load</td>
<td>20,000 veh/24h</td>
<td>70,000 veh/24h</td>
</tr>
<tr>
<td>Share of HGV</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>Congested traffic</td>
<td>30h per year</td>
<td>30h / 500h per year</td>
</tr>
</tbody>
</table>

As representative tunnel cross section the standard type RQ 10.5T with 2 traffic lanes was selected. For longitudinal ventilation the same tunnel cross section was used, but without intermediate ceiling.

**Configuration of fire-fighting system**

As basis for the study a typical high pressure water mist system was used. The length of a zone is 25m, with 3 zones operating at the same time; a water density rate of 4 l/m²min (0.89 l/m³min) was applied. As it was not the focus to study different design parameters of FFFS or to compare different system types, no variation of FFFS design parameters was done. However, the activation time was varied in a sensitively study.

**Risk model**

As basis for the risk calculations the German risk model defined in the research report FE03.378/2004/FRB “Assessment of Safety in Road Tunnels” [16] was used. For the purpose of the present study this model had to be modified to some extent by implementing features of the new Austria Tunnel risk Model TuRisMo [13] to be able to study key aspects in a realistic manner; furthermore the effects of FFFS had to be implemented in the smoke propagation model.

The model calculates an overall expected risk value for fire risk, based on representative traffic scenarios (for low-average-high traffic situations), which are taken as basis for the calculation of the development of the initial air flow conditions in a 1D CFD model. The resulting air flow velocity in dependence of time is introduced as boundary condition in a 3D CFD model based on FDS.

The results of the 3D modelling (temperatures and flue gas concentrations at a level of 1.6m in the tunnel in dependence of location and time) are used as input to an aggress model, which simulates the effects of smoke on people movement (reduced walking speed / immobility due to bad visibility and cumulated effects of flue gases) based on an accumulative intoxication model (Purser model [7]). By superposing the result of the evacuation simulation (maximum covered distance in dependence of starting point) with the emergency exit configuration, zones can be defined, where people cannot evacuate successfully; by superposing this zones and the present location of people inside the tunnel, the consequences for one scenario can be calculated.
By repeating this procedure for all scenarios investigated and calculating a weighted average over all scenarios the statistically expected damage of one fire scenario can be calculated. This procedure is then repeated for all fire scenarios.

This risk model is rather complex and a lot of parameters need to be defined; as an example in particular relevant for studying the interaction effects, the time line of the most important actions involved in the process shall be addressed more specifically (see Figure 6)

![Figure 6](image.png)

**Figure 6  Timeline for most key actions in the risk modelling.**

The people’s behaviour model is a key parameter; being aware that in reality a great variety of different behaviour patterns are to be expected, for the purpose of this study a unified behaviour was assumed, in order to get comparable results. The subsequent assumptions were made:

- People evacuate spontaneously, if the smoke is approaching them (extinction coefficient in 1.6m height reaches 0.1).
- After 90s people get the information to evacuate immediately; they react 60s later.
- Different evacuation velocities for different groups of people are included in the model; if covered by smoke, these are modified according to reduced visibility and the cumulated toxic effects of smoke.

During evacuation the ventilation system is operated according to the requirements for emergency ventilation of RABT (critical velocity in unidirectional tunnels without congestion; longitudinal velocity < 1.5m/s – in bidirectional tunnels with congested traffic and bidirectional tunnels, smoke extraction through dampers at a distance of 100m). For implementing the effects of FFFS in the risk model, the two main effects of FFFS were modelled separately:

- The effect on fire development was taken into account by a simplified approach:
  For the case “FFFS activated” the fire curve was modified, based on the results of various real scale fire tests (e.g. [14], [15]). Assuming a shielded fire (as most probable scenario) a reduction of the maximum heat release rate of 50% was taken into account. A physical modelling of the combustion process was not envisaged due to the limited resources of the study.
- The effects on smoke propagation (due to the impulse of the injected water droplets) and the cooling effect on smoke was simulated in FDS, which allows the modelling of the interaction between water droplets and air flow and temperature conditions in the tunnel atmosphere.

**Results**

Typical results are presented on the basis of the bidirectional model tunnel with longitudinal ventilation; in case of a fire vehicles are trapped on both sides of the fire. Smoke is blown into the direction of the initial air flow prevailing at the beginning of the incident. As a consequence a long tunnel section, in which a lot of people may be present (depending on the traffic scenario) is affected by smoke. This results in a relatively high fire risk – compared to model tunnels with unidirectional traffic or smoke extraction instead of longitudinal ventilation. The risk values do not include aversion factors.
In the figure below the fire risk (expected value) of the model tunnel with an emergency exit distance of 300m and without FFFS is defined as reference risk level and the influence of an activation of FFFS and a modification of emergency exit distance is shown as relative increase or decrease of risk. The picture shows a high effect of FFFS on fire risk, i.e. a reduction in the order of magnitude of 30% to 50%. The influence of an increase / decrease of the emergency exit distance can clearly be seen as well; this way of presenting results is well suited to display options for compensation: in this case an increase of emergency exit distance from 300m to 400m could nearly be compensated by the implementation of FFFS (see last column).

Other results of the study can be summarized as follows:

- In all cases with longitudinal ventilation a high effect of FFFS on fire risk could be demonstrated; the highest effect could be achieved in unidirectional tunnels with only 30 hours of congested traffic. This is, however, the tunnel type with the lowest fire risk – even without FFFS.

- For tunnels with smoke extraction the situation is much more complex: not in all cases a risk reduction effect of FFFS could be identified and in general this effect is much less pronounced than in tunnels with longitudinal ventilation, in particular if the smoke extraction system has a high smoke extraction capacity (design fire 100MW); this is due to the effect, that the vertical impulse of the water mist systems, transfers highly concentrated smoke cumulated at the tunnel ceiling (stratification) into lower parts of the tunnel section (and increasing the smoke concentrations there) thus counteracting the smoke extraction, which extracts the smoke at the tunnel ceiling. It seems that the FFFS activation and smoke extraction are counteracting and impairing each other, which can be concluded from the risk assessment results as well as from evaluation of partial results. Gas measurements from real scale tests seem to support this thesis.

- The sensitivity analysis regarding activation time clearly showed the high influence of this parameter – a delay in activation of 7 minutes (instead of 1 minute) after detection makes FFFS practically ineffective with respect to risk reduction in a longitudinally ventilated tunnel. However, in a tunnel with a strong smoke extraction system this delay shows almost no effect: because smoke is extracted efficiently, the risk can be reduced to the same extent by the ventilation system itself – there is no further improvement due to the FFFS anyway – with early as well as with delayed activation.

Figure 6 Bidirectional tunnel with longitudinal ventilation: effects of FFFS and variation of emergency exit distance on fire risk.
CONCLUSIONS AND WAY FORWARD

On the basis of the detailed studies of interaction effects of FFFS with human behaviour as well as with other technical safety measures, the subsequent conclusion can be drawn:

- The proband study in VR confirmed as expected, a strong reducing effect of the FFFS on sight. This effect was even higher when sitting in the car than when walking outside. Furthermore, most participants were surprised when the FFFS was activated and rated the water mist as potential danger. Interestingly, this leads not to a negative effect on the evacuation behavior. Maybe these alerting properties of an activated FFFS even have positive aspects. However, the probability to evacuate and the latency for starting the evacuation were not changed significantly, even if there is a trend towards an enhanced latency. Importantly, in this study the FFS was activated directly after the evacuation announcement, and we did not simulate haptic aspects of the FFFS. Thus, further research is needed to generalize the actual results.

- The risk based studies demonstrated that with respect to the effects of FFFS on fire life safety of tunnel users a lot of parameters interact in a very complex manner, hence general conclusions are difficult. The clearest conclusion can be drawn with respect to the activation time: if activated early and fire growth can be reduced efficiently, than the production of flue gas is still limited resulting in a high risk-reducing effect. This conclusion is relevant, when discussing potential effects on human behaviour with respect to self-rescue. However, if FFFS are activated as soon as possible, the traffic in the affected tunnel section should have stopped already, to award the risk of collisions.

- The risk study demonstrated high risk reducing effect for tunnels with longitudinal ventilation – for unidirectional tunnels with and without congestion as well as bidirectional tunnels. However, for tunnels with smoke extraction no clear conclusion can be drawn. The results shows, that under the given conditions the efficiency of the smoke extraction (at the tunnel ceiling) and of the FFFS system are counteracting, thus impairing each other.

- In general the study revealed, that the interaction of FFFS and ventilation raise a lot of complex questions, which require further investigations.

- The study demonstrates that FFFS has a high potential for compensation of other safety measures (such as reduction of emergency exit distance, selection of longitudinal ventilation instead of smoke extraction, reduction of design fire size), but this requires a detailed study based on a sophisticated risk model, taking the specific conditions of an individual tunnel into account; conclusions of general relevance cannot be drawn.
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Design Fires for Tunnels with Water-Based Fire Suppression Systems

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ABSTRACT

A series of tests were carried out to investigate design fires for tunnels with water-based fire suppression systems under different conditions in a 1:4 model scale tunnel. The key parameters including fuel load covers, activation time, water flow rate, nozzle type, ventilation velocity, sprinkler section length and tunnel width were tested. Technical information and analyses of test data are presented with a focus on the influence of these different parameters on the design fire in a tunnel with a water-based fire suppression system. Further, guidance for the design fires in tunnels with water-based fire suppression systems is proposed.

KEYWORD: design fire, tunnel fire, fire suppression, ventilation, activation

INTRODUCTION

The use of water-based fire suppression systems in tunnels is increasing. The development that has taken place over the past decade has not yet been reflected in regulations and standards. By introducing changes that may lead to so-called technical trade-offs, benefit from the installation of a new cost effective safety systems can be improved. The reason why this opportunity has not been exploited in the current regulatory framework is mostly due to the uncertainty concerning these issues. There have been many FFFS tests conducted in full scale or large scale tunnels [1], e.g. the tests carried out in the Second Benelux Tunnel near Rotterdam in the Netherlands during 2000 and 2001 [2], the Hagerbach tunnel test in Switzerland in 2005 [3], the San Pedro de Anes test tunnel tests carried out in the framework of SOLIT in 2008 [4] and SOLIT2 in 2012 [5] and the tests by Efectis commissioned by Land Transport Authority (LTA) Singapore [6]. Most of these large scale tests were carried out to check the performance of specific systems that were planned to be installed in a given tunnel. There are also some model scales tunnel fire suppression tests that have been conducted for research purposes, for example [7, 8]. However, some common conclusions about the efficiency of water-based fire suppression systems with respect to the reduced fire size or reduced impact on the design of ventilation system and tunnel structural protection have not been done. Some trade-off benefits have been discussed by Ingason and Li [9].

The design of the Stockholm Bypass, which is the largest road tunnel project in Sweden has been discussed lengthily among engineers and authorities in Sweden. After introducing water-based fire suppression systems in the tunnel, some benefit could be obtained in the design and development of other safety features. A water-based fire suppression system affects the rate of fire development and therefore the environment in the tunnel. This in turn affects the design of the ventilation system and also the temperature load on the structure. The only question is how much and in what way? There are many parameters that can affect the outcome, such as water density in mm/min, droplet size, the activation time, longitudinal ventilation velocity and burning vehicle design and size. Today the design fire for the ventilation system is an around 100 MW fire, but if the water-based fire suppression system is installed it could be reduced to 50 MW, dependent on the system used and the
fire scenario. This lower heat release rate (HRR) in turn affects the design of the ventilation system, making it possible to work with a smaller fan capacity. This in turn affects the total investment cost. Another consequence is that the gas temperature in the ceiling near the fire could be reduced. In order to get the benefit from lower design fires for tunnels with water-based fire suppressions, the reliability of the systems has to be clearly addressed. It is a complex issue that probably cannot be simply answered in this paper, but it will be included as a parameter and discussed later.

There is also a discussion within NFPA502 [10] concerning which design fire to choose for a road tunnel installed with water-based fire suppression system. NFPA502 committee works out a standard on fire safety in road tunnels. PIARC, i.e. World Road Association, has also discussed the issue. There are two discussion groups, i.e. those who are for the introduction of a reduced design fire, and those who do not believe that one can choose a new design fire because of the ignorance that prevails on the issue. An important reason for the discussion of existence is the lack of holistic approach to objectively discuss the issue on the basis of known facts. Most attempts which have been made today are water-based fire suppression systems such as water mist systems with relatively low water flow rate and small droplets. It is known that small droplets cools the gas temperature very efficiently compared to large droplets. The reduction in the HRR can vary significantly, but in these cases even if the fire size is not clearly affected, the surrounding fire gases are cooled effectively. The large droplets coming from the low pressure system, however, survive the hot fire plume and can cool the fuel surface more efficiently and thus reduce the fire size. The benefits may reduce if the vehicle is covered with sheet metal or any other material that prevent the drops to reach the fuel surfaces. However, the risk of fire spread to outside of the vehicle is greatly reduced. The manufacturers of water mist systems have access to many experimental data but the data are generally not available. Regardless, there are many authorities, consultants and tunnel owners who put great efforts in resolving the issue of the influence of water on the design fire. By compiling the knowledge available today and make a judgment based on that, there is ample opportunity to resolve the problem.

The main objective of the tests is to investigate the performance of water-based fire suppression systems in tunnel fires under different conditions. In addition, one special purpose is to obtain additional information for the full scale fire suppression tests that were carried out in the Runehamar tunnel in 2013 [11].

EXPERIMENTS

The Froude scaling technique has been applied. Experience of model tunnel fire tests shows a good agreement between model scale and large scale test results on many focused issues, e.g. fire development [12]. A total of 18 tests were carried out in the 1:4 model scale tunnels with water-based fire suppression systems together with one free-burn test. The key parameters including fuel load covers, activation time, water flow rate, nozzle type, ventilation velocity, sprinkler section length and tunnel width were tested. The test set-up and measurements are shown in Figure 1. The model tunnel itself was 15 m long, 2.8 m wide and 1.4 m high. The scaling ratio was 1:4. This suggests that the corresponding full scale dimensions would be 60 m long, 11.2 m wide and 5.6 m high, respectively. In some tests, the model tunnel width was changed to 1.88 m, corresponding to 7.5 m in full scale.

Three types of nozzles were tested, including one scaled T-Rex nozzle and two normal nozzles K5 (K-factor 5) and K9 (K-factor 9). The full scale T-Rex nozzles are now manufactured under the name of TN-25. The sprinkler section length was either 12.5 m (50 m in full scale) or 7.5 m (30 m in full scale). A measured ceiling gas temperature of 141 °C is used as the criteria for fire detection in the tests, that is, a tunnel fire is detected after a gas temperature of 141 °C is measured by one of the ceiling thermocouples (T5 to T9). The corresponding fire is expected to be large enough to be detected easily by most of the detectors, that is, the criterion tends to be conservative. Further, note that in reality after fire detection, it takes some time for the tunnel operators to respond to the situation. This delay is also simulated and by default set to be 1 min in full scale, i.e. 0.5 min in 1:4 model scale. In the tests, different delay time was tested.
Wood pallets were used as fire sources based on a validated advanced scaling theory. The fuel load was designed to produce a maximum HRR of approximately 100 MW in full scale, excluding the target.

Analyses of test data are presented with a focus on the influence of these different parameters on HRR in tunnels with water-based fire suppression systems. These parameters include activation time, water flow rate, nozzle types, coverage, end blockages (in front and at the end of the fuels), ventilation, sprinkler section length, tunnel cross section. Further, guidance for design fires will be provided. A free-burn test in the tunnel was also carried out and the maximum HRR obtained is 3.56 MW (incl. target), corresponding to 114 MW in full scale. These values match very well with the designed values. By default, in the following analysis, the ventilation velocity is 1.5 m/s, the water flow rate 5 mm/min, the tunnel width 2.8 m, and the sprinkler section length 12.5 m.

Effect of activation time
In the following, the effect of activation time on the performance of the fire suppression systems is analysed for tests without ceiling coverage and with ceiling coverage, respectively.

**Tests without ceiling coverage – K5 nozzles**
Figure 2 shows the influence of the activation time delay on the performance of the fire suppression system with the K5 nozzles in the tests without ceiling coverage. Comparing tests 1, 3, 4 and 5 shows that the fires in tests 1, 3 and 4 with an activation delay of 0.5 min, 1 min and 2 min were suppressed immediately after activation, and the fire in test 5 with an activation delay of 4 min was also suppressed but took much longer time to extinguish. The main reason could be that the fire suppression system is much more efficient in suppressing the fire by pre-wetting the un-burnt fuel surfaces to prevent further flame spread, rather than by extinguishing the existing burning surfaces. Further, the solid fuel fires were burning in three dimensions and thus took some time to have effect on the deepest fuel surfaces and the HRR after activation.
Tests with ceiling coverage – T-Rex nozzles

Figure 3 shows the influence of the activation time delay on the performance of the fire suppression system with the T-Rex nozzles in the tests with ceiling coverage and wide tunnel. The maximum HRR is 177 kW in test 12 with an activation delay of 0.5 min and 413 kW in test 13 with an activation delay of 2 min. Clearly, the late activation results in a much greater maximum HRR, however, the fires were suppressed efficiently in both tests after activation of the fire suppression system.

![Figure 3](image1.jpg)

Figure 3  Effect of activation time on HRR in T-Rex tests without coverage (wide tunnel).

Figure 4 shows the effect of the activation time delay on the performance of the fire suppression system with the T-Rex nozzles in the narrow tunnel tests with ceiling coverage. Note that test 18 is a repeat of test 16 with the only difference that the wood pallets had a higher moisture content with the exception of the first 2 piles. Clearly, it shows that the fire in test 17 with an activation delay of 0.5 min was suppressed efficiently. However, the fires in 16 and 18 with an activation delay of 2 min were not efficiently suppressed, and the HRRs increased continually to approx. 1 MW in test 16 and 0.8 MW in test 18.

![Figure 4](image2.jpg)

Figure 4  Effect of activation time on HRR in T-Rex tests with ceiling coverage (narrow tunnel).

As can be expected, the activation time plays an important role in fire suppression. For a late activation, the fire could approximate a fully developed fire and result a much more severe fire. In these cases, the fires are much more difficult to suppress and further the benefit from a fire suppression system becomes small.

In order to reduce the HRR and suppress the fire rapidly, the fire suppression system should be activated as early as possible in case of a fire accident.
Effect of water flow rate

In the following, the effect of water flow rate on the performance of the fire suppression systems is analysed for tests without ceiling coverage and with ceiling coverage respectively.

Tests without ceiling coverage – K5 nozzles

Figure 5 shows the effect of water flow rate on HRR in K5 tests without ceiling coverage. In both tests shown in Figure 5, the activation had a delay of 1 min. Clearly it shows that in test 8b with a water flow rate of 2.5 mm/min the fire suppression system did not suppress the fire efficiently after activation, and the fire continued to grow until around 42 min when it reaches the maximum heat release of approx. 1.5 MW, 46 % of the maximum heat release in a free-burn test. In test 3 with 5 mm/min, the fire was suppressed immediately after activation and the HRR decreases rapidly.

The results shown here indicate that the water flow rate of 2.5 mm/min (5 mm/min in full scale) is not high enough to efficiently suppress such a fire without ceiling coverage. Instead, the water flow rate of 5 mm/min (10 mm/min in full scale) is able to suppress such a fire efficiently. This could also indicate that in such a scenario, increasing the water flow rate to a greater value, e.g. 10 mm/min (20 mm/min in full scale), does no significant improvement to the performance of the fire suppression system since 5 mm/min (10 mm/min in full scale) has already been able to suppress the fire efficiently. Note that these conclusions are drawn from the tests without ceiling coverage.

Tests with ceiling coverage – K5 nozzles

Figure 6 shows the effect of water flow rate on HRR in the K5 nozzle tests with ceiling coverage and an activation delay is 0.5 min. The maximum HRR in test 10 with 7.5 mm/min decreases by 28 % relative to test 2. Note that the water flow rate is 1.5 times greater in test 10 compared to tests 2 and 7. Compared these values to the maximum HRR in the free-burn test, the maximum HRRs in the suppression tests with 5 mm/min was 32 % of that in a free-burn test, and the maximum HRRs in tests with 7.5 mm/min was 23% of that in a free-burn test. This indicates that an increase of 50 % in the water flow rate from 5 mm/min to 7.5 mm/min only results in a decrease in the maximum HRR of approximately 9 % of that in a free-burn test. In other words, the influence of the water flow rate on the fire development in the tests with ceiling coverage is insignificant for the tested water flow rate ranging from 5 mm/min to 7.5 mm/min, corresponding to 10 mm/min to 15 mm/min in full scale.

Effect of nozzle types

Figure 7 shows the influence of nozzle types on the performance of the fire suppression systems in the tests with ceiling coverage and an activation delay of 0.5 min. Clearly, the T-Rex system efficiently suppressed (extinguished) the fire in these tests with ceiling coverage, and its performance was much better than K5 and K9 systems. On the other hand both K5 and K9 systems controlled the fires. The maximum HRR for the K5 system was 32 % of that in a free-burn test, and 24 % of that in a free-burn test for the K9 system. Although the difference between K5 and K9 is insignificant, it can still be seen
that the K9 system discharging larger droplets performed slightly better than the K5 system. Note that the T-Rex nozzles which performed better than the other two systems discharged even larger droplets. Although the droplets were discharged in a different way for the T-Rex nozzles, it could still be concluded that the nozzle type with large droplets slightly performs better in suppression of vehicular fires with ceiling coverage.

![Figure 6](image-url)  
*Figure 6  Effect of water flow rate on HRR in K5 tests with coverage.*

![Figure 7](image-url)  
*Figure 7  Effect of nozzle types on HRR in the tests with ceiling coverage and activation delay of 0.5 min.*

Further, it can be seen from Figure 7 that even for a delay of 2 min, the fire with ceiling coverage was successfully suppressed by the T-Rex system immediately after activation. The test data show that the T-Rex system can effectively suppress the fires, except in the tests with the narrow tunnel and an activation delay of 2 min. It can be concluded that in the scenarios tested, the T-Rex system with larger droplets performs better than the other two systems with normal nozzles.

**Effect of ceiling coverage**

Figure 8 shows the effect of the ceiling cover on top of the fuel load on the performance of the fire suppression system with the K5 nozzles. Clearly, it shows that in the test without ceiling coverage, the fires were effectively suppressed. In contrast, in the test with steel ceiling coverage, the fire was not efficiently suppressed and the fire continued to grow up to approximately 1.15 MW, 32 % of the maximum HRR in the free-burn test. The main reason is that the surface cooling is the main mechanism of an effective suppression of this type of fire, however, in the tests with ceiling coverage on the top of the fuels, most of the water spray cannot discharge water directly to the fuel surfaces and take heat away from the fuels, instead the water sprays only impinged on the ceiling cover and cooled.
the plate. It can be concluded that the fire with a ceiling coverage is much more difficult to suppress and corresponds to a worse scenario and thus the steel ceiling cover was used in most of the tests.

Figure 8  Effect of ceiling coverage on HRR in the tests with K5 nozzles.

Effect of ceiling coverage materials
Figure 9 shows the test results with different ceiling coverage materials and a delay of 0.5 min. In test 2 the top cover of the main fuel load was a steel plate and a plywood plate in test 7. Comparing test 2 and test 7 shows that the HRR curve obtained from the tests with the combustible plywood ceiling cover was approximately equivalent to that with the non-combustible steel ceiling. The main reason is that the water spray discharged to the top surface of the ceiling cover significantly cooled down its surface temperature. Therefore the temperature on the bottom side of the cover was also significantly lowered. The overall effect is that only a small piece of the combustible plywood ceiling (less than 10%) was burnt and most of the plywood cover was only charred on the bottom side in test 7. Note that the process activation was simulated well in the tests by use of the commonly-used heat detection algorithm (or even conservative in some tests), therefore the scenario simulated should be quite realistic. Therefore, in the tested scenarios, the effect of ceiling coverage materials is not significant. In other words, a thick combustible ceiling cover could be equivalent to an uncombustible ceiling cover.

Assuming that the ceiling plate is very thin and highly combustible, e.g. thin tarpaulin, the ceiling cover above the initial fire source could burn out before the activation of a fire suppression system. Therefore the results could be completely different, and the scenario could be more similar to the scenario without ceiling coverage.

Figure 9  Effect of ceiling coverage materials on HRR in the tests.
In any case, this indicates that the influence of ceiling coverage materials is insignificant in such a tunnel fire with a suppression system with the exception that the ceiling cover is very thin and highly combustible such as thin tarpaulin. This could be applied to general cases.

**Effect of end blockages**

Figure 10 shows the effect of end blockages on the performance of the fire suppression system with an activation time delay of 0.5 min. Note that both tests were carried out without ceiling coverage. Clearly, there exists a huge difference between the tests. The fire in test 1 with end blockages was suppressed immediately after activation, however, the fire in test 9 without end blockages had a maximum HRR of 1.4 MW. This suggests that high ventilation significantly increases the fire growth rate (see Figure 10) and thus increase the difficulty in fire suppression for fuels directly exposed to wind. For fuels with end blockages, the fire develops much more slowly and could be easily suppressed. According to this, a suggestion can be made to the vehicle industry that the heavy good vehicles should all have steel end blockages.

![Figure 10 Effect of end blockages on HRR in the tests without ceiling coverage.](image)

**Effect of ventilation velocity**

Figure 11 shows the effect of ventilation velocities on the performance of the fire suppression with the K5 nozzles and an activation delay of 1 min. The tests correspond to Test 3 and test 6, both without ceiling coverage. Clearly, the fire was suppressed in both tests. Under low ventilation, heat based fire detection systems can be triggered much earlier and fire suppression was activated earlier. Thus the HRR was smaller at the activation time. Also note that the fire grows up more slowly in test 6 with a ventilation velocity of 0.5 m/s.

**Effect of sprinkler section length**

In some tests, the water spray system was shortened to 7.5 m, corresponding to 30 m in full scale. Figure 12 shows the influence of the sprinkler section lengths on the performance of the fire suppression systems with T-Rex nozzles (12.5 m long or 7.5 m long sprinkler section). Clearly, the HRR curves are approximately the same, and both fires were suppressed in the tests. This suggests that the longer sprinkler section does not improve the performance of the system, and the key sprinkler section corresponds to the section covering the fire source. In other words, the cooling effect of the sprinklers far away from the fire source is rather limited, at least for large droplet nozzles such as T-Rex.

**Effect of tunnel cross section**

Figure 13 shows the HRR curves in the T-Rex tests with a tunnel width of 2.8 m (wide tunnel) and 1.88 m (narrow tunnel) and an activation delay of 2 min. Note that test 18 is a repeat test of test 16 except that some piles of pallets had higher humidity in test 18. In Test 14 with a normal cross-section, the fire was extinguished immediately after activation. However, in tests 16 and 18 with the
1.88 m tunnel width, the fire was not efficiently suppressed. The main reason could be that in the vicinity of the fire source, the fuels together with end blocks blocked the tunnel cross section and thus increased the local gas velocity, which stimulates the fire growth and make the fire more difficult to suppress. Note that in the narrow tunnel, the blockage ratio is greater than that in the wide tunnel.

![Figure 11](image1.png)

**Figure 11** Effect of ventilation velocity on HRR in the K5 tests without ceiling coverage and activation delay of 1 min.

![Figure 12](image2.png)

**Figure 12** Effect of sprinkler section length on HRR in the tests.

![Figure 13](image3.png)

**Figure 13** Effect of tunnel cross section on HRR in the tests.

Figure 14 shows the HRR curves in the T-Rex tests with a tunnel width of 2.8 m (wide tunnel) and 1.88 m (narrow tunnel) with the activation delay of 0.5 min. Clearly it shows that both fires were
effectively suppressed immediately after activation and the maximum HRRs were lower than 200 kW. Further, the influence of tunnel width on the performance of the fire suppression system appears to be weak in the tests with the activation delay of 2 min, on contrary to the cases with the activation delay of 0.5 min.

![Figure 14 Effect of tunnel cross-section on HRR in tests with activation delay of 0.5 min.](image)

**Guidance for the design fire**

A key interest of the study is the design fire for a tunnel with a water-based fire suppression system. As analyzed in the above sections, the performance of a fire suppression system depends mainly on fuel load covers, activation time, water flow rate, nozzle type and ventilation. In order to give a general idea of the design fire with fire suppression, all the HRR curves in tests with fire suppression were plotted together with the curve obtained from the free-burn test, see Figure 15. Clearly, the HRRs in the tests with any type of fire suppression are at a much lower level than that in the free-burn test. The maximum HRR in these tests with fire suppression is less than 50 % of that in the free-burn test. Note that these tests cover a wide range of scenarios, i.e. referring to different nozzle types, ventilation velocities, activation time, with or without ceiling coverage. If we ignore the test with water flow rate of 2.5 mm/min (5 mm/min in full scale) and the test without end blockages, i.e. test 8b and test 9 (two curves with the peak value over 1.4 MW in Figure 15), the results show that the maximum HRRs in tests with fire suppression is less than 30 % of that in the free-burn test.

![Figure 15 A summary of HRR curves from the tests.](image)

This indicates that for a normal deluge water spray system operated at a water flow rate of approximately 10 mm/min (or higher than this value), 50 % of the maximum HRR in the free-burn
test (test without fire suppression) could be considered as the design fire or the maximum HRR with fire suppression. If the burning vehicle has steel end blocks, 30% of the total HRR without fire suppression could be considered as the design fire. These results correspond to full scale activation delay less than 4 min after a gas temperature of 141 °C was measured beneath the ceiling (heat detection), or the activation HRR not over 16 MW.

**Structural protection**

Time-temperature curves, e.g. the ISO, HC and RWS curves, are widely used for testing of tunnel structure [1]. The maximum gas temperatures measured in the ceiling are shown in Figure 16. Clearly, all test data with suppression lie below the HC curve and RWS curve. In reality, for all the tests with T-Rex nozzles, most test data lie below ISO curve. Most temperature data are at least 50 °C lower than that in the free-burn test. Many of the data with high temperatures correspond to late activation.

![Figure 16](image)

*Figure 16  A summary of maximum ceiling temperature curves from the tests.*

**CONCLUSIONS**

The activation time plays an important role in fire suppression efficiency. For a late activation, the fire could approximate a fully developed fire and result in catastrophic consequences. The fire suppression system should therefore be activated as early as possible.

The water flow rate influences the performance of a fire suppression system in a tunnel fire without ceiling coverage significantly and the water flow rate of 5 mm/min (full-scale 10 mm/min) is efficient to extinguish the fire, but not for 2.5 mm/min (full-scale 5 mm/min) which resulted in a maximum HRR of 46 % of that in a free-burn test. In comparison, with ceiling coverage the system performance was not significantly improved after an increase of flow rate from 5 to 7.5 (full-scale 15 mm/min).

The fire suppression systems with normal nozzles cannot effectively suppress the fire with ceiling coverage, but the nozzles K9 discharging larger droplets performs slightly better. As a comparison, the T-Rex systems with a water flow rate of 5 mm/min (10 mm/min in full scale) effectively suppressed the fires, except in the tests in the narrow tunnel with an activation time delay of 2 min.

The ceiling coverage plays an important role in fire suppression. The fire with a ceiling coverage is much more difficult to suppress. In these tests, the system performed well with the T-Rex nozzles but not with the two normal nozzles. Further, the ceiling coverage materials may mostly not affect the system performance as the tests showed that even a thin combustible cover was protected well after activation. One exception could be a thin and highly combustible ceiling cover such as thin tarpaulin. Without the end blockages, the fuels were directly exposed to wind, and the high ventilation 
significantly increased the fire growth rate and thus increased the difficulty in fire suppression. For fuels with end blockages, the fire develops much more slowly and could be more easily suppressed.

Tunnel ventilation affects the performance of a fire suppression system by influencing the fire development. Further, under low ventilation conditions, heat or smoke fire detection systems can be triggered much earlier. Therefore, the fire under low ventilation is more easily suppressed due to both the low HRR at the activation time, and the slow fire growth.

A key interest of the study is the design fire for a tunnel with a water-based fire suppression system. From the analysis of test data, it is concluded that for a normal deluge water spray system operated at a water flow rate of approx. 10 mm/min (or greater), 50 % of maximum HRR in the free-burn test (without suppression) could be considered as the maximum HRR with fire suppression. If the burning vehicle has steel end blockages, 30 % of the total HRR without fire suppression could be considered as the maximum HRR. These results correspond to full scale activation delay less than 4 min after a gas temperature of 141 °C was measured beneath the ceiling (heat detection), or the activation HRR was not over 16 MW in full scale. Lower ceiling gas temperatures were obtained with fire suppression systems, that is, a lower time-temperature curve could be used in testing of tunnel structure. These conclusions are confirmed by the full scale tests carried out in the Runehamar tunnel in 2013 [11].

REFERENCES

Canadian Tunnels from the Perspective of Safety-Security Issues

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ABSTRACT

As many other infrastructures Canadian tunnels were built according to the needs and the requirements of the past. It is known today that the fire size of “standard cargos” in road and railway tunnels is higher than initially anticipated and very high temperatures reached within minutes can lead to heavy damages or even a loss of a tunnel. The newly designed tunnels reflect requirements regarding fire related issues but only few of the existing tunnels in Canada were built accordingly to the new criteria. The traffic on roads and railway tracks has increased dramatically and the risks related to the transportation of crude oil from Western Canada across the country have added to those “normal”, existing everywhere. The disaster in Lac Megantic (Quebec) in 2013 has demonstrated how risky such cargos could be. Unlike some other countries, Canada has a limited number of tunnels but they are a significant part of Canada’s economic fabric and their performance when exposed to fire could have an important economic impact. An assessment based on engineering analysis would allow determining their actual conditions and define if required, measures for their upgrading.

KEYWORDS: Canadian tunnels, life-cycle, safety-security, vulnerability, assessment methods.

INTRODUCTION

As many other transportation infrastructures most of Canadian road and railway tunnels were built according to the needs and the requirements of the past. Almost all of them are still in operation and based on the experience, it could be assumed that they will continue to serve also in the future. Such assumption would be justified in the case of bridges, retaining walls and other infrastructures “paving” Canadian roads and railways; in the case of tunnels the context is different. The experience from the series of major fires in Europe between 1996 and 2001, led to significant changes in requirements with respect to the safety-security issues. We know today that the fire size which can be expected in the case of “standard” cargos in both road and railway tunnels could be much higher than anticipated in the past. The development of fire is very rapid and after few minutes, temperatures reach about 1000°C, this is far more than the resistance of concrete or rebar. Concrete structures require in such conditions special protections and they should be redesigned for temperature loads; evacuation egresses and ventilation systems should also respond to the new criteria. Since the construction of first Canadian tunnels, the needs of public have evolved and the traffic on roads and railway tracks has increased significantly. New fuels are in use by cars today having an impact on the safety-security issues in road tunnels. The use of railways for transportation of crude oil from Western Canada, more volatile than anticipated, became an important issue after the disaster in Lac Megantic (Quebec) in 2013; such event in tunnel would lead depending on type to heavy damages or even a total loss.

CANADIAN TUNNELS - REVIEW

Unlike some other countries, Canada has a limited number of tunnels but they are an important part of the economic fabric of the country. Tunnels were built for the railway network and as road or subway tunnels mainly in Eastern part of Canada. Considering different characteristics of road, railway and
subway tunnels, the review of Canadian tunnels is summarised following their category. The short tunnels such as The Esquimalt and Nanaimo Railway Tunnel or The Fraser Canyon Tunnels in Br. Columbia are not included in the review.

1. Canadian Railway Tunnels

- **First Railways Tunnels between Canada and USA**
  - The St. Clair River Tunnel (Sarnia, Ontario – Port Huron USA); 1891 & 1995
    The tunnel is 1.8 km long and it was the 1st underwater railway tunnel in North America. It was built between 1889 and 1891 as the 1st tunnel in North America under compressed air using shielding of cast-iron elements. The first tunnel was closed in 1994 and was then replaced in 1995 by the second tunnel still in operation; the construction of the new tunnel followed the signature of the NAFTA agreement. The tunnel is the 1st in the series of tunnels under the Great Lakes St-Lawrence Seaway inaugurated in 1959. A replacement project of the tunnel has been decided in 2013.
  - The Michigan Central Railway Tunnel (Windsor, Ontario – Detroit USA); 1910
    The tunnel is 2.6 km long and was built under the Detroit River connecting Windsor with Detroit; it was opened in 1910. The tunnel is still in use by the Canadian Pacific.

- **Tunnels in Rocky Mountains, British Columbia**
  - The Spiral Tunnels; 1909
    At the beginning of the 20th century Canadian Pacific Railway was achieved through Rocky Mountains without tunnels. The grades (up to 4%) made however operation difficult and the Spiral Tunnels were added in 1909 to reduce the grade to 2.3 %.
  - The Connaught Tunnel; 1916
    The tunnel is 8 km long and was added in 1916 under the Rogers Pass to reduce grades and eliminate troubles from avalanches.
  - The Mount MacDonald Tunnel; 1916
    The tunnel is 14.6 km long and the longest railway tunnel in Canada; it was built in 1916 under the Rogers Pass as “a twin” of the Connaught Tunnel for the west-bound direction.
The Mont Royal Tunnel (Montreal); 1918
The tunnel is 4.8 km long and was built in 1918 for the Canadian Northern Railway to access downtown Montreal. The tunnel is the 2nd longest tunnel in Canada and it is considered as the first subway tunnel of the country. An evaluation-upgrading process has been initiated in 2013.

2. Canadian Road Tunnels

The Detroit–Windsor Tunnel (Windsor, Ontario – Detroit USA); 1930
The tunnel is 1.57 km long, has two lanes and it was completed in 1930. The tunnel was built as immersed caissons floated into place and sunk into a trench dug in the river bottom. It was then the 3rd underwater road tunnel built in North America after the Holland Tunnel (Jersey City – Manhattan) and the Posey Tube (Oakland – Alameda). With 13,000 vehicles per day, it is the 2nd busiest crossing between Canada and the United States after the nearby Ambassador Bridge. No dangerous goods are allowed in the tunnel.

The Melocheville Tunnel (Quebec); 1957
The tunnel is 230 m long and was built as part of the Great Lakes St-Lawrence Seaway in 1957 at the same time as the Beauharnois Canal. The tunnel was constructed as a series of caissons laying on the rock. Until the construction of the nearby Highway 30 extension in 2012, it was a busy tunnel with 4 million crossings per year. An evaluation-upgrading process has been initiated in 2014 and dangerous goods are presently not allowed in the tunnel.
The Melocheville Tunnel (Vancouver); 1957
The tunnel is 630 m long and was built as immersed caissons floated into place and sunk into a trench dug in the river bottom. To resist soil liquefaction during an earthquake a retrofit project was done in 2004-2006. A new bridge will be built starting 2017 to replace the tunnel. No dangerous goods are allowed in the tunnel.

The Massey Tunnel (Vancouver); 1959

The Lafontaine Tunnel (Montreal); 1967
The tunnel is 1.4 km long and part of the link on the Trans-Canada Highway crossing the St. Lawrence River. The link consists of a bridge and a tunnel which was built under the shipping channel to the Port of Montreal. The tunnel was built before Expo 67 by immersion of precast prestressed caissons. It is one of the largest pre-stressed concrete structures in the world. The tunnel is the only Canadian Tunnel which “has passed” the test of a major fire during its life-cycle. In 1985, a truck caught fire in the tunnel damaging a large portion of the ceiling in one sector. In results of some specific characteristics of the structural system, the loss of the tunnel could have been avoided. An evaluation-upgrading process has been initiated in 2009. No dangerous goods are allowed in the tunnel.
Tunnels under The Welland Canal; part of The Great Lakes St-Lawrence Seaway; Ontario

The Thorold Tunnel; 1967
The tunnel is 840 m long and was built in 1965-1967 as part of the Highway 58. The section under the canal was built in the winter when the canal was drained and the portals were constructed in the summer while the canal was open for shipping. On 20 May 2015, a passenger car caught fire causing the closure of the tunnel for about 4 hours.

The Townline Tunnel; 1972
The tunnel is 330 m long and was built in 1972 under The Welland Canal as part of the Welland By-Pass project. The tunnel has 2 lanes for road traffic and 2 lanes for railway tracks. It is a bi-tube tunnel built using a simple cut-and-cover method.

The Main Street Tunnel; 1972
The tunnel is 330 m long and the 3rd tunnel built under the The Welland Canal as part of the By-Pass project; the tunnel was constructed in the same way as the Townline Tunnel.

The Ville-Marie/Viger Tunnel (Montreal); 1970 and 1987
The tunnel is 4 km long and has 3 lanes in each direction. It is part of the Ville Marie Expressway crossing the Montreal city core; it was constructed between 1970 and 1987. The initial section of the tunnel was built using a cut-and-cover method; the remaining expressway remained an open trench. The trench was later covered by streets, overpasses and buildings; The Montreal Convention Center is one of them. The tunnel with its exits and access roads builds a true underground interchange system. An evaluation-upgrading process has been initiated in 2009. No dangerous goods are allowed in the tunnel.
The Cassiar Tunnel (Vancouver); 1992
The tunnel is 730 m long, has 2 lanes in both directions and was completed in 1992; it is part of the Cassiar Connector on the Trans-Canada Highway in Vancouver. No dangerous goods are allowed.

The Toronto Subway; opened 1954
It was Canada’s 1st completed subway system; the 1st line was opened in 1954 with 12 stations. The subway includes today 4 lines, 69 stations and 68 km of track. A continuous upgrading of the subway system is underway.

The Montreal Metro; opened 1966
The first 2 lines were opened for Expo 67. Now the Metro is Canada’s busiest subway and the 3rd in North America after New York and Mexico City. The Metro has 68 stations on 4 lines and 71 km of tracks; cars use rubber tires. On 9 Dec. 1972 a fire has occurred causing one death, many injuries, a loss of 24 cars and spalling of concrete; the fire lasted 19 hours. The 2nd fire was on 23 Jan. 1974; it lasted few hours causing a loss of 9 cars but no injuries. A continuous upgrading of the subway is underway.

4. Canadian LRT Tunnels

The Dunsmuir Tunnel - SkyTrain (Vancouver); 1932 & 1986
The tunnel is 1.4 km long and originally built in 1932. Then it was integrated in the SkyTrain in the 1980’s for Expo 86. The width of the tunnel allowed a single railway track so a structure was built inside the tunnel to carry the westbound track above the eastbound direction.

The Calgary LRT Tunnels; opened 1981
The LRT system in Calgary (C-Train) is in operation since 1981 and has been extended until 2012 throughout a series of projects. It has today 4 tunnels making about 3.4 km or ± 6% of the system.
The Dunsmuir Tunnel 1932 & 1986                          Calgary 1981
Figure 12 Canadian LRT Tunnels: 1932 – 1981

The Canada Line Tunnel (Vancouver); 2009
The tunnel is 2.7 km long and has opened in 2009; it begins in a cut-and-cover section and transitions into twin bored tunnels.

The Edmonton LRT Tunnel; 2014
The LRT system is 21 km long; 3 sections of the system are underground.

The Confederation Line Tunnel (Ottawa); opening scheduled for 2017
The tunnel is 3.2 km long and will make part of the LRT in Ottawa in the city’s core; 4 underground stations are projected.

Vancouver (Can. Line) 2009                        Edmonton 2014                                      Ottawa 2017
Figure 13 Canadian LRT Tunnels: 2009 – 2017

MAJOR FIRE – A CHALLENGE TO TUNNELS

Since the first tunnel constructions about 200 major fires have marked the domain; the most devastating occurred in Europe between 1996 and 2001 (Eurotunnel 1996, Mont-Blanc 1999, Tauern 1999, Kaprun 2000, St-Gothard 2001) causing the death of more than 200 people and leading to important economic losses; the tunnels remained closed for months. The fires led to an in depth revision of safety/security requirements for tunnels and to the changes in codes and standards related to the matter [2]. Some aspects with regards to safety-security are briefly summarized hereafter. The recently published handbook on tunnel fire dynamics [3] is an excellent source of information regarding fire related issues.

Roads Tunnels
The incidents and resulting fires in road tunnels in the recent years were due mainly to two factors: the amount of traffic on roads and the increased presence of heavy goods vehicles loaded with cargos previously considered as less dangerous. As example, the Belgian truck which caught fire in the Mont-Blanc Tunnel in 1999 transported flour and margarine; Figure 14 on the left, shows the damages after the fire. To illustrate the character of fire in road tunnels, Figure 14 shows also the photo of the fire in the St-Gothard Tunnel in 2001.
Railway Tunnels

As on roads, the traffic on railway tracks has increased dramatically and the needs for transportation of crude oil from Western Canada across the country have added the new risks to those existing before. The risks related to this type of cargo are higher and the recent Lac Megantic disaster in Quebec which occurred on 6 July 2013 has demonstrated how explosive such cargos can be; the downtown of Lac Megantic was destroyed completely what is reflected on Figure 15. The properties of crude oil from oils sands or extracted by cracking are different what have been confirmed by unexpected explosions in Lac Megantic; an event of such proportions in a tunnel would have most probably led to its loss.

The recent full scale tests on train cars done in 2012 in Sweden [4] and in Canada [5] have provided us with new information regarding the fire size; the results have showed values in the range of 40 MW. To illustrate the character of the fire in the case of passenger trains, Figure 16 shows some recent examples of fires.

Structural integrity of tunnels exposed to a major fire

The development of fire in tunnels is very rapid and the temperatures very high when compared to the fire resistance of structural elements. The limits of performance for concrete and rebar are shown on the temperature-time RWS curve for road tunnels [6], reproduced on Figure 17. It is important mentioning that tunnels bored in rock like the Mont-Blanc Tunnel for example, would be affected by
the fire but remain “a hole in the mountain”; this would not be the case of tunnels built as caissons or using the cut and cover method.

**Figure 17** Limits of structural performance compared to the temperatures on the RWS curve [6].

**RISKS RELATED TO FIRE**

**Performance of tunnels exposed to a major fire**

The performance of tunnels exposed to a major fire can be compared to the sustainability of infrastructures exposed to unusual loads, such as loads resulting from climate changes [7]. Figure 18 shows the performance of tunnels in function of the life time. The limits of the original performance on Figure 18 correspond to the original design criteria plus a margin of safety factors. Hazards resulting from a major fire are reflected on the figure as “a demand” for an “increased performance”; when the “increased performance” exceeds the limits of the original performance, a loss of functionality of the tunnel occurs.

**Figure 18** Performance of tunnels during a major fire

The situation shown on Figure 18 would lead in the case of structural tunnels to a total loss of the section exposed to fire. Theoretical reserves of capacity depend normally on live loads considered in the original design and these loads are normally absent during an extreme event. In the case of structural tunnels live loads are practically inexistent, tunnels being designed for earth and water pressure. Theoretical reserves of capacity for structural tunnels are therefore reduced to the safety factors used in the design. Structural tunnels are very vulnerable while exposed to a major fire and this fact explains the needs for the passive protection added on walls and ceilings in upgrading projects as well as the verification of tunnels for temperature loads.

**CANADIAN TUNNELS - LIFE-CYCLE**

The Life-Cycle of Canadian Tunnels is summarized in Table 1. The recent events related to the matter are also indicated in the table; the series of five fires in European tunnels (1996-2001), the last major fire in 2007 in The Burnley Tunnel (Melbourne, Australia) and the fire in Lac Megantic (2013).
The revisions reflected in the NFPA 502 “Standard for Road Tunnels, Bridges and Other Limited Access Highways” are also shown in the table.

**Table 1  Life-Cycle of Canadian Tunnels.**

<table>
<thead>
<tr>
<th>Canadian Tunnels - Life-Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fires - Major Recent Events</td>
</tr>
<tr>
<td>The St. Clair River Tunnel 1.8 km (Sarnia, ON)</td>
</tr>
<tr>
<td>The Spiral Tunnels (Rocky Mountains, BC)</td>
</tr>
<tr>
<td>The Michigan Central Railway Tunnel 2.6 km (Windsor – Detroit)</td>
</tr>
<tr>
<td>The Connaught Tunnel 8.0 km (Rocky Mountains, BC)</td>
</tr>
<tr>
<td>The Mount MacDonald Tunnel 14.6 km (Rocky Mountains, BC)</td>
</tr>
<tr>
<td>The Mont Royal Tunnel 4.8 km (Montreal)</td>
</tr>
<tr>
<td>The Detroit–Windsor Tunnel 1.57 km (Canada – USA)</td>
</tr>
<tr>
<td>The Melocheville Tunnel 230 m (QC)</td>
</tr>
<tr>
<td>The Massey Tunnel 830 m (Vancouver)</td>
</tr>
<tr>
<td>The Thorold Tunnel 840 m (under The Welland Canal, ON)</td>
</tr>
<tr>
<td>The Lafontaine Tunnel 1.4 km (Montreal)</td>
</tr>
<tr>
<td>The Townline Tunnel 330 m (under The Welland Canal, ON)</td>
</tr>
<tr>
<td>The Main Street Tunnel 300 m (under The Welland Canal, ON)</td>
</tr>
<tr>
<td>The Ville-Marie/Niger Tunnel 4.0 km (Montreal)</td>
</tr>
<tr>
<td>The Cassiar Tunnel 730 m (Vancouver)</td>
</tr>
<tr>
<td>Toronto Subway; opened 1954</td>
</tr>
<tr>
<td>Montreal Metro; opened 1966</td>
</tr>
<tr>
<td>The Dunsmuir Tunnel - SkyTrain (Vancouver)</td>
</tr>
<tr>
<td>The Calgary LRT Tunnels; opened 1981</td>
</tr>
<tr>
<td>The Canada Line Tunnel (Vancouver)</td>
</tr>
<tr>
<td>The Edmonton LRT Tunnel (Edmonton)</td>
</tr>
<tr>
<td>The Confederation Line Tunnel (Ottawa)</td>
</tr>
<tr>
<td>NFPA 502</td>
</tr>
</tbody>
</table>

A brief look at the table leads to the conclusion that only three LRT tunnels (blue pale) have been designed after the major fires and changes in the code; the remaining nineteen tunnels were built before. The dark blue colour reflects an evaluation-upgrading process initiated by the authorities to bring the tunnels to the level of actual requirements regarding safety/security; in the case of The Massey Tunnel and The St-Clair River Tunnel projects of replacement.

**Canadian tunnels – Potential risks related to a major fire**

As explained before, structural tunnels such as tunnels poured in place or constructed by immersion of caissons, are much more vulnerable than tunnels “bored” trough a mountain. Based on the difference between tunnels “bored” in rock and structural tunnels, potential risks related to a major fire for Canadian tunnels can be summarized as shown in Table 2.
Table 2  

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Type of Tunnel</th>
<th>Fire - Risks Related</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bored in Rock</td>
<td>Structural Tunnel</td>
</tr>
<tr>
<td>The St. Clair River Tunnel 1.8 km (Sarnia, ON); 1891</td>
<td>x</td>
<td>Sector lost, tunnel flooded</td>
</tr>
<tr>
<td>The Michigan Central Railway Tunnel 2.6 km (Windsor - Detroit); 1910</td>
<td>x</td>
<td>Sector lost, tunnel flooded</td>
</tr>
<tr>
<td>The Spiral Tunnels (Rocky Mountains, BC); 1909</td>
<td>x</td>
<td>Lining damaged</td>
</tr>
<tr>
<td>The Connaught Tunnel 8.0 km (Rocky Mountains, BC); 1916</td>
<td>x</td>
<td>Lining damaged</td>
</tr>
<tr>
<td>The Mount MacDonald Tunnel 14.6 km (Rocky Mountains, BC); 1916</td>
<td>x</td>
<td>Lining damaged</td>
</tr>
<tr>
<td>The Mont Royal Tunnel 4.8 km (Montreal); 1918</td>
<td>x</td>
<td>Lining damaged</td>
</tr>
<tr>
<td>The Detroit-Windsor Tunnel 1.87 km (Canada - USA); 1930</td>
<td>x</td>
<td>Sector lost, tunnel flooded</td>
</tr>
<tr>
<td>The Melocheville Tunnel 220 m (QC); 1967</td>
<td>x</td>
<td>Sector lost, tunnel flooded</td>
</tr>
<tr>
<td>The Massey Tunnel 830 m (Vancouver); 1969</td>
<td>x</td>
<td>Sector lost, tunnel flooded</td>
</tr>
<tr>
<td>The Thordal Tunnel 840 m (under The Welland Canal, ON); 1967</td>
<td>x</td>
<td>Sector lost, tunnel flooded</td>
</tr>
<tr>
<td>The Lafontaine Tunnel 1.4 km (Montreal); 1967</td>
<td>x</td>
<td>Sector lost, tunnel flooded</td>
</tr>
<tr>
<td>The Townline Tunnel 330 m (under The Welland Canal, ON); 1972</td>
<td>x</td>
<td>Sector lost, tunnel flooded</td>
</tr>
<tr>
<td>The Main Street Tunnel 330 m (under The Welland Canal, ON); 1972</td>
<td>x</td>
<td>Sector lost, tunnel flooded</td>
</tr>
<tr>
<td>The Ville-Marie/Viger Tunnel 4.0 km (Montreal); 1967</td>
<td>x</td>
<td>Sector lost</td>
</tr>
<tr>
<td>The Cassier Tunnel 730 m (Vancouver); 1992</td>
<td>x</td>
<td>Sector lost</td>
</tr>
</tbody>
</table>

DISCUSSION

The safety-security issues related to a tunnel could be addressed in a specific way allowing an assessment of risks which would reflect the character and the location of the tunnel [8], [9]. The assessment procedure includes an evaluation of the fire size based on the type of cargo and the development of the fire scenario [10, 11]. The structural performance under temperatures loads and the needs for protection are part of the analysis [12]. The results obtained in this evaluation allow to state on the performance of the tunnel which can be expected in case of fire. The risks analysis includes the economic aspect; the fires in the transit tunnels in Europe for example, led to their closure for months and had important economic impact. The tunnels under the Great Lakes St-Lawrence Seaway are probably of the similar importance; over 200 million tons of cargos are moved per year through the Seaway.

Existing Tunnels - Hazard Investigation and Assessment of Risks

Prescriptive methods to evaluate an existing tunnel do not exist in Canada however some countries have developed such methods and France can be considered as a leader in the domain with the “Centre d’Étude des Tunnels” (CETU), an organization dedicated exclusively to tunnels. CETU has developed a method of investigation to assess and evaluate hazards with regards to a major fire [13]; the method is used for years as legal approach by owners and operators of tunnels in France. The method developed by CETU has been adapted to the Canadian context to assess via an engineering analysis the performance of both Montreal main road tunnels; The Lafontaine Tunnel under the St-Lawrence River and The Ville-Marie/Viger Tunnel in the downtown core [8]. The method combines the CETU methodology and the evaluation grid in the manual of maintenance and rehabilitation of tunnels of the Federal Highway Administration in the USA [14]. It allows establishing priorities in reference to actual conditions of the tunnel. The development of a fire scenario is normally part of an investigation procedure for an existing tunnel to see if the emergency exits allow a safe evacuation of road users. Figure 19 shows an
example of graphical presentation of the fire scenario; smoke control and propagation are reflected in the presentation.

![Graphical Presentation of Fire Scenario](image1)

**Figure 19** Example of graphical presentation of a fire scenario [15]

**Engineering Evaluation based on Fire Related Analysis**

A rapid development of fire and an intense heat created in tunnel conditions make the firefighting impossible; hoorer in relatively short tunnels and in the case when fire is close to the portal the situation could be different. An immediate intervention of a fire brigade could allow bringing under control the development of fire and the resulting release of heat and smoke. In such cases an engineering evaluation based on fire related analysis can lead to more promising results. Figure 20 presents the effect of such intervention in one case investigated by the authors [9]; heat release rates as per design fire are shown with a dotted line and the heat release reflecting the action of the fire brigade with a solid line.

![Heat Release Rates](image2)

**Figure 20** Control of the development of fire by Firefighting [9]

The heat release rates shown on Figure 20 can be used to establish in analytical procedure the temperatures in a tunnel and on the surface of structural elements in function of time, Figure 21 shows results obtained in the case referred above [8]. The first representation in this figure allowed confirming that the temperatures were low enough to make the firefighting possible.
CONCLUDING REMARKS

The good performance of Canadian tunnels during their life-cycle should not be seen as a guarantee in case of a major fire. The European experience between 1996 and 2001 was a demonstration of results we could expect in tunnels if the fire related issues are not addressed and the proper steps are not undertaken to limit the consequences when a major fire occurs.

The conditions on roads and railway tracks have changed with the years and those in the tunnels with regards to the safety-security issues as well. The parameters related to the Life-Cycle performance of tunnels are today different than before contrarily to a “steady character” of parameters related to the performance of other infrastructures in our transportation system. The management of this new reality needs to be considered and represent a real challenge for authorities and engineers in the near future.

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Road Tunnel Safety: Lateral Obstacle Treatment in Europe and in France

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ABSTRACT

Since the accident that occurred in the Sierre tunnel in Switzerland which caused the death of 28 bus passengers, 22 of whom were children, lateral obstacle treatment in tunnels has become a preoccupation in numerous countries. The European members of the PIARC have addressed this issue in order to establish an inventory for each country, providing details of the lateral obstacles found in tunnels, feedback on related accidents and actions taken. In France, the CETU has established a methodology in order to identify existing lateral obstacles, rank them according to risk and determine whether to remove them or to implement preventive or protective measures. In order to identify protective measures that could be implemented, notably in lay-bys, the CETU joined forces with TRANSPOLIS-LIER (Laboratory for assistance in the development and assessment or road safety systems). The aim was to determine which sort of protective devices could be adapted so as to improve safety in the event of a collision involving a light vehicle or a bus.

KEYWORDS: road tunnel safety, lateral obstacle treatment, European and French approaches, concrete barrier, numerical simulation.

INTRODUCTION

Vehicle collisions involving lay-bys or other lateral obstacles in tunnels are fortunately a relatively rare occurrence. However, the consequences of such a collision are extremely severe and more often than not result in fatalities. The most dramatic example of this is the accident which occurred in the Sierre tunnel in Switzerland in 2012, when the collision of a bus with the back wall of a lay-by caused the death of 28 passengers, including 22 children. This accident sparked discussions on lay-bys and lateral obstacles in France and in other European countries.

Three different avenues have been identified for the treatment of lateral obstacles. The first is to ensure user awareness. A presentation of this topic was made by the CETU during the ISTSS of 2012 [1]. Another avenue to be explored is the development of ‘in-vehicle’ systems which are designed to minimise accidents by addressing the main causes of collisions: driver error, distraction and drowsiness. These systems are currently only available in ‘top-of-the-range’ vehicles. The third avenue, which will be developed in this paper, focuses on infrastructure. A description will be provided of the different obstacle treatment approaches adopted in European tunnels and the methodology developed in France by the CETU.

EUROPEAN APPROACH ON ROAD SAFETY

The accident in the Sierre tunnel sparked discussions on lay-bys and lateral obstacles in tunnels among members of the World Road Association Technical Committee 3.3 on Road Tunnel
Operations. A workshop on this topic, organized by France (CETU) in October 2013, was attended by Belgium, The Netherlands, Spain, Switzerland, Italy, France, Slovenia and Norway. Within the eight countries concerned, the number of tunnel lay-bys varies considerably, ranging from none at all in the Netherlands to over 200 in Italy, on the Trans-European Road Network (TERN) alone.

This workshop confirmed the will of PIARC to urge EU member states to be vigilant with regard to road infrastructure safety management issues in the context of road tunnels. In December 2013, PIARC proposed a recommendation on how to adapt the objectives of Directive 2008/96/EC on road infrastructure safety management to the context of road tunnels, when implementing Directive 2004/54/EC [2].

The fruitful exchanges initiated in October 2013 led the Committee to produce a report. This report outlines the situation in the above-mentioned countries in terms of tunnel lay-by regulations and presence, feedback on accidents involving lay-bys or other lateral obstacles and studies performed in terms of prevention and/or mitigation. All the countries agreed closure of all lay-bys is not a desirable solution. Although they are safety facilities, they can be removed in existing tunnels with an emergency lane or shoulders wide enough to allow an emergency stop. The number of lay-bys can also be reduced if excessive. To protect lay-by walls, especially those perpendicular to the direction of traffic, two main measures can be implemented: crash cushions or barriers (metallic or concrete). These measures shall not block access to lay-by equipment (fire extinguishers, telephones etc.) and emergency exits or be obstacles to user evacuation in emergency situations.

Additional preventive measures must be also considered such as rumble strips on edge lines, or increased visibility of lay-bys by signing, painting, lighting, etc.

For example, in Spain, in two new tunnels that were put into operation a few months after the Sierre tunnel accident, the end walls of lay-bys are protected by metal barriers. They were installed before the tunnel was opened to traffic.

In Slovenia, a pilot test with a shortened metal barrier was conducted in a motorway tunnel. However, the generalisation of this barrier was not approved by the safety inspectorate and police representatives. Simulation tests conducted by the University of Ljubljana concluded that a modified crash cushion would be preferable to both short and long barriers. However, the number of necessary crash cushions did not justify the actual cost of the crash test with the modified crash cushion. In addition, as legislation requires the installation of CE certified equipment, the decision was taken to conduct on-site experiments with equipment already available on the market, even if this equipment did not conform to the ideal characteristics defined in simulations.

An article which summarises the contents of this report was published in Routes/Roads magazine in July 2015 [3].

**FRENCH APPROACH TO LATERAL OBSTACLE TREATMENT**

The French approach, developed by the CETU in close collaboration with French road tunnel operators, has resulted in a methodology aimed at improving road tunnel safety by lateral obstacle treatment.

The design of new tunnels must integrate road infrastructure safety management principles and every lateral obstacle must be identified and taken into account. Design regulations may eliminate the need for certain lateral obstacles. In terms of lay-bys, for example, French regulations state that they are only obligatory for tunnels over 1,000 metres long, where available width does not allow the number of lanes to be maintained in case of a stationary vehicle. At the design stage, there must therefore be a general reflection on the need to install and protect them.
For existing tunnels, this methodology highlights the need to compare the safety factors specific to each obstacle with the risks of collision entailed. The treatment of lateral obstacles has already been the subject of numerous discussions in the context of open air roads, as they feature numerous obstacles which constitute considerable safety issues. The 2002 technical guidelines on 'Treatment of lateral obstacles on open roads outside urban areas' [4] offer a situational diagnosis method. The CETU has adapted this method to the specific context of tunnels. It enables a risk index to be established for each obstacle. Calculating this risk index therefore allows for a ranking of the lateral obstacles within a given tunnel or section of road including tunnels with identical characteristics. This ranking may aid decision-making in the process of lateral obstacle treatment in tunnels.

The primary solution is to consider removing the lateral obstacle if this does not reduce the level of safety for users.

When the removal of lateral obstacles is inappropriate, as is the case for lay-bys and emergency exits, preventive and/or protective measures must be explored.

Figure 1  French approach to lateral obstacle treatment.

**IMPROVING SAFETY WITH PROTECTION SYSTEMS SUCH AS CONCRETE BARRIERS**

In order to identify protective measures that could be implemented, notably in lay-bys (and with the Sierre tunnel accident in mind), the CETU joined forces with TRANSPOLIS-LIER (Laboratory for assistance in the development and assessment or road safety systems). The aim was to identify which
sort of protective systems could be adapted so as to improve safety in the event of a collision involving a light vehicle or a bus. This collaboration resulted in an initial study on low-energy absorption systems such as metal or concrete barriers. The study, carried out with a metal barrier, has not been developed below as the results obtained are very similar to those obtained for concrete barriers, and implementing the modelling hypotheses (in particular fixing the ends of the three rails to the lay-by wall) would require developing a technical solution.

**Research programme and test methods**

The research programme for low-energy absorption systems presented in this paper consisted of numerical simulation of collisions involving two types of vehicles (light vehicle, bus) at varying approach angles and speeds.

The dimensions of the lay-by were 3 metres by 40 metres. The barrier installed with an angle of 15° is a concrete New Jersey profile barrier as shown in Figure 2. The restraint system was modelled to be rigid (non-deformable) and fixed to the lay-by wall. The point of impact was positioned one third of the way along the restraint system.

![New Jersey profile concrete barrier.](image)

Simulations were carried out using the LS-DYNA software that uses a finite element method. The light vehicle model used in the simulations was made up of around 16,000 finite elements distributed between 222 components. The bus model was made up of around 53,000 finite elements distributed between 140 components. The dimensions, mass and location of the centre of the mass of each vehicle conformed to the vehicle specifications of Standard EN1317-1[5].

Initial speeds and impact angles with the barrier were defined in reference to Standard EN1317-2, as described in Table 1. The lowest impact angle corresponds to that of a moving vehicle following the tunnel axis, and therefore at an angle of 15° in relation to the restraint system. The angles of 20° and 25° in relation to the system correspond to 5° and 10° respectively in relation to the tunnel axis. A decision was made not to allow for an angle of 20° in relation to the tunnel axis in compliance with Standard EN1317 for open air sections. This angle is applied for tests on restraint systems installed parallel to the road axis, and for when an out-of-control vehicle could potentially travel in the third lane. In a tunnel, the number of lanes is generally lower. In addition, whereas on 'open air' road sections the speed limit is 130km/h, tunnels generally have a lower speed limit. The speed limits used were therefore 60, 80 and 100 km/h for light vehicles and 50, 70 and 90 km/h for buses.
Table 1  Research programme for barriers (vehicles, speed, impact angle).

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Impact angle with the barrier (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light vehicle 900 kg</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>15 – 20 - 25</td>
</tr>
<tr>
<td>80</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Bus 13 000 kg</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>15 – 20 - 25</td>
</tr>
<tr>
<td>70</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3  Research programme for barriers.

The ASI (Acceleration Severity Index) and the THIV (Theoretical Head Impact Velocity) are the two evaluation criteria for the severity of an impact for a light vehicle. An ASI of over 1.9 constitutes a deceleration that is too fast to be acceptable to the human body. The THIV represents the speed of a free-moving object within the vehicle (identical to the head of a human) on impact with the vehicle interior. It cannot exceed a value of 33 km/h. These criteria are defined by Standard EN1317-2. In this study, rolling was chosen as an acceptance criterion. The vehicle was not allowed to roll over (including onto its side) during or after impact. Any rolling could therefore not exceed 45°.

For buses, the ASI and THIV are not representative. Therefore, the maximum value of the acceleration curve of the bus was measured.

Vehicle intrusion, as defined in EN1317, refers to the intrusion of the vehicle in relation to the front of the restraint system, and therefore allows the calculation of the total volume that must remain free of any obstacle so that the restraint system can carry out its redirection function in a satisfactory way. It is useful to take into account this criterion when installing the restraint system, as it helps to prevent contact with the structure of the tunnel. It was calculated for information purposes.

All the test evaluation criteria are summarised in Table 2.

Table 2  Test evaluation criteria.

<table>
<thead>
<tr>
<th>Light Vehicle</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASI – Acceleration Severity Index</td>
<td>&lt; 1.9</td>
</tr>
<tr>
<td>THIV – Theoretical Head Impact Velocity</td>
<td>&lt; 33 km/h</td>
</tr>
<tr>
<td>VI – Vehicle Intrusion</td>
<td>Calculated in g (=9.81 m.s⁻²)</td>
</tr>
<tr>
<td>Maximum value of the resulting acceleration curve</td>
<td></td>
</tr>
<tr>
<td>Exit speed</td>
<td>Calculated in kilometres per hour (km/h)</td>
</tr>
<tr>
<td>Exit angle</td>
<td>Calculated in degrees (°)</td>
</tr>
<tr>
<td>Rolling</td>
<td>&lt; 45°</td>
</tr>
</tbody>
</table>
Test campaign and results

Table 3  Test results for a light vehicle with a concrete barrier.

<table>
<thead>
<tr>
<th>Light vehicle impact speed [km/h]</th>
<th>Impact angle in relation to restraint system (°)</th>
<th>Without system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15°</td>
<td>20°</td>
</tr>
<tr>
<td>60</td>
<td>ASI</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>THIV [km/h]</td>
<td>20.6</td>
</tr>
<tr>
<td></td>
<td>Exit speed [km/h]</td>
<td>44.6</td>
</tr>
<tr>
<td></td>
<td>Exit angle [°]</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td>Rolling [°]</td>
<td>8.7</td>
</tr>
<tr>
<td>80</td>
<td>ASI</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>THIV [km/h]</td>
<td>21.1</td>
</tr>
<tr>
<td></td>
<td>Exit speed [km/h]</td>
<td>65.6</td>
</tr>
<tr>
<td></td>
<td>Exit angle [°]</td>
<td>20.8</td>
</tr>
<tr>
<td></td>
<td>Rolling [°]</td>
<td>13.5</td>
</tr>
<tr>
<td>100</td>
<td>ASI</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>THIV [km/h]</td>
<td>23.0</td>
</tr>
<tr>
<td></td>
<td>Exit speed [km/h]</td>
<td>85.5</td>
</tr>
<tr>
<td></td>
<td>Exit angle [°]</td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td>Rolling [°]</td>
<td>37.8</td>
</tr>
</tbody>
</table>

Figure 4  Test results for a light vehicle with a concrete barrier
Table 4 Test results for a bus with a concrete barrier.

<table>
<thead>
<tr>
<th>Vehicle impact speed [km/h]</th>
<th>Impact angle in relation to restraint system</th>
<th>Without system</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>Maximum resulting acceleration (g)</td>
<td>29.7 29.8 29.7 81.0</td>
</tr>
<tr>
<td></td>
<td>VI [m]</td>
<td>0.2 0.4 0.8</td>
</tr>
<tr>
<td></td>
<td>Exit speed [km/h]</td>
<td>44.1 41.6 38.0</td>
</tr>
<tr>
<td></td>
<td>Exit angle [°]</td>
<td>16.9 16.8 17.2</td>
</tr>
<tr>
<td></td>
<td>Rolling [°]</td>
<td>4.5 5.1 5.1</td>
</tr>
<tr>
<td>70</td>
<td>Maximum resulting acceleration (g)</td>
<td>35.2 36.6 37.8 119.5</td>
</tr>
<tr>
<td></td>
<td>VI [m]</td>
<td>0.4 0.6 1.1</td>
</tr>
<tr>
<td></td>
<td>Exit speed [km/h]</td>
<td>60.4 56.5 50.0</td>
</tr>
<tr>
<td></td>
<td>Exit angle [°]</td>
<td>16.3 16.4 24.5</td>
</tr>
<tr>
<td></td>
<td>Rolling [°]</td>
<td>4.7 5.5 8.7</td>
</tr>
<tr>
<td>90</td>
<td>Maximum resulting acceleration (g)</td>
<td>43.5 42.4 42.7 108.6</td>
</tr>
<tr>
<td></td>
<td>VI [m]</td>
<td>0.6 1.0 1.6</td>
</tr>
<tr>
<td></td>
<td>Exit speed [km/h]</td>
<td>76.4 67.5 56.2</td>
</tr>
<tr>
<td></td>
<td>Exit angle [°]</td>
<td>16.5 23.6 19.8</td>
</tr>
<tr>
<td></td>
<td>Rolling [°]</td>
<td>9.9 17.0 50.7</td>
</tr>
</tbody>
</table>

Figure 5 Test results for a bus with a concrete barrier.
The right column indicates the values obtained in the case of a frontal impact on the back wall of a lay-by (without the installation of a protection system) depending on the vehicle speed. The grey boxes indicate that the measured value exceeds the acceptance criteria defined in Table 2.

**Observations**

All the configurations show that the installation of a barrier contributes to reducing the intensity of the impact. Overall, the values obtained with a restraint system are equivalent to one third of those obtained without a restraint system, whether for light vehicles or buses.

For light vehicles, the majority of configurations satisfy the acceptance criteria of Standard EN 1317-2. Simulations at 60 and 80 km/h show acceptable results. Vehicle rolling and an unacceptably severe impact can only be observed for simulations at 100 km/h.

For buses, the most severe cases result in the bus rolling over.

In all cases, the vehicle exit angle (if it has not rolled) is slightly higher than the angle of the restraint system in relation to the side wall. It varies between 16 and 25°. The exit speed of the vehicle is reduced by around a third.

**Initial lessons drawn from simulations**

In light of the results detailed above, a concrete barrier positioned at an angle of 15° in relation to the road axis represents a means of protection that could improve the safety of light vehicle or bus users in the event of a collision with the back wall of a lay-by, especially for speeds below 90 km/h. The tests carried out show that limiting the speed of a vehicle is a simple measure that can limit the consequences of an impact.

As the exit angle of a vehicle is very close to the installation angle of the restraint system, it should be as low as possible in order to allow the vehicle to return to its lane following impact with the restraint system. Reducing the installation angle means neutralising a larger space in the lay-by, a space which has been optimised for use as an emergency stopping area for vehicles in distress. Also, barrier restraint systems installed at an angle of 15° can only be considered for unidirectional tunnels, as the vehicle is systematically deflected by the restraint system.

**IMPROVING SAFETY WITH PROTECTION SYSTEMS SUCH AS CRASH CUSHIONS**

The alternative to these low-impact energy absorption systems which redirect vehicle movement is to use high-impact energy absorption systems. On initial analysis, this type of system seems more suitable for bidirectional tunnels than barriers.

Standard EN1317-3 does not take buses into account. It is therefore difficult to turn to the existing crash cushion market for a solution to the problem of protecting back walls in tunnel lay-bys. Our initial approach was to estimate the energy to be absorbed in the event of an impact of a light vehicle and a bus, and to calculate the number of crash cushions that would need to be installed in order to absorb this energy.
Table 5  Selection table for crash cushions by level of energy to absorb.

<table>
<thead>
<tr>
<th>Performance class</th>
<th>Absorbable energy (KJ)</th>
<th>Number of devices needed to absorb the estimated energy</th>
<th>50 km/h</th>
<th>80 km/h</th>
<th>100 km/h</th>
<th>110 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Vehicle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1500 kg at 110 km/h</td>
<td>700</td>
<td></td>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Bus weighing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13,000 kg at 70 km/h</td>
<td>2460</td>
<td></td>
<td>28</td>
<td>8</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Bus weighing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17,000 kg at 70 km/h</td>
<td>3220</td>
<td></td>
<td>37</td>
<td>10</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

Based on practical installation situations, this table clearly shows that systems whose performance class is 50 km/h, 80 km/h and even 100 km/h cannot meet the expected performance levels. Only systems whose performance class is 110 km/h can be considered for improving the outcome in the event of the impact of a light vehicle or bus with the back wall of a tunnel lay-by.

After having eliminated end treatments (terminals) that can protect against intermittently spaced obstacles, and crash cushions composed of materials that can emit dangerous toxic substances in the event of a fire, four crash cushion technologies have been identified as potentially suitable for use in tunnels within the framework of this study.

A partnership has been forged with one of the four companies in order to design a new crash cushion capable of stopping a light vehicle and improving the outcome in the event of impact involving a bus. Design studies are in progress.

CONCLUSION

This document shows that there is no obvious solution for the treatment of lateral obstacles in tunnels.

The PIARC recommendation to adopt the principles of road safety management in the tunnel environment is a first step in this process of treating lateral obstacles. European countries are unanimous in opposing the systematic closure of safety facilities such as lay-bys, even though they can represent an obstacle for users. Other solutions will need to be researched.

France, via the CETU, has established its own methodology on the subject and has carried out a study in collaboration with TRANSPOLIS-LIER into the efficiency of a barrier-type concrete restraint system positioned at 15° along the back wall of the lay-by. Numerical simulation results for several speeds and impact angles on the restraint system have shown that this solution generally improves the outcome of an impact involving a light vehicle or bus. However, due to the exit speed and angle of the vehicle, this solution is only suitable for unidirectional tunnels. A study is currently in progress to design a non-redirective, high energy-absorbing crash cushion-type restraint system that could be used in bidirectional tunnels.
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Fire in the Heinenoordtunnel, Lessons Learned

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ABSTRACT:
On May 21th 2014 a truck blew out a tyre and crashed into the wall of the Heinenoordtunnel nearby Barendrecht, The Netherlands. On impact the truck instantly caught fire and slided over more than 75 meters to the lowest point of the tunnel. The Rotterdam-Rijnmond Fire Department, the Ministry of Infrastructure and Environment (owner of the tunnel) and Efectis Netherlands BV collected information about this recent fire, focussed on fire fighting operations, communication during the incident, fire development in the tunnel and the performance of tunnel safety measures like escape doors, ventilation system and tunnel lining. The Fire Departments Investigation Team collected information in the tunnel, about the origin and specific development of the fire, the performance of the tunnel safety measures, like escape doors and fire fighting equipment. The Ministry collected data from the traffic cameras in the tunnel. These cameras recorded the accident, large parts of the evacuation and the fire fighting efforts. The Fire Department, the Ministry and the Police collected information about the tunnel safety measures. They also collected data about the incident management by debriefing the Fire- and Police officers and traffic managers involved in rescue, fire fighting, communications and traffic management. This was done in a round table discussion with all first responders involved (Leertafel). Efectis NL collected data on the development of the fire, the fire load of the truck and the structural damage to the tunnel and estimated the Heat Release Rate during the fire. The research resulted in two reports [1, 2], one about the incident management and communication and one about the fire development.

KEYWORDS: tunnel fire, spalling, fire development, evacuation, fire fighting, human behaviour

INTRODUCTION
In the Netherlands tunnels in highways are mostly used to cross the rivers and therefore tunnels are immersed. These immersed tunnels are build on a remote location, the segments are sealed and transported floating over the river to the tunnel construction site, placed in a trench on the river bottom and covered with dirt. New tunnels are designed to withstand a fire related to the RWS - fire curve for 2 hours. Existing tunnels are retrofitted with a tunnel lining to withstand this fire curve. Because a lot of the tunnels are positioned in the highway network used for transport to and from the ports of Rotterdam, Amsterdam and Schiphol, the tunnels should withstand such a large fire mainly to prevent a long closure of this tunnels and to prevent the blockage of (one of) the most important transport network(s) in The Netherlands.

On May 21th 2014 a truck crashed into a wall of the Heinenoord tunnel near Barendrecht, The Netherlands and caught fire. The Heinenoord tunnel was closed for traffic for almost 19 hours. This caused a 100 km long traffic jam in the area of Rotterdam.

The truck driver didn’t survive the accident and two other people who were involved in the accident managed to escape their burning vehicle but got severely injured. The tunnel (owned bij Rijkswaterstaat, Ministry of Infrastructure and Environment) is monitored by an operation centre for traffic management near Rotterdam. The Netherlands is divided into 25 safety regions, each with it’s
own combined dispatch for Police, Fire Department and Ambulance. The Heinenoordtunnel is placed on the border between two of these Safety regions (Rotterdam-Rijnmond and Zuid-Holland Zuid). Fire Departments and Police units from both sides of the tunnel responded to the fire.

THE HEINENOORD TUNNEL
The Heinenoordtunnel was opened in 1969 as part of the highway A29 near Barendrecht. The tunnel is part of the European Trans European Tunnel network (TEN-netwerk). It fulfills all the criteria from EU directive EU 2004/54/EG [13] and the more strict safety criteria from the Dutch legalisation (Wet Aanvullende Regels Veiligheid Wegenverkeerswet, WARVW) [14]. The tunnel is an immersed tunnel under the river “Oude Maas” that was built in sections of 8,8 meter high, 30,7 meter wide and 115 meter long and gives room to 2x 3 traffic lanes. The tunnel has a length of 614 meters and is used by ±85.000 motor vehicles/day [3].

The original tunnel design for a combination of high speed and low speed traffic (Figure 2) was altered to a tunnel only for high speed traffic. Along the wall in the middle of the tunnel, concrete barriers are placed on both sides to create an 1,25 meter wide evacuation path. Every 100-125 meters
an escape door is positioned in the middle wall. The tunnel is equipped with a longitudinal ventilation system, a public address (PA) system, emergency phones and fire hoses. The lights on the tunnel roof are made of LED’s. Illuminated signs point to the nearest escape door and the fire fighting equipment. The tunnel ceiling and upper part of the walls are protected with a 27,5 mm thick PROMATECT-H lining.

Figure 3   Longitudinal cross section of the tunnel.

THE INCIDENT

At 13:30:51 on May 21th the Fire department was alarmed for a fire in the tunnel. According to an eye witness on Youtube (and the camera footage), a tyre of the truck (a Mercedes-Benz Actros 1841 LS) involved in the accident blew up. The truck drove into the concrete barrier and the tunnel wall on the left side. After hitting the wall the truck turned over and immediately caught fire. In the crash the truck hit another car (Ford Fiësta, 2013). The truck slid while burning over approximately 100 meters through the tunnel and stopped, blocking 2,5 lanes of the tunnel. The car that was hit by the truck turned upside down right behind the truck. The driver and passenger of the car got out on their own with severe (burn) injuries. The truck driver died in the accident.

Figure 4   Crash and start of the fire.

The truck stopped near the middle of the tunnel. Traffic in front of the truck was able to exit the tunnel. The traffic behind the truck came to a halt. Through the PA system people were instructed to leave their car and exit the tunnel. An eye witness (a public bus driver) who entered the tunnel right behind the truck describes a calm evacuation [4]. According to the bus driver people were following instructions.

The camera images show people backing up and turning their cars (Figure 5). One person parked his car across the third lane and leaves it there. According to the camera images from the tunnel, the fire lasted for about 31 minutes. The cabin of the truck, the container floor, the truck tyres, the (diesel) fuel and the front of the car were consumed by the fire. The cargo load of the truck in the 40’container consisted of drums filled with salt, stacked on wooden pallets. Most of the wooden pallets and the drums were consumed by the fire. The salt was still in the container.

DATA COLLECTION

To estimate the heat release rate of the fire, data about the fire load, the duration of the fire and the fire fighting operations were collected. Data collection started with an inspection of the tunnel directly after the fire was extinguished. A team of fire investigators from Efectis and the Rotterdam-Rijnmond Fire department made pictures of the fire damage and the truck involved in the accident. The speed of the fire growth and the duration of the fire were determined from the camera footage. The data about
the fire fighting operation was collected by a method called “Leertafel”. This method is used to evaluate the operations of Fire Department, Police and other agencies involved during an incident by letting the first responders tell their story about what they saw, did and experienced. The goal of this method is to learn from an incident and to improve procedures and gain knowledge about specific incidents. This method is not used for juridical reasons or to blame persons for possible mistakes. It requires an open mind from the persons involved in the incident to tell their story in a save environment. This method is relatively new in the Netherlands and have recently been used at other incidents.

**Figure 5** Evacuation.

![Evacuation](image)

**Figure 6** Picture taken from the tunnel entrance. The cross section of the tunnel just behind the truck is engulfed in flames (source: Twitter @RichardMaasdijk).

**Fire load**

The fire load was estimated based on information of several sources [5, 6, 7, 8]. In table 1 an estimation of the fire load involved in the fire is given.
Tunnel protection and damage to the tunnel

The tunnel roof and the upper parts of the walls are protected with a 27.5 mm thick PROMATECT-H lining. The lining is mounted in 1990. The damage patterns on the wall next to the truck cabin indicate the influence of longitudinal ventilation. Figure 7 gives an impression of the damage pattern on the tunnel wall. The damage extends in the direction of the airflow. The lines in Figure 7 give an indication of the shape of the damage.

In the direct vicinity of the truck cabin the concrete wall showed damage due to spalling. A maximum spalling depth of 2.5 cm was measured. The concrete showed a buff discolouration, which indicates temperatures reached more than 1,000 °C [9]. The discolouration of the concrete was only visible around the cabin and can be explained by direct flame impingement.

<table>
<thead>
<tr>
<th>Object</th>
<th>Mass (kg)</th>
<th>Total Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics on the truck</td>
<td>572</td>
<td>17.732</td>
</tr>
<tr>
<td>Tyres on the truck</td>
<td>420</td>
<td>11.760</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>360 (worst case)</td>
<td>15.120</td>
</tr>
<tr>
<td>Trailer floor</td>
<td>590</td>
<td>9.912</td>
</tr>
<tr>
<td>Trailer tyres</td>
<td>420</td>
<td>11.760</td>
</tr>
<tr>
<td>Trailer load (pallets)</td>
<td>480</td>
<td>8.380</td>
</tr>
<tr>
<td>Trailer load (cardboard or cellulose fibre)</td>
<td>1.080</td>
<td>17.604</td>
</tr>
<tr>
<td>½ Car (Ford Fiësta)</td>
<td>n/a</td>
<td>2.625</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>94.893</td>
</tr>
</tbody>
</table>

Table 1 Estimation of the fire load.

Under the tunnel ceiling a lighting system was installed consisting of LED lights. Most part of this lighting system was still working after the fire. Some parts were melted or soothed. In Figure 8 the damage to the lighting system is visible in an overview of the accident area in the tunnel.

Fire Fighting operations

The accident in the tunnel was called in at the dispatches of Rotterdam-Rijnmond and Zuid-Holland Zuid. A person in the tunnel called the the emergency number 112 and told the Fire Department at Rotterdam-Rijnmond Dispatch that a bus was on fire in the tunnel. At the same time Rijkswaterstaat
Traffic Control reported the accident (collision with a fire) in the tunnel to the Police Department at Rotterdam-Rijnmond dispatch. The Police told the traffic controller to report the fire at the dispatch in Dordrecht.

The traffic controller immediately, after seeing the accident, pushed the emergency button to put the tunnel in “accident mode”. Pushing this button makes the fire extinguishing pumps and ventilation start, the light level goes to 100% and the P.A. system starts giving the evacuation instructions.

The first arriving unit was a Police unit from the south side of the tunnel. At that moment the tunnel was closed for traffic and the P.A. system urged people to evacuate the tunnel. The first Fire truck (from Zuid-Holland Zuid) also came from the south side. This fire truck was responding to a 112 call for a car or bus fire just outside the tunnel. When they arrived they were confronted with a tunnel fire with a lot of smoke coming out of the tunnel exit (Figure 9). This unit decided to drive the fire truck over the tunnel complex to get to the other lane and went into the tunnel through the safe side of the tunnel. The unit tried to investigate the situation in the tunnel tube where the fire was by entering through the escape doors in the tunnel wall.

![Figure 9 First arriving Fire truck.](image)

The Traffic control centre has not communicated the right (escape)door number, related to the position of the burning truck, to the Fire Brigade. Some of the escape doors were jammed which made the search for the fire location and the position of potential victims on the downstream side of the fire difficult. The second Fire truck (from Rotterdam-Rijnmond) arrived at the north side of the tunnel. They had to wait until the correct barriers at the side of the road were opened before they could enter the tunnel trace. This took some time and because of that the third unit (from the Rotterdam fire department) arriving at the fire from the north side, was the first unit who could actually see the fire. This unit was not in (radio)contact with the unit from Zuid-Holland Zuid. Because they were going for an incident with a potential for a lot of victims (a bus fire in a tunnel), they went (not conform procedure) into the tunnel tube with the burning truck and discovered the two victims from the car involved in the crash. The victims were able to escape their car by them self. The fire was first attacked using a hoseline from a tunnel emergency unit. Because of a malfunction in this unit a foam tender was called to fight the fire in the tunnel.

**ANALYSES**

**Heat release rate**

Based on the duration of the fire and the estimated amount of materials consumed by the fire, it is possible to calculate the heat release rate during the fire.

The data collection shows that a total amount of energy of 94,893 MJ was present in the tunnel. Most part of this “fuel” was consumed by the fire. Parts of the pallets in the container were still visible. The amount of fuel burned is estimated to be 90%. The heat release rate is calculated based on a total
amount of energy of 85.404 MJ. The camera footage shows that the fire grew quickly (within one minute) directly after the crash. This rapid fire development can only be explained by a ruptured fuel tank. The hypothesis of a ruptured fuel tank is confirmed by the fact that just after the crash a reflecting surface (pool of diesel fuel) is visible between the truck and the car behind the truck.

The fire department was alarmed around 13:30 h and the first attempt to extinguish the fire was made around 13:46 h. It is estimated that between the crash and the alarm a couple of minutes passed by. An exact timeline could not be defined, because there was a difference in time registration on the involved systems from the Traffic control Centre and the Police and Fire Departments of Rotterdam-Rijnmond and Zuid-Holland Zuid.

The analysis of camera footage leads to a fire curve that grows to a maximum in 1 minute and maintains about the same rate of heat release (HRR) during 18 minutes. The fire lasted for a total of 31 minutes. Within the remaining 12 minutes the fire decayed and was extinguished by the fire department.

The peak output of the fire is estimated to be between 50 and 65 MW. In Figure 9 the estimated fire
curve is given. The fire curve given in figure 9 is a simplified curve because there is only limited data on the development of the fire. The Dutch highway tunnels are designed to withstand a fire according to the RWS [10] curve for 2 hours. The heat output and the duration of the fire in the Heinenoordtunnel was below this curve. Tests performed under the UPTUN [11] and Eureka [12] projects showed the HRR for a heavy goods vehicle to be between 70 and 200 MW. Due to the fact that the truck load did not burn in this fire the HRR was much lower than could be expected.

Performance of the tunnel lining
From within the tunnel the PROMATECT-H lining showed no visible damage. After editing the photo used in Figure 7 it became visible that some parts of the tunnel lining were cracked. It is not possible to determine whether these cracks are a result of the fire or were present in the lining before the fire occurred.

Performance of the longitudinal ventilation system
On the video footage no back layering of smoke is visible. The smoke stain on the tunnel ceiling and walls indicate that the ventilation system in the incident tube was functioning properly. It is safe to state that the ventilation system in the incident tube was functioning the way it should during the fire. Almost no heat damage occurred beyond 40m from the fire (downstream). 60 m beyond the burning truck and further away there was more damage and pollution to the installations in the tunnel. Although all systems remained functional, the damage and smoke pollution in and on the installation makes a replacement in due time over a total length of 200 m necessary. The tunnel cross section behind the burning truck was filled with smoke which indicates a laminar flow through the tunnel cross section.

Evacuation
The evacuation is visible on the video footage. Traffic stopped directly behind the truck and the car involved in the crash. At first some cars backed up and one van turned around. One car was parked
across the left lane. The professional drivers (two public bus drivers) initiated an evacuation and through the PA system people were told to leave their car and exit the tunnel. One of the truck drivers instructed other drivers to leave the tunnel. The evacuation went calm and in order. None of the people in the tunnel used the escape doors located in the tunnel wall. All people walked towards the tunnel entrance. The escape route these people took had a length of about 200 - 250 meters. Between the accident and the first car that stopped were two escape doors. All people evacuating from the buses and the cars directly behind the accident passed at least one escape door on their way towards the tunnel entrance.

The two victims in the car managed to escape the burning vehicle. When the fire department arrived they walked towards the fire truck and were treated for burn injuries by the first arriving fire fighters.

**Fire Fighting operations**

In the Netherlands it’s not usual to get into a tunnel tube with a fire truck while there is an actual fire going on in that tunnel tube. According to the tunnel procedure the first fire truck approaches a fire in a tunnel with separated tunnel tubes along with the direction of travel through the opposite and secure tunnel tube. Through the emergency doors a search is performed to determine from which tunnel the fire can be safely attacked. The investigation (Leertafel) performed by the fire department, police and Rijkswaterstaat made clear that the decision to enter the tunnel with a fire truck was based on a lot of different aspects in the fire fighting operations. The first arriving fire truck was on the wrong side of the tunnel because it was called for a fire outside the tunnel. Another fire truck was waiting for the barrier to open to enter the tunnel on the safe side. These barriers were not clearly marked which lead to the fact that the wrong barrier opened and the fire truck could not enter the tunnel. By that time a fire truck arrived at the entrance of the tunnel where the fire was. The commander in chief decided to enter the tunnel based on the following facts:
- He could see the fire from the tunnel entrance (300 meter);
- The ventilation system pushed the smoke away from the fire so he could, in a safe way, get close to the fire;
- There were no fire fighters in the tunnel attacking the fire or searching for victims.

The evaluation of this operation learned that three escape doors were blocked so the fire fighters could not enter the tunnel from the safe side to search for victims on the down stream side of the fire during the first search. Later they were able to enter the tunnel and start with the search for victims and the attack of the fire.

Communication between units, dispatches and traffic control was not flawless. Traffic control didn’t report the escape door numbers through which the fire department could reach the fire and the fire department didn’t ask for it. It was not clear which barriers had to be opened.

At the dispatches the communication between police and fire department can be improved to prevent that some units are called for a fire outside the tunnel and some units for a fire in the tunnel.

**CONCLUSIONS**

- The estimated heat release rate during the fire (between 50 and 60 MW) and the duration of the fire is below the design criteria of the tunnel;
- The tunnel lining performed as expected;
- The P.A. system made a smooth evacuation possible;
- The Traffic Controle Centre did not communicate conform procedure, the right (escape)door number to the fire brigade;
- The presence of professional (truck and bus) drivers was a benefit to a quick evacuation;
- The longitudinal ventilation system provided an environment where drivers could escape the tunnel and the fire department was able to fight the fire in the tunnel from a short distance.
- In general the procedures from the incident management plans where followed. Where the situation did not exactly fit to the procedures the professionals where by resilience able to adapt to the situation.

**RECOMMENDATIONS**

- Better maintenance of tunnel safety measures like escape doors and fire extinguishing equipment is necessary;
- Communication between the three dispatches involved should be improved through training and education and connecting the tunnel camera system to the different dispatches;
- Fire department and Police personal need more training on the use of communication systems when switching between dispatches in different regions of the country;
- Fire Police and Traffic control personal should be trained in procedures as described in the incident management plans;
- Add resilience to the planning and training system to make the incident management system more robust for unexpected changes

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The AMT's Tunnel-Reno Program: Improving Safety in the Mount Royal Tunnel is the Result of a Partnership with the Montreal Fire Department

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ABSTRACT

The Mont Royal Tunnel is a critical rail link for the Agence métropolitaine de transport (AMT). It gives nearly 8 million people per year—or more than 50% of the AMT's total clientele—direct access to downtown Montréal on the commuter trains of the Deux-Montagnes line and the new Mascouche one, whose total of 65 trains run through the tunnel daily.

With the commissioning of the new Mascouche line and the introduction of AMT’s new rolling stock, namely its dual mode locomotives (electrical and diesel powered), many challenges related to the safety and security of commuters, operators and emergency services personnel were highlighted. To answer to those issues AMT created an ambitious initiative named Tunel-Reno program a two phases project.

The success of the Mascouche line commissioning and more particularly of the first phase of the Tunnel-Reno program work is largely attributable to the close collaboration that the AMT and the Service de sécurité incendie de Montréal (SIM) – Montreal Fire Department – have developed over the last few years.

AMT presents in this paper the development of the Tunnel-Reno program scope, in a context of a normative gap relating to existing infrastructure and discuss how the close ties that were developed with the SIM have contributed to the project success so far and how the ethical approach used could be apply to similar situations.

KEYWORDS : Tunnel rehabilitation, Stakeholder relationships, Value analysis, Users safety, Risk analysis, Emergency response, Emergency measures plans, Fire prevention, Firefighting, Ethic

INTRODUCTION

Faced with growing needs and increasingly limited means, public transport organizations must optimize the use of their infrastructures. In this spirit, in 2007, the Agence métropolitaine de transport (AMT), the government agency in charge of developing and promoting public transport in Greater Montréal, began planning and building a new commuter train line running on a rail section in the existing Mount Royal Tunnel.

This new Mascouche train line project, much like the AMT's commitment to increase traffic on the existing Deux-Montagnes train line, which also runs through the Mount Royal Tunnel, raised questions and issues regarding safety in the tunnel connecting the city's north end to downtown, as the following two figures show.
The first goal of this paper is to explain the AMT's methodology for defining the scope of the Tunnel-Reno project in a context where there are no prescriptive standards regarding the improvement of existing tunnel infrastructures. Secondly, it describes the quality of the relationship the AMT and the Service de sécurité incendie de Montréal (SIM) have forged, which has greatly contributed to the project's success. That last aspect is analyzed using the ethics theory, which offers a framework for understanding the conditions for the success of a sensitive project in order to better replicate such conditions.
DEFINITION OF THE PROJECT SCOPE

The Mount Royal Tunnel

The Mount Royal Tunnel was built in the early 20th century, between 1912 and 1913, by the Canadian Northern Railway. It was commissioned in October 1918 and is still in operation. Initially used to transport both passengers and freight, the tunnel has been exclusively used by passenger trains since 1995.

The tunnel is 5 km long and features a ventilation shaft located 1.6 km from its northern portal. It connects Canora station to Central Station, an underground complex in downtown Montréal with some twenty platforms and railway shops. Two railway tracks electrified by a 25 kV catenary run Deux-Montagnes line and through the entire tunnel. The following two figures illustrate the tunnel's geometry and sections.

Figure 3  Tunnel geometry

Figure 4  Sections of the Mount Royal Tunnel
New projects for the Mount Royal Tunnel

In 2007, the Québec government and the AMT announced the construction of a new commuter train line to connect Montréal's north-east suburbs to downtown to improve public transit service in the city's east end. This new corridor required the construction of a new rail section from the city of Mascouche to the island of Montréal, the use of existing CN tracks on the island and access to downtown through the Mount Royal Tunnel. The Mascouche line's route thus increased rail traffic in the Mount Royal Tunnel by more than 20% compared with the existing situation, in which only trains from the Deux-Montagnes line used this access. In addition, because the Mascouche line is not completely electrified, the AMT had to acquire new rolling stock for use in the tunnel, including its dual-mode (electric and diesel) locomotives. Although the dual-mode locomotives met the latest rolling stock construction standards, they would nonetheless carry relatively significant quantities of flammable fuel inside the tunnel.

Aside from the Mascouche line, the AMT also had a project to improve existing service on the Deux-Montagnes train line. With its 54 daily passages, or more than 7.5M passengers in 2014, the Deux-Montagnes line is the busiest on the AMT network. Adding the Mascouche line's 16 new trains a day, plus the projects to increase service on the Deux-Montagnes line, constituted a real challenge.

For the AMT and its partners, including the SIM, these significant changes in the Mount Royal Tunnel's use required reviewing certain elements regarding the safety of the facilities and processes. Ensuring the ongoing safety of users, rail operators and emergency services personnel who work, travel or respond in the Mount Royal Tunnel gave rise to the AMT's Tunnel-Reno program.

Defining the scope of the Tunnel-Reno program

From the beginning of the project, the AMT created a steering committee composed of the stakeholders having jurisdiction over the tunnel, namely Canadian National (operator of the Deux-Montagnes line and, until February 2014, also the line's owner), the Ministère des Transports du Québec, and the emergency services, including the SIM, to lay the groundwork for the project. The committee's first observation was that the tunnel's infrastructure, nearly 100 years old, did not meet the latest rail and fire safety standards, such as NFPA 130, despite major work carried out in the summer of 1995. The committee therefore agreed to assess the situation to understand the gaps between current standards and the existing infrastructure.

To do so, the AMT mandated experts from Hatch Mott MacDonald. In addition to validating current standards and best industry practices, their study had to include an exhaustive qualitative risk analysis to identify the various situations that could cause safety issues in the tunnel. This analysis identified more than 70 such situations and risks. Listed according to different categories, these risks cover railway track maintenance defects, the lack of radio communications, as well as inclement weather and unauthorized entry into the tunnel. Based on this analysis and the review of standards, practices and industry recommendations ([1] and [2]), 16 main recommendations were formulated. These recommendations focused on modifying the tunnel infrastructure equipment and response modes and procedures.

Following the assessment of the situation, the AMT created a technical committee bringing together experts from the various stakeholders to explore the technical feasibility of the recommendations to modify the infrastructure as part of a preliminary design study (the recommendations regarding the response modes and procedures were reviewed and discussed by another committee). This preliminary design study helped highlight the technical issues in line with the recommendations from the assessment of the situation and test their constructability, in so far as the tunnel is a strategic transport corridor for the city of Montréal and that, because it is operated 7 days a week, the work blocks are limited and short. The conclusions of the preliminary design study brought to light the complexity of bringing an old infrastructure like the Mount Royal Tunnel up to standard in such a restrictive operational environment.
Faced with this complexity and considering that in the meantime the AMT and SIM refined their knowledge of the issues and risks specific to the tunnel, the project team decided to conduct a value analysis. The analysis had two major objectives. The first was to review the preliminary design study's outline to validate whether the technical choices were optimal. The second and probably most important objective was to revisit the previous risk analysis to validate to what extent recommendations made as part of the assessment of the situation actually mitigated the risks. Taking inspiration from the emergency response philosophy and principles put forward in the UIC's technical note (prevention, impact mitigation, facilitating evacuation and facilitating rescue), the analysis helped prioritize the various recommendations according to their impact on risk reduction and costs. The AMT's objective in this approach was to ensure that the sums invested would effectively contribute to limiting risks in the tunnel, considering that there is no such thing as zero risk. The SIM confirmed that the AMT's approach was thorough and based on best practices, insofar as it took into account its concerns.

The value analysis therefore served to rally partners like the SIM around the same project scope. The project proposed by the AMT had to be carried out in two separate phases: a first phase before the commissioning of the new Mascouche line, and a second subsequent phase. This phasing was necessary due to the time frames required for a public body like the AMT to obtain the necessary government authorizations and finalize the most complex technical recommendations.

The Tunnel-Reno project (infrastructure program only) breaks down as follow:

- **Tunnel-Reno Phase 1:**
  - Install and commission radio communication equipment for the SIM
  - Improve the directional signage in the tunnel in the event of an evacuation
  - Improve the existing evacuation walkways in the tunnel
  - Acquire a hy-rail emergency response vehicle for the SIM
  - Install a first ventilation system next to the tunnel's existing ventilation shaft

- **Tunnel-Reno Phase 2:**
  - Install a full ventilation system in the tunnel and at the existing ventilation shaft
  - Install emergency blue stations every 250 m in the tunnel
  - Install an intercom every 125 m
  - Install a smart sensing system to prevent unauthorized entry in the tunnel's two portals
  - Install smoke and heat detectors
  - Install automated catenary sectioning and grounding equipment to accelerate emergency responses
  - Install hot box and dragging parts detection equipment

In addition to this infrastructure investment program, the AMT and its partners implemented various operational initiatives, including:

- Matching the emergency measures plans of the SIM, CN, AMT and Cominar (owner of Central Station)
- Creating an AMT fire brigade to accompany the SIM and other emergency services into the tunnel when required
- Preparing training materials on the tunnel and catenary environment for firefighters
- Providing ongoing training to all Montréal firefighters who could be called to respond in the tunnel

Phase 1 of the project was delivered on time, allowing the AMT to commission the new Mascouche commuter train line on December 1, 2014. Phase 2 is at the final design review stage, and will be submitted to the government for approval. The work should begin in early 2017.
THE AMT-SIM RELATIONSHIP: CENTRAL TO AN ETHICAL APPROACH

The previous paragraphs explained how the scope of the Tunnel-Reno project was defined. This methodology may at first seem customary and conventional. However, this is the project's most complex and delicate exercise to date due to several factors.

Firstly, the normative gap for improving and bringing major infrastructures up to safety standards created uncertainty and expectations for the AMT and its partners, including the SIM. It was quickly determined that bringing the tunnel completely up to standard would be difficult due to technical and operational complexities and financial constraints. Collaboration and partnership between the stakeholders was thus necessary to define a project that everyone, including the general public, could accept but without bringing the tunnel completely up to standard.

The political, media, organizational and ethical sensitivity inherent to the source of the project—user and personnel safety—was another complex factor in defining the project scope. Indeed, the public safety questions raise fundamental ethical issues. How do we increase traffic in the tunnel without affecting public safety? What project scope is acceptable considering the normative gap? These delicate questions require reflection insofar as the ethical issues bring up emotions that dominate the discussions and dialogue, as we will explain later, and stoke passions that sometimes confuse rather than inform stakeholders.

Due to this emotional component, the Mount Royal Tunnel was the subject of extensive media coverage in 2011. The SIM, AMT, CN and MTQ were thus put under the spotlight in numerous articles and reports regarding the Mount Royal Tunnel and its safety. This media coverage could have caused the AMT's partners to withdraw their commitment or dig their heels in. However, because the SIM and AMT had established a climate of trust and collaboration, even at the height of the media coverage, the emotional aspect of the project was kept under control and the discussion and ethical dialogue were pursued in the interest of all concerned, including the AMT's clientele. A true climate of partnership was thus created. This exemplary collaboration between the AMT and the SIM played an essential role in the project's development and "peaceful" unfolding. Applied ethics specialists would see it as a perfect example of the pragmatic approach theory in the resolution of ethical issues. This approach is central to the Tunnel-Reno project's success and could be replicated elsewhere, though it would not necessarily ensure a project's success.

Ethics and the pragmatic approach

It is important to note certain basics specific to applied ethics used to solve ethical problems.

An ethical problem underlines the presence of a conflict between two opposing or contradictory values that initially appear to be irreconcilable. The person faced with this problem, usually called the moral agent, is thus ensure how to resolve the issue, hesitating between prioritizing one value over another, often in an environment where the standards (law, rules, morals, rules of conduct, etc.) are weak, vague or literally do not address the specific situation. Ultimately, the moral agent's reflection must culminate in a decision or solution that will be deemed acceptable by him or her and the other stakeholders in an objective of reconciliation or, at the very least, the best decision in light of the situation.

One of the approaches used in applied ethics to resolve this kind of problem is the pragmatic approach. It proposes a methodology to remove tension from the situation by highlighting the prescriptive stasis of the standards because, one way or another, they cause a problem. This is done by applying a dynamic solution-creation process that addresses the specificities of the problem, not to develop a new standard but rather a methodology that can be transposed to other similar situations [3]. That is to say that the ethical reflection, through the prism of pragmatism, no longer seeks to meet the standard, but rather to define which actions could be considered the most reasonable for the various actors under the circumstances specific to the problem [4]. The reflection must therefore hinge on the
experience rather than predefined principles without however—and this is an important nuance—throwing those principles out altogether to avoid the relativism trap. The pragmatic approach also requires deconstructing preconceptions to analyze the situation in its specific context and circumstances, and reconcile principles and practice [5]. This reconciliation is achieved by building a common sense between stakeholders. This element of common sense is essential. The father of pragmatism, Dewey, proposes that the very act of seeking out this common sense, between the standard and the very concrete situation of the problem, helps the actors in the deliberation develop a shared understanding of the issues and a clearer and more detailed picture of the situation. "Knowing is doing." [6].

In short, pragmatism rests enormously, even chiefly, on the relationship between the stakeholders and is operationalized through their discussion and dialogue. The theory suggests a pure dialogue, exempt from any form of position of strength or negotiation [7]. Although it is not always easy for public actors to achieve this type of dialogue, certain basics are nonetheless fundamental to its success and smooth functioning. Recognition of the other as a stakeholder and the creation of a common language are undoubtedly the most important. Both promote a climate of trust and respect in which the desired creativity, and the development of a common language and common sense, can break the deadlock.

In summary, the pragmatic approach aims to resolve an ethical issue involving seemingly contradictory values by rallying the stakeholders around a relationship and dialogue of trust, based on a common language that allows them to arrive, together, at a solution that is deemed acceptable by all within the circumstances and the context of the situation.

Establishing a common language between the SIM and the AMT

By considering this theoretical model of ethical conflict resolution through the pragmatic approach, we can understand the full extent of the success of the AMT and SIM commitment to work together within a technical committee. This working committee brought together safety and fire prevention experts and engineers. It was, and is still, based on a pivot formed of the AMT Security and Safety Department Operation Chief and the SIM Division Chief – special advisor to the SIM senior management (see figure 4). These actors, both from the fire prevention sector, were able to use the same language, interpret the requests from their respective organizations and translate the meaning for the other party. When questions, expectations or requests were formulated by one of the parties, the same language was used by the committee to put them into context, which facilitated the other party's understanding and acceptability. This strong communication helped establish a climate in which each party's technical expertise was recognized and a climate of trust, openness and creativity. As already stated, the trust and recognition of the other as part of the resolution of an ethical issue is a fundamental building block of the resolution.
By capitalizing on this fluid and open communication, the AMT's engineering department was able to understand the SIM's operational mode should an event occur in or around the tunnel, and the SIM was able to understand the AMT's operational mechanisms and the risks connected to the tunnel. This helped develop proposals regarding the project scope and the parties' commitment to its implementation. The quality of the dialogue also contributed to developing a common knowledge of the tunnel's infrastructure and specific characteristics, thereby resulting in a greater collaboration in developing an infrastructure improvement plan and refining the related emergency measures plan.

CONCLUSION

The case of the Mount Royal Tunnel raised several ethical issues insofar as some put forward values that could be perceived as contradictory. Ensuring public safety and developing AMT operations without making significant changes to the infrastructure raised important questions.

The Mount Royal Tunnel is an existing infrastructure in a built environment that has changed considerably since its construction. Far from claiming that current standards, such as those of the NFPA, are not valid or necessary, it is clear that bringing an existing infrastructure completely up to standard raises several issues regarding feasibility, the impact on the owner's operations and on customers, and the availability of required funds. In the case of public infrastructures, the reality is that governments are grappling with more and more needs and increasingly limited means. Across North America and Europe, public infrastructures are ageing and now require significant investments. It is therefore in a context of scarce resources that the pragmatic approach to applied ethics can help find innovative solutions that are considered reasonable and socially acceptable by all stakeholders. This pragmatic approach requires reconciling principles and practice, and a dialogue between stakeholders. The case of the Mount Royal Tunnel is a concrete example that this approach can be successful.
REFERENCES


Safety Analyses of a Five-Lane Double-Decked “Full-ADR” TERN Tunnel in Antwerp Belgium

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ABSTRACT
This paper provides an insight in a variety of safety analyses which were necessary to ensure a safe design of a five-lane double-decked TERN tunnel, named OKA, which is designed to accommodate all transport of dangerous goods. The methodology for the design of this tunnel is a performance based approach, where in addition to a purely prescriptive approach, it is analysed if additional risk mitigation measures should be implemented. This paper will focus on some key aspects of the OKA tunnel safety design, in particular on the emergency ventilation, the Quantitative Risk Analyses (QRA), the design of the tunnel portals, the structural integrity in case of an explosion as well as on the explosion probability. From the safety analyses of this 800m long tunnel it is concluded that a safe tunnel can be build when all mitigation measures are implemented.

KEYWORDS: Transport of dangerous goods (full-ADR), gas and BLEVE-explosions, QRA (Quantitative Risk Analyses), structural integrity, TERN-tunnel, Fixed Fire Fighting System, MEP-systems, CFD, uncertainty analyses, emergency ventilation

INTRODUCTION
The Oosterweel Link project will relieve traffic congestion on the Antwerp Ring and improve accessibility from and to the Antwerp port. When finalized, the Link will also result in a reduction of noise levels in surrounding residential areas. More public area will be created, and natural landscape will either be preserved or created. This 3.2 billion euro project consists of three new tunnels which will be constructed in the Antwerp Ring underneath the river Scheldt, the "Straatsburgdok" docks and the Albert Canal. The latter crossing will consist of a five-lane 800m long double-decked tunnel, which is designed to accommodate all transport of dangerous goods (EU-TEN Tunnel). The safety level of this tunnel and the risks involving dangerous goods transport has been extensively analysed, by means of Quantitative Risk Analyses (QRA), Computational Fluid Dynamics (CFD) and by studying structural blast loads. In these analyses e.g. the throttling effect of a large (200MW) fire in a five lane tunnel, the impact of vapour cloud explosions, BLEVE scenarios and GEE (gas-expansion-explosions) were taken into account, the latter being a supplement to the existing Dutch QRA-model (which, among others, is implemented in Flanders). This scenario was analysed specifically for the Oosterweel project in order to provide a comprehensive identification of all the possible risks involved in transport of dangerous goods.

This paper will provide a state-of-the-art insight into the tunnel safety engineering of the five-lane double-decked ‘full-ADR’ OKA tunnel, addressing the QRA, emergency ventilation, the design of the tunnel portals, the structural integrity for several explosion scenarios as well as additional probabilistic modelling and uncertainty analyses. First, a brief overview of the calculation methods and adopted Dutch tunnel safety decree will be provided (the Flemish competent authorities adopt the Dutch requirements), as well as additional analyses to ensure the design of a safe construction. Eventually, the results of these analyses of the OKA tunnel will be discussed. It is concluded that the tunnel can comply with the Dutch tunnel and building decrees and safety levels when all the described mitigation measures are implemented.
DESCRIPTION OF THE OKA TUNNEL

The construction of the OKA tunnel will relieve traffic congestions and improve accessibility to and from the Antwerp port. The tunnel is part of the Trans-European Road Network (TERN), meaning that all the requirements of the 2004/54/EC directive should be met. The new link, passing underneath the Albert Canal, will consist of two five-lane tunnel tubes stacked on top of each other. At the north and south interface of the tunnel, the portals of both the OKA tunnel and the Kanaalzone tunnel (4x2 lanes) will meet, meaning that the north portal will consist of four (partly) stacked tunnel tubes in three layers (as displayed in figure 2a). On the tunnel's southside these individual tunnel tubes will be situated next to each other resulting in an approximately 90 meter wide split level tunnel portal (as displayed in figure 2b). Next to the OKA tunnel a stacked 2 meter wide escape gallery will be implemented as well as a vertical intervention shaft each 100 meter. This intervention shaft will contain a staircase to connect both escape galleries. Emergency doors from the approximately 800 meter long tunnel to the escape gallery are located every 50 meter.

Figure 2. impression of the OKA tunnel portals, with a. the north portal consisting of the stacked five lane OKA tunnel as well as the entry and exit of the 2x2 Kanaalzone tunnels, b. the south portal consisting of the entry and exit of both the OKA tunnel and Kanaalzone tunnels.
METHODOLOGY

In tunnel safety engineering a variety of analyses are necessary in order to ensure the design of a safe construction. The amount of possible scenarios and their impact increase significantly when the construction has to accommodate the transport of all dangerous goods. The Dutch tunnel decree imposes one of two comprehensively defined standard package options for the design of tunnels of various length. Among others, these standard package options point out which mitigation measures require implementation, the minimal dimensions of the escape gallery with emergency doors, and the firefighting installations and equipment. In the Netherlands, the Department of Public Works and Water Management (Rijkswaterstaat) manages and maintains the country's highway tunnels. This Department defines any additional requirements (LTS) concerning the construction of such tunnels. The benefit of such standard package options is that for a 'normal' Dutch tunnel the requirements can be easily defined, e.g. if the standard option doesn’t include a Fixed Fire Fighting System (FFFS), this can be used as an argument to not include a FFFS. This approach does not necessarily result in a robust design with respect to tunnel safety (this is especially the case for specific and frequently used tunnels whereas the availability is a main requirement). As mentioned in the Handbook of tunnel Fire Safety[6] a purely prescriptive approach may result in unawareness of all the possible risks. It is also mentioned [7] that there needs to be a general ‘obligation to take care’ and ‘not merely comply with the law’. The methodology for the OKA tunnel design is therefore not to adopt a Dutch standard tunnel package and all its prescriptive requirements completely, but to follow the Dutch requirements and to analyse if additional risk mitigation measures (like a FFFS) or additional simulations are necessary. This performance based methodology results in a more integrated approach and consequently in an in-depth identification of the possible risks, but evidently also increases the design challenge significantly. In the following chapters an overview is provided of the different analyses that were performed. Each chapter will start with the method for the specific analyses; subsequently the results are discussed. The results as presented in this paper will focus on the emergency ventilation, the Quantitative Risk Analyses (QRA), the OKA tunnel portal design and the structural integrity for explosion scenarios. An extensive variety of additional analyses has been performed focusing among others on emergency services accessibility and pressurisation of the emergency gallery. These analyses are not within the scope of this paper.

EMERGENCY VENTILATION

The longitudinal ventilation system of the five-lane double decked OKA tunnel is designed to prevent back-layering in the case of a fire with a heat release up to 200MW. A maximum heat release of 200MW is a realistic assumption in the case of transport of dangerous goods, where a scenario with a 100m² heptane pool fire can possibly occur.

Methodology for emergency ventilation analyses

Following the methodology as mentioned above, the necessary jet-fans and ventilation clusters are calculated, based on the (failure) risk for not obtaining the critical velocity (based on the Dutch tunnel decree). This probabilistic analysis is performed by the software program ProTuVem [18] which takes into account the tunnel geometry, wind speed and direction probability for the location of the tunnel (including roughness as depicted below), as well as up to 1,000 fire locations in the tunnel. The velocity in the tunnel is calculated as a function of the pressure drop due to friction of the tunnel walls, friction by stationary traffic, the pressure drop due to wind, the pressure drop due to the fire itself, the stack effect (which can both be positive or negative depending on the fire location), the pressure rise of the jet-fans (as a function of local temperature and velocity).

The Dutch tunnel decree dictates the maximum chance of failure of the longitudinal ventilation system for several heat release rates of a fire. Since the occurrence of fires with a high heat release (e.g. 100MW or higher) is lower, the decree accordingly allows higher chances of failure for a higher heat release (as depicted below). For a 200MW fire the maximum chance of system failure is 0.05 [-].

Following a performance based methodology it is subsequently checked by CFD if the 1D-calculation method is also valid for a five-lane tunnel. The main reasons for this additional analysis are on one hand the throttling effect (it is plausible that the calculation method in ProTuVem is not entirely suitable to calculate this effect accordingly for a five-lane tunnel). The importance of this
effect is e.g. stated by Vaitkevicius et al. 2014, were it is concluded that ‘In tunnel design for fire safety, the throttling effect must be considered’. On the other hand it was unclear to which extent the shielding of trucks on one side of the tunnel could result in (local) back-layering. The CFD simulations were performed by FDS version 6. The results of these analyses will be discussed in the chapter on the emergency ventilation results.

<table>
<thead>
<tr>
<th>Fire heat release</th>
<th>Maximum chance system failure</th>
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<tbody>
<tr>
<td>20MW</td>
<td>1E-3 (0.1%)</td>
</tr>
<tr>
<td>50MW</td>
<td>5E-3 (0.5%)</td>
</tr>
<tr>
<td>100MW</td>
<td>15E-3 (1.5%)</td>
</tr>
<tr>
<td>200MW</td>
<td>50E-3 (5.0%)</td>
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</tbody>
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Figure 3. Emergency ventilation, with A. maximum chance of system failure in conformity with the Dutch tunnel decree. and B. the roughness of the area surrounding the tunnel portals as used in the analysis.

Results of the emergency ventilation analyses
According to the Dutch tunnel decree the required emergency ventilation is based on the chance of not achieving the critical velocity. For a 200MW fire this chance should be lower than 0.05. In order to establish a robust emergency ventilation concept for the OKA tunnel at least 15 jet fans are required for the tunnel tube from north to south, which results in a chance of system failure of 0.025. For the tunnel tube leading from south to north at least 21 jet-fans are required, which results in a chance of system failure of 0.036. The difference between the two tunnel tubes is caused by the vertical alignment, the south to north tunnel tube does include a longer downward slope as opposed to the north to south tunnel tube, which results in an increased chance of a higher (negative) stack effect (the fire location is a random variable in the probabilistic ProTuVem model). In conformity with the Dutch approach for the ventilation clusters location, one cluster is located at the entrance of the tunnel and another ventilation cluster is located inside the tunnel (approximately 400 meter from the entrance for both tunnel tubes). A sketch of the jet-fans at the entrance of both the tunnel portals is displayed below.

Figure 4. Sketch of the location of the jet-fans at the entrance of the north to south OKA tunnel tube. At the entrance 10 jet-fans are required.
As indicated in the methodology section, it was unclear to which extent a negative placement of trucks in combination with the throttling effect in a five-lane tunnel is adequately modelled by ProTuVem. For this reason a CFD model was set-up in order to check the results as maintained by ProTuVem. Out of these results is was conclude that the capacity of emergency ventilation was adequate, since the CFD analysis also showed that back-layering could be prevented.

QUANTITATIVE RISK ANALYSES

The European guideline 2004/54/EG [8] requires a risk analyses for tunnels which are part of the Trans-European network. As a result the Dutch tunnel decree states a maximum norm for societal risk and requires the use of the Dutch QRA-tunnels model by which the risk analyses should be performed. In this chapter both the methodology and the results of the QRA will be discussed.

Quantitative Risk Analyses Calculation method

The Dutch norm states that the frequency of occurrence (year^−1) should be lower than 0.1/N^2, where N is the number of fatalities per kilometre tunnel (tube) [9] (this requirement is more strict when compared to the unacceptable risk or ALARP standard following PIARC). For the OKA tunnel the QRA-tunnel model calculates approximately 935,000 scenario’s. These scenarios range from small fires to large explosions for different periods of the day, including the possible failure of detection, failure of the tunnel operator to take appropriate actions, including the possibility of a downstream traffic jam and many more alterations (more information about the model can be found in [10] and
For each of the scenarios both the chance of occurrence and the consequences are calculated. The probability of specific scenarios is based on an event-tree in which the probability of independent events leading to the scenario are subsequently multiplied. The consequences for fire scenarios are calculated by a surrogate model based on CFD simulations performed by the Department of Public Works and Water Management (Rijkswaterstaat) for a tunnel up to a limited number of lanes.

Since the OKA tunnel is expected to be open for transport of all dangerous goods, all possible ADR scenarios should evidently be analysed. The consequences of explosion scenarios were analysed in collaboration with TNO [5]. It was concluded that the QRA-tunnel model as developed by the Department of Public Works and Water Management does include all the scenarios with full ADR transports. However, since the model only accounts for the loaded/full transports, possible scenarios involving empty (not cleaned) tankers are currently not included in the Dutch QRA model. As a result a Gas Expansion Explosion (GEE) with an empty tanker which was filled with liquefied flammable and/or toxic gas is currently not included in the model (confirming the statement in [6] that a purely prescriptive approach might result in unawareness of all the possible risks).

Following the performance based methodology, the GEE scenario was added to the analysed scenarios. For this reason an isolated GEE QRA was performed to determine the effect of a GEE solitary. This GEE scenario (with its FN curve) was subsequently added to the original QRA. In this additional QRA it was assumed that a GEE can both be the result of impact and of fire involving an empty (not cleaned) transport of liquefied flammable and/or toxic gas. In case of a GEE as a result of heating by a fire, the time to explosion was estimated by the time required for heating a full tanker above its fuel level as discussed by Kamperveen et al. [12].

In addition, the prescriptive method for a QRA includes an uncertainty analysis, which should provide insight in the effect of uncertainty in the input-parameters on the calculated societal risk. The method as provided by Dutch law prescribes the parameters which should be changed (one at the time), and subsequently its impact is determined. In addition to the prescribed method to determine the effect of uncertainties, a Monte Carlo analysis is performed in which multiple input parameters are changed simultaneously. The mean reason for this approach is that multiple of (small) alterations in the input parameters can have a more significant impact on the societal risk as changing one parameter at the time. This type of probabilistic risk analysis with multiple Fn curves is part of the highest level (5) as proposed by Paté-Cornell (1996) and indicated in Gehandeler et al. 2014 [21].

![Uncertainty propagation through a model](image)

Figure 7. Uncertainty propagation through a model (in this case the QRA model). The parameter uncertainty is specified as a probability density functions. Figure adopted from IAEA 1989 [22].

The method developed for this probabilistic QRA is based on a Monte Carlo simulation in which a normal distributed change (10%) of 28 input parameters is based on a Latin Hyper Cube sample. This
method of performing an uncertainty analyses is e.g. discussed in [13] or [23]. For the OKA tunnel the total uncertainty propagation though the QRA model consisted of 996 individual QRA calculations (automated sequence, totalling approximately one billion analysed events). For all of these samples the FN curve is analysed and the point closest to the standard was identified (the number of fatalities at which this occurs, changes for the different samples). Subsequently, the safety factor was calculated for the point closest to the standard. Repeating this methodology results in the expected distribution of the safety factor as a result of the uncertainty propagation. The results of this analysis as well as the deterministic QRA will be discussed in the following chapter.

Results of the Quantitative Risk Analyses (QRA)
As the tunnel will accommodate all transport of dangerous goods, all the possible incident scenarios have been taken into account and have been analysed by means of the Dutch QRA-model. The frequency of occurrence for each scenario and the consequences are investigated (expressed by the number of fatalities) to comply with the societal risk criteria imposed by the governmental law (the Quantitative Risk Analyses is implemented in the Dutch law based on the 2004/54/EG European guideline). In addition to the standard model, the impact of a Gas Expansion Explosion (GEE) which can occur with the transport of empty (not cleaned) tankers which transport(ed) liquefied flammable and/or toxic gas was added to the QRA model in order to obtain a complete insight in all the possible scenarios. Based on an uncertainty analysis for the mitigating impact of specific technical installations such as smoke and fire detection, tunnel closure and operator control, traffic management and water mist system, etc, the Mechanical Electrical and Plumbing (MEP) system for the tunnel has subsequently been defined. From a conservative point of view, the full effect of a water mist system was not implemented in the risk analyses which are shown below.

Currently the effect of the water mist system is implemented in the QRA in a conservative approach. It is assumed that this system is effective in 95% of the fire scenarios which do not involve the transport of dangerous goods. For the transport of dangerous goods it is assumed on basis of Lemaire et. al. [17] that the system is effective to prevent the occurrence of a BLEVE (in 95% of the scenarios leading to a BLEVE). For all other scenarios involving the transport of dangerous goods as e.g. liquid pool fires and vapour cloud explosions the water mist system is conservatively assumed to be ineffective for the prevention of fatalities. The adopted approach with regard to the effectiveness of a water mist system is considered to be conservative since it has currently become an established technology [e.g. 19], Butz concluded that water mist could be used as a mitigation measure for explosion hazards [24] (although water mist cannot inert a compartment completely). Within Europe there’s currently no country with national regulations with regard to the requirement of a FFFS [20]. However there is a growing recognisable tendency to equip tunnels (especially new tunnels) with such
systems [20], which in Europe is therefore a result of a performance based safety analysis. In addition to the deterministic QRA, a probabilistic QRA was performed taking into account the uncertainty propagation of 27 input parameters. Results are shown in figure 8B, from which it is concluded that the safety factor is likely to be 1.5 and between 1.1 and 1.9 (when the full effect of a water mist system, from a conservative point of view, is not taken into account).

DESIGN OF TUNNEL PORTALS
In this section the aspects of tunnel safety with regard to the design of the tunnel portals will be discussed. One important aspect with regard to the tunnel portals is to prevent the possibility of smoke entering the non-emergency tunnel tube at the portals, since this tube will be used by the emergency services. The emergency ventilation can be reversed in order to prevent repercussion of smoke in the non-emergency tunnel tube. A proper design of the portals can therefore be seen as an additional passive but necessary measure.

Tunnel portals design method
Regarding the tunnel portal design several sources are available, among others the VRC [14], AVV [15] and ASTRA [16]. One significant aspect regarding the portal design is which will start first: either the tunnel exit portal or the tunnel entry. This is depicted below (sketch based on Swiss standards). When the longitudinal location of both the start and the exit of tunnel tubes located abreast is the same, a smoke wall is necessary. The prescribed length of this wall differs slightly in different standards. The Dutch guidelines state that the length of the wall should be at least twice the hydraulic diameter of the tunnel tube, or in case of the portal below ground level, this should be 40 meters to prevent smoke entering the tunnel. These dimensions were determined for Dutch standard portal configuration in a wind tunnel. As a reference the Swiss guidelines state that the length of these walls should be at least 30 meters. It is therefore clear that the Dutch guideline is more strict for tunnel portals below ground level, and that the Swiss guideline is more strict for a portal above ground level. Since the OKA portals consist of four tunnel tubes (from both the OKA tunnel as the Kanaalzone tunnels) the strictest requirement was applied. In addition, this perceptive requirement was checked by means of CFD. This is in line with the performance based methodology as described above.

Figure 9. Sketch of necessary walls to prevent repercussion of smoke in the non-emergency tunnel tube (based on Swiss standards). For the south portal of the OKA tunnel configuration C is used. For the North OKA portal configuration F is used (in combination with configuration A for the Kanaalzone tunnel portals).
Results of the OKA Tunnel portals design

The OKA tunnel portals were designed in conformity with both national and international guidelines on the prevention of repercussion of smoke in the non-emergency tunnel tube. The applicability of these guidelines for an approximately 90 meter wide portal was subsequently checked by the use of a CFD simulation (the south portal was expected to be most prone to repercussion of smoke). In this section the results of this simulation will be presented. The simulation in FDS was performed for 25 MW fire located in the tunnel near the south portal, incorporating a cross wind of 9 m/s (worst case wind direction since smoke is forced towards the adjacent tunnel tube). A relatively low heat release was assumed since the resulting lower smoke temperature is more significantly influenced by wind, subsequently driving smoke towards the adjacent tunnel. The simulation is performed under worst case condition where a driving wind is still assumed to be present in the tunnel tubes (indicated by the white arrows in the figure depicted below).

The results indicate a distinction between two different kinds of smoke movement. One movement indicates a standing vortex between the walls in the south portal. This movement is a result from the (steady) wind direction across the portal, in combination with the relatively low heat release of the fire. Smoke is also forced over the smoke wall, however the iso-surface showing the local visibility equal to 30 meters will not reach the entry of the adjacent tunnel. It is therefore concluded that the local visibility in the adjacent tunnel tube will stay above 30 meters at this whole tunnel tube entrance, and therefore (under worst-case conditions) there is no reason to expect unacceptable conditions in the adjacent tunnel.

The CFD simulation therefore indicated that the guidelines are applicable for a portal consisting of 2x5 + 2x2 driving lanes + 2 emergency lanes, with a total width of approximately 90 meter (portal includes OKA tunnel and Kanaalzone tunnels). With the implementation of the smoke wall, repercussion of smoke in the adjacent tunnel can be prevented.
STRUCTURAL INTEGRITY FOR EXPLOSION SCENARIOS
The OKA tunnel will allow transport of all dangerous goods. Therefore, the impact of several explosion scenarios (related to ADR transport) on the OKA tunnel structure have been determined in collaboration with TNO. The method and results will be discussed in this chapter, methods based on [1,2,5].

Determination method of structural integrity for explosion scenarios
To mitigate the effects of explosions on the tunnel structure, a thicker tunnel roof (from 2 to 3 meter concrete) is incorporated as well as blast floors and anchoring to the diaphragm wall (anchoring will be activated when blast floors fail). A “not beyond repair” ambition is formulated for the status of the tunnel structural integrity after an explosion scenario. This ambition reflects that all viable methods to prevent structure failure are incorporated in the design. For scenarios in which this ambition can’t be met, it will be shown that the chance of these events is at an acceptable (low) level.

Results of Blast impact scenarios
Several explosion scenarios have been investigated in order to determine the impact of explosions on the tunnel structure. The blast impacts have been determined in collaboration with TNO.
Subsequently the impact on the structure was determined for the following explosion scenarios:
1. BLEVE;
2. Instantaneous vessel rupture followed by a gas-explosion;
3. Gas vessel leakage followed by a gas-explosion;

Based on the analyses, it was concluded that instability of the structure cannot be prevented for all of these scenarios. However, by incorporating a thicker tunnel roof (from 2 to 3 meter concrete) and blast floors, and by anchoring to the diaphragm wall (anchoring activated when blast floors fail), the
tunnel structure can stay within formulated ambition “not beyond repair” for most of the explosion scenarios. For the scenarios which can potentially (under unfavourable circumstances regarding air-velocity, temperature and sluice-conditions) lead to the status “beyond repair”, the chance was (conservatively) determined by the use of the event-tree adopted in the Dutch QRA-model. Based on this analysis, it was concluded that the chance of the scenarios which can potentially result in a “beyond repair” tunnel structure status, is approximately a factor two lower than the allowable chance of infrastructure failure crossing a dike in the Netherlands, or the failure of a reliability class 3 construction. The chances of an explosion as calculated with the Dutch QRA model, are displayed below.

<table>
<thead>
<tr>
<th>Explosion scenario</th>
<th>Chance [km(^{-1}) year(^{-1})]</th>
<th>Expected ones every .. years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour cloud explosion (after instantaneous tanker rupture)</td>
<td>2.464E-6</td>
<td>427.000</td>
</tr>
<tr>
<td>Vapour cloud explosion (after continuous flow of gas)</td>
<td>3.043E-6</td>
<td>346.000</td>
</tr>
<tr>
<td>BLEVE (without water mist system)</td>
<td>5.750E-6</td>
<td>183.000</td>
</tr>
<tr>
<td>BLEVE (with water mist system as designed)</td>
<td>2.875E-7</td>
<td>3.660.000</td>
</tr>
<tr>
<td>GEE (gas expansion explosion)</td>
<td>1.408E-6</td>
<td>710.000</td>
</tr>
</tbody>
</table>

For the extreme blast scenarios with possible tunnel structure loss, the actual occurrence and possible effects of inundation of the infrastructure and flooding of the surroundings have therefore been determined. Mitigating measures are incorporated in the design and the remaining risk of failure “not beyond repair” has been assessed and compared to the safety integrity levels and codes of large infrastructures.

CONCLUSION

This paper provides a state-of-the-art insight into the tunnel safety engineering of the five-lane double-decked ‘full-ADR’ OKA tunnel, addressing the QRA, emergency ventilation, the tunnel portals design, the structural integrity for several explosion scenarios as well as additional probabilistic modelling and uncertainty analyses. The methodology for the design of the tunnel was to meet the prescriptive requirements from building and tunnel decrees as well as all guidelines. To ensure an integral approach, the applicability of these prescriptive requirements was checked in order to provide a holistic identification of all possible risks. The methodology increased the design challenge significantly, since additional (CFD) analyses as well as uncertainty and sensitivity analyses were performed. To ensure a safe and robust OKA tunnel design, the following performance based mitigation measures are implemented (additional measures to the prescriptive requirements):
- A fixed fire fighting system (water mist);
- Emergency doors each 50 meter, connected to a 2 meter wide escape gallery;
- Intensification of fire detection;
- Increased blast resistance of the structure by a thicker tunnel roof;
- Increased blast resistance of the structure by additional anchoring of the diaphragm walls;

As a result of the integral performance based approach with its additional analyses (with respect to a prescriptive approach) it is conclude that a safe OKA tunnel can be built when all mitigation measures are implemented.

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Fire Safety in The North/South Line Project: Designing Measures for Fire Resistance in Infrastructure

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ABSTRACT

In this paper the design and application of the fire resistance measures in the North/South metro line during the finishing phase are explained, where safety requirements were still being (re)defined during the concrete works. This paper describes how the challenge of changing requirements was handled and how fire resistance was designed in the finishing phase. Cooperation between client and contractor was a key to the success in the project, as well as keeping the authorities involved. During the process the requirements for specific construction elements have been deduced from the basic starting points like the building permit and the safety strategy. Additionally, as spalling of concrete turned out to be the decisive phenomenon affecting the fire resistance, fire tests have been carried out to assess the spalling behaviour of the different concrete mixtures in the North/South metro line and determine the required amount of passive fire protection.

KEYWORDS: case study, fire resistance, on-site fire test, client contractor cooperation, changing requirements, safe haven principle, spalling

INTRODUCTION

In the North/South metro line project there are separate contractors for the concrete works and the finishing works. Additionally safety requirements were (re)defined during the concrete works and it was decided that fire protection of the submerged tunnel and the underground stations was to be handled in the finishing phase. This paper describes how the challenge of coping with changed requirements was handled and how fire resistance was designed in the finishing phase.

The North/South metro line will run 9.7 kilometres from Buikslootmeren in the north of the city to Amsterdam Zuid station in the south and opening is planned in 2017. The North/South metro line runs below the historic city centre of Amsterdam, where a twin bored tunnel is applied that follows the street pattern as closely as possible. Additionally, the river IJ is crossed by an immersed tunnel. In the line 5 underground stations are located. The client is the City of Amsterdam and the finishing contractor is VIA NoordZuidlijn (a combination of Visser en Smit Bouw and Imtech Building Services). Efectis is contracted as fire safety specialist by VIA.

Infrastructure projects take years to decades from idea to realisation. In the North/South line project the requirements for the metro system were changed during the construction process. Additionally, it was decided that fire resistance should be realised in the finishing phase of the project. Advancement of the state of the art in fire safety engineering made it clear that spalling of concrete needed to be taken into account. This was taken care of by starting a team of decision makers (contract, process and
project managers) and specialists (fire safety and structural engineers) from client and contractor working together on the subject. The team defined the approach and criteria together and kept the authorities informed on the approach and progress. Key issue in the project is that the compliance of approach and solutions must always be proven.

**APPROACH**

The process started with defining the approach supported by the whole team. The steps in the approach are explained in the paper. As a reference the process including all process steps is visualised in figure 1 below. The upper part of the process scheme is the determination of the requirements per construction member from the building permit and safety strategy applying fire safety engineering. The lower part of the process scheme is the translation of the requirements to a design for the fire resistance for all construction members.

**DEFINITION OF STATION/TUNNEL**

The segmental lining of the twin bored tunnel consists of concrete with polypropylene fibres and supporting fire test data regarding the spalling behaviour in case of fire exists. For the submerged tunnel, in-situ tunnel parts and the stations, concrete without polypropylene fibres has been used and the application of passive fire protection has been foreseen, to be designed and applied during the finishing phase. As different requirements exist for the tunnel and the stations (which will be explained below), it has been important to define and visualise what parts of the metro line are regarded part of the “station” and what are part of the “tunnel”.

First, the building permits for the stations define formally what is “station”. Additionally, the bored tunnel parts with polypropylene fibre are clearly defined as well. However, for the remaining parts a choice has been made based on the physical shape of the geometry, the structural characteristics (dilatations) and the locations of smoke compartmentation. A quite straightforward example for the Rokin station is shown in figure 2 below.

**Figure 1 – Process steps in the process leading to the design of the fire resistance for the North/South line**

**Figure 2 – Example of the resulting definitions of “station” and “tunnel” around the Rokin station**
SAFETY STRATEGY AND FIRE SCENARIOS

In the North/South line project, the ‘Safe haven principle’ is applied. The ‘Safe haven principle’ can be summarised with two key points: make sure the metro train always stops at a station and make sure that the station is a safe haven, a place with (more) robust safety measures. As the design of the metro line and the applied systems are completely based on this strategy, it can be shown that the probability of a fire is much lower in the tunnel parts than in the stations.

The fire scenarios are based on the fire safety strategy and the available fire load. In the public areas of the stations, the fire load is limited, leading to the fire scenario: compartment with limited fire load. In other compartments of the station (e.g. technical cabinets) the fire load is regarded normal (compartment with normal fire load). Finally, of course, the metro train fire is a scenario to be considered in both the tunnel and the station.

So, concluding, the following fire scenarios are considered in the metro line:

- Metro train fire in station/tunnel;
- Compartment with normal fire load;
- Compartment with limited fire load.

FIRE CURVES

Fire curves in stations and tunnel differ because of the ‘Safe haven principle’. In the stations, the probability of a fully developed metro train fire is low, but given the safety strategy it is still more likely than in the tunnel. Therefore, the thermal load on the structure to take into account is translated into the conservative EUREKA or RABT 60 fire curve during 120 minutes (EUR120), which can be seen as the envelope of the available fire test data of (metro) train fires.

In the tunnel it is less likely that a fully developed metro train fire will occur and the fire curve associated with the metro train fire scenario is a project specific one. The fire curve, the “Specific fire curve North/South line” is based on the realistic worst case thermal load on the structure as found in a series of CFD calculations under different ventilation conditions. For the compartments with limited or normal fire load the ISO fire curve is applied, with a duration of 90 (ISO90) or respectively 120 (ISO120) minutes. The fire curves are shown in figure 3. The translation from fire scenario to fire curve, taking into account the safety strategy, is visualised in figure 4.
Figure 3 – Fire curves in the North/South line project

Figure 4 – The translation of fire scenarios to fire curves, taken into account the ‘Safe haven principle’ as safety strategy

DEMARcation BETWEEN DIFFERENT FIRE CURVES

In the stations, the normative fire scenarios depend on the position in the station and the available fire load: close to the track the normative fire scenario is a metro fire, further away from the track (on the platform and distribution level) there is only a limited fire load available. As the stations of the North/South line include large halls, it is quite unlikely that the severe EUREKA/RABT 60 fire curve is still applicable on structural elements far away from the metro train.

Therefore a model has been developed to assess the direct area of influence of the metro train fire. This has been done using an external flaming model, based on the external flaming model in the Eurocode. The model is based on a fully developed metro train fire, with the doors on one side of the train as ventilation openings. The model includes added safety factors for unexpected effects of ventilation, incomplete combustion and objects influencing the flame shape (flame elongation). The demarcation is chosen as the contact surface of the flame. This approach is conservative, because the actual thermal load in the ISO zone is expected to be lower than the ISO fire curve. The structure and the results for different ceiling heights above the track (Hpl) and distances from the train edges to the walls (Rw) are given in figure 5.
In this way, applying this flaming model is a quick, conservative alternative to analysing many different CFD simulations. Given the limited available time, the simplicity of the model turned out to be an important advantage in the project.

**FIRE RESISTANCE OF CONCRETE**

The fire resistance of the concrete structure depends on many factors and spalling of concrete is one of them. Nevertheless, in the project it was decided that concrete structures in the ISO zone are regarded, as any other building where the ISO curve applies, according to the Eurocode approach, where spalling is assumed to have limited effect on the fire resistance under given conditions. According to the Eurocode, the fire resistance can then be based on a minimum required concrete cover and it turns out that the concrete structure in the ISO zone can stay largely unprotected for the North/South Line.

In the direct area of influence of the metro train fire, spalling will not be neglected as the temperature development is fast, the maximum temperature of the fire curve is high and direct flame impact can not be excluded. In this area spalling of concrete has turned out to be the decisive parameter when assessing the need for fire protection.

Spalling of concrete is a complex phenomenon caused by restrained thermal expansion of concrete and by pressure build-up in the pores due to the heating of the water inside the concrete. Both mechanisms are dependent on a large amount of parameters, such as
- The geometry and support and restraint conditions: is the structure able to deform and accommodate the thermal expansion, or is the thermal expansion counteracted by very large restraint forces induced by the surroundings or by its own geometry?
- The concrete mix: does the concrete mix include ingredients that promote the effects leading to spalling, e.g. by reducing the permeability or increasing the thermal expansion? Or does the concrete mix include ingredients that reduce the effects leading to spalling, such as special polypropylene fibres or low-expansion aggregates?
- The age and climate: is the concrete young (more water but also more permeable) or old (less water but also less permeable); is the surface exposed to a moist environment, causing a high water content in the pores?
- The heating rate: faster heating can lead to thin layers violently spalling off the surface, progressively consuming the cross section during the period of heating. Slower heating can delay spalling, but may still lead to spalling on later moment with more accumulated energy and therefore more explosive behaviour.

A complicating factor is that each of the mechanisms depends on temperature dependent material properties that cannot be determined accurately in a practical manner at elevated temperatures.

Moreover, the stresses due to thermal expansion and pore pressures due to water are interacting. Thermal expansion may lead to cracks on different scales (from micro-cracks to macro-cracks) which, when they occur, provide new ways for the water in the concrete to migrate to zones with lower pressure. Pore pressures, on the other hand, may also reach levels high enough to cause cracking of the concrete. When a crack in the concrete is parallel to the exposed surface a layer may fall down. As the formation of such a crack usually means the release of a significant amount of energy in the form of compressed concrete and compressed water (liquid or vapour), spalling is often a quite violent effect, involving pieces of concrete coming off the surface with loud noises and high speeds.

**IN-SITU TEST PROGRAMME**

As spalling of concrete is the result of an enormous amount of variables and complex interactions, and each of the mechanisms depends on material properties that are hardly known, it is not possible yet to accurately model the spalling behaviour of a given concrete structure. For this reason it was decided to assess the spalling behaviour using in-situ fire tests [1].

However, as many different concrete mixtures and loading conditions were present a practical approach was applied. The selection of the locations for the fire tests was based on the information about the applied concrete mixtures. As the concrete works were partly finished and partly still in progress, the information about the concrete mixtures was gathered, as far as possible, from the concrete works contractors resulting in overviews as shown in figure 5. However, the decisive parameters that affect spalling are generally not distinctive parameters recorded by the concrete manufacturers: e.g. microfillers like fly ash strongly affect spalling behaviour, but are not always mentioned on the specification of the concrete manufacturers. This has resulted in an overview of the applied concrete mixtures for all construction elements as shown in figure 6. Based on the concrete mixtures (the factors in the mixture that are believed to affect spalling), the occurrence of the mixtures (representativeness) and the stresses in the structure the worst-case and most representative locations were selected with the worst-case loading conditions.

![Figure 6](image_url)

**Figure 6 – Applied concrete mixtures for one of the facing walls of a station: two concrete mixtures have been used for the walls, and one mixture for the floors**
The fire tests have been carried out by Efectis using a mobile furnace [1][2]. On each of the selected locations, multiple tests were performed to determine the spalling sensitivity. In practice, this meant that per location a number of test areas were chosen directly adjacent to each other, within one area with the same concrete mix. Each of the test areas was exposed to a gradually increasing temperature. The rate of temperature increase was varied per test area. When exposed to higher heating rates, the concrete would typically spall and with lower heating rates the concrete would not spall. If a certain heating rate led to spalling, the test was immediately stopped, in order to avoid unnecessary damage to the tunnel. Moreover, if the test result should give reliable information with regard to the spalling rate and depths, a larger area should be exposed [3].

By iteratively changing the heating rate for each next test, the limiting temperature rate at the concrete surface could be established for the given location. The test setup with the mobile furnace during a fire test in the “Europaplein” station is shown in figure 7.

![Figure 7 – Fire tests in one of the stations of the North/South Line](image)

**TEST RESULTS**

The chosen iterative approach resulted in 36 fire tests, spread over 14 locations in the 5 underground stations and the immersed tunnel below the river IJ. Based on the results, time-dependent interface temperatures that prevent spalling of concrete have been deduced. These time-dependent interface temperatures have been used to assess the required amount of passive fire protection to limit the temperature development of the concrete sufficiently when exposed to the fire curve.

![Figure 8 – Concrete surface after a fire test where spalling occurred](image)
In total, out of the 36 fire tests, 22 tests resulted in spalling of concrete and 14 tests were continued to the end (121 minutes) without occurrence of spalling. Out of the 22 tests that showed spalling, 21 tests spalled between 26 and 77 minutes; in one case spalling occurred at the end of the test, just after 120 minutes but before switching off the furnace. It is noted that each of the 14 locations is specific in terms of orientation (wall or ceiling), concrete mix and or compression level at the exposed surface. Therefore, in principle the spalling sensitivity varies over the locations.

The average concrete surface temperatures during the tests are shown in figure 9, both for the spalled and non-spalled test results, for all locations. The green lines represent the average temperature development curves on the concrete surface where no spalling occurred within 121 minutes. The average temperatures vary between 200°C and 350°C after 120 minutes (excluding the fire test leading to spalling just after 120 minutes with an average temperature of slightly over 400°C). The red dots represent the moment of spalling for the spalled tests, where the average temperatures were between 200°C and 400°C.

Due to the shape of the fire curve including a cooling down phase, the concrete surface temperatures do not further increase after approx. 80 minutes. The results show that after this time, with more or less constant concrete surface temperatures, no further spalling occurs, except for the one result that spalled after 120 minutes.

Figure 9 shows a significant overlap of the non-spalling and spalling areas. This is attributed to the properties of each given location (wall or ceiling, concrete mix, loading level). For each individual location, the results are fully consistent, meaning that the spalled tests (“red dots”) are always above the non-spalled test results (“green lines”), which is shown for a specific situation in figure 10. In this way, for each location critical interface temperature curves were determined, which were the basis for the choice of the fire protection thickness.
FIRE PROTECTION

Based on the found critical temperatures for the concrete and steel elements, the passive fire protection was designed, engineered and applied. The time-dependent interface temperatures can vary per concrete mixture and therefore the amount of applied passive fire protection can vary per concrete mixture as well. This can result in different required thicknesses in one station or even within e.g. a facing wall. To prevent mistakes in the application, practical choices have been made such that the applied thickness on the ceiling or the walls can differ, but that all walls or all ceilings have the same applied thickness. This has resulted in maximum interface temperatures between 200°C and 380°C, depending on the location.

In the design the effect of heat sinks caused by mounting accuracy (joints) or heat sinks was taken into account. To allow for joints with a given width, the applied thickness of passive fire protection was larger than the minimum required thickness assuming butt joints. The effect of joints and the locally required additional fire protection around heat sinks was calculated using finite element simulations.
SUMMARY AND CONCLUSION

In this paper the design and application of the fire resistance in the North/South metro line during the finishing phase is explained, where safety requirements were still being (re)defined during the concrete works. This paper describes how the challenge of coping with changed requirements was handled and how fire resistance was designed in the finishing phase. Cooperation between client and contractor was a key to the success in the project, as well as keeping the authorities involved. During the process the requirements for specific construction elements have been deduced from the basic starting points like the building permit and the safety strategy. Additionally, as spalling of concrete turned out to be the decisive phenomenon affecting the fire resistance, fire tests have been carried out to assess the spalling behaviour of the different concrete mixtures in the North/South metro line and determine the required amount of passive fire protection. The on-site spalling tests in the North/South metro line confirm that for a given concrete mixture with given loading conditions there is a limiting interface temperature development. Above that temperature development, spalling occurs and below that temperature development spalling does not occur.

However, various concrete mixtures and loading conditions exist in the metro line and this leads to a different limiting interface temperature development for the various locations. For the different stations, temperature developments with maximum values of between 200°C and 380°C were found to be limiting values to prevent spalling. In the design of the fire protection, practical and conservative choices were made to cover the whole range of situations and simultaneously prevent mistakes in the application of the passive fire protection, creating a robust design.

Although the process to design the fire resistance in the finishing phase with an enthusiastic team was exciting, it is recommended to design/assess the fire resistance and spalling behaviour as early as possible in the construction process as then there are much less boundary conditions and limitations to the designed fire protection solutions.

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Tunnel Safety and Quantitative Risk Analysis of Gas Explosions

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ABSTRACT

Tunnel accidents with transports of combustible liquefied gases may lead to explosions. Depending on the substance involved this can be a Boiling Liquid Expanding Vapour Explosion (BLEVE), a Gas Expansion Explosion (GEE, a physical explosion) or a gas explosion (a deflagration or detonation). Quantification of the risk of these scenarios is important to take informed decisions on tunnel design and routing of dangerous goods. At the ISTSS2014 conference a summary and state-of-the-art on the explosion modelling was presented \cite{1}. The explosion models that predict physical effects like overpressure and fire are essential in Quantitative Risk Analysis (QRA). Other key-components are the consequence models for damage to the tunnel, lethality and injury, and the probability assessment. The current paper addresses the latter aspect (i.e. probability assessment) for the gas explosion scenarios. First the gas explosion mechanism is summarized to introduce the key parameters for the explosion load in a tunnel. Then an integrated model for the dispersion and probability of ignition is presented -. Reliable data on ignition conditions and criteria for accident scenarios in tunnels are not available. But for road tunnels the ignition probability will depend on the “car density” and the duration that cars are within that part of the gas cloud with a gas concentration within the flammability limits. These aspects are included in the model and illustrated in a set of case studies. The case studies with an instantaneous LPG release show that the cloud is initially too fuel-rich to be ignited. Subsequently the gas concentration either remains mostly fuel-rich by the time the cloud reaches the end of the tunnel or falls within the flammability limits before the tunnel exit, depending on the initial amount of fuel released. A case study with a continuous LPG release shows that it depends on the release rate and the ventilation speed whether a tunnel may be completely filled with a combustible fuel-air mixture or not. The simulations provide the overpressure for different scenarios linked with their probability of occurrence. A higher basic ignition probability (per car per second), generally leads to lower overpressures. This is caused by the fact that for a higher basic ignition probability the cloud ignites earlier, at a time when the cloud is less developed. The presented case studies clearly show the capability to quantify the gas explosion load and probabilities for various accident scenarios. The combination of the gas dispersion, gas explosion and ignition models are needed to develop safety measures, to derive design loads for tunnels, and to perform tunnel safety assessments. They form the backbone for quantitative risk assessments.

KEYWORD: explosion, tunnel design, probability, risks, models, transport dangerous goods.

INTRODUCTION

At the ISTSS 2014 conference the authors presented the background of the tunnel explosion safety research and modelling development in the Netherlands related to transport of combustible liquefied gases \cite{1}. Depending on the substance involved this can be a Boiling Liquid Expanding Vapour Explosion (BLEVE), a Gas Expansion Explosion (GEE) or a gas explosion. In the current paper the focus is on gas explosions, the probability of ignition forming the input for Quantitative Risk Analyses (QRA’s). In sequence the paper summarizes how (i) the gas explosion mechanisms, (ii) the
dispersion of the gas cloud after release and (iii) the way the ignition probability are modelled. Next the models are applied in three case studies to illustrate and taken into account. Next three case studies are presented to show the capability to quantify the gas explosion load and probabilities for various accident scenarios.

**GAS EXPLOSION**

**Explosion mechanism and model description**

A mixture of a fuel and air can only be ignited when its composition is between the flammability limits. For propane these limits are 2 and 9%. Such a mixture is called an explosive mixture. When the mixture ignites, for instance by a spark or a hot surface, a flame front will start propagating into the reactive mixture. The flame propagates due to the transport of heat. Heat is produced in the combustion reaction in the flame front, the flame sheet is transported into the unburned mixture ahead of the flame by molecular transport processes such as conduction and diffusion of heat and species. In this way the mixture in front of the reaction zone is heated up to ignition whereupon it starts to react. The strength of the explosion, i.e. the generated overpressure, depends on the amount of explosive mixture that reacts combined with the time in which the mixture reacts. Both increase with the size of the explosive cloud. The amount of gas that reacts per time unit increases significantly when the flame propagation process can generate its own turbulence in interaction with the boundary conditions for the flow field. Then the reaction process, i.e. a deflagration, intensifies and the generated overpressures can increase up to 800 kPa. Beyond these pressure levels the mechanism can change from deflagration to detonation. Detonation pressures for propane mixtures are in the order of 1500 - 2000 kPa. For a thorough description of the gas explosion see [1, 2 and 3].

From the gas explosion mechanisms the parameters relevant for gas explosions in tunnels emerge. Considering an accident with the bulk transport of LPG in which the vessel is damaged and the gas is released, the tunnel will be filled with a gas cloud. The dispersion of the gas and the development of the gas concentration depends on the gas release rate, the amount of gas, the tunnel size and geometry and of course the ventilation rate in the tunnel. This is a dynamic process and the length as well as the position of the cloud with a concentration within the explosion limits vary in time. Referring to the explosion mechanism, cars within the cloud are obstacles in the flow field and the generated turbulence will enhance the deflagration process and so the explosion strength. Also the tunnel walls constitute boundary conditions and will generate additional turbulence.

**Explosion model**

Based on reactive gas dynamics and computational fluid dynamics (CFD) the gas explosion mechanism can be modeled taking all conditions into account. Theoretically this should be feasible, but covering all phenomena at all relevant length scales (10^-4 - 10^1) is still not possible for practical applications. TNO developed her own CFD, gas explosion code to study the phenomena. Based on the knowledge and experience gained simplified, engineering models were developed for tunnel conditions.

As mentioned in the mechanism description, pressure loads are related to flammable cloud lengths. In [4] Van den Berg, Rhijnsburger and Weerheijm compiled guidelines for the explosion load as a function of the cloud length with a stoichiometric concentration. The guidelines have been drawn up by exercising a highly simplified model for the gas dynamics of a gas explosion in a tube, see [4,5,6]. For the current paper we consider scenarios in which the explosive mixture ignites as soon as it meets a stationary ignition source somewhere. The explosion overpressures compiled for edge-ignition are applied. The maximum pressure loads dependent on cloud lengths have been tabulated in Table 1. Note, that for cloud lengths larger than 50 m the explosion pressure load rapidly increases up to 800 kPa and the deflagration to detonation transition might occur.
Table 1 Explosion pressure load on the tunnel lining dependent on explosive cloud lengths [3]

<table>
<thead>
<tr>
<th>explosive cloud length (m)</th>
<th>explosion pressure load (kPa)</th>
<th>explosion pressure impulse (kPa.s)</th>
<th>relative rise time β#</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>13</td>
<td>1.9</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>32</td>
<td>4.9</td>
<td>0.6</td>
</tr>
<tr>
<td>6</td>
<td>47</td>
<td>7.1</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>65</td>
<td>9.4</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>83</td>
<td>11.5</td>
<td>0.4</td>
</tr>
<tr>
<td>20</td>
<td>190</td>
<td>21.2</td>
<td>0.2</td>
</tr>
<tr>
<td>30</td>
<td>340</td>
<td>28.8</td>
<td>0.1</td>
</tr>
<tr>
<td>40</td>
<td>500</td>
<td>36.3</td>
<td>0.1</td>
</tr>
</tbody>
</table>

# β is the ratio of the pressure rise time and the positive phase duration of the explosion pressure.

S In this paper the explosion load, the “overpressure”, is the load acting on the tunnel structure.

Dispersion

When the gas is released, initially the concentration varies over the cross section. Downwind, the distribution gets more and more equally distributed and at sufficient distance from the release point the distribution along the tunnel axis can be considered to be one-dimensional. The one-dimensional dispersion model of Taylor [7] has been applied in the TNO model to determine the concentration distribution of the gas as a function of time and distance to the release point. Calculations can be made for instantaneous release of gas as well as for different release rates. See [2] for detailed description of the model.

Figure 1 shows how the concentration distribution in a cloud of 500 m³ LPG has developed at 10, 20, 50, 100, 200, 500, 1000, 2000 and 5000 s respectively after release. It shows how the concentration gradually falls relative to the flammability region of propane in air. Initially, two areas of a flammable composition on either side of the cloud are separated by an area of a composition too rich to be able to propagate a flame. Subsequently, when the maximum concentration falls below the upper flammability limit, there is one continuous area of a flammable composition. This has been demonstrated Figure 1 (middle and right), which show the downwind concentration distributions at 100 s and 500 s after the instantaneous release respectively.

Figure 1: (Left) Consecutive concentration distributions downwind of an instantaneous release of 500 m³ gas in a long tunnel tube (logarithmic downwind coordinate); (middle) Concentration distribution downwind of a release of 500 m³ propane after 100 s and 500 s, showing how the flammable part of the cloud develops from two separated areas on either side of the cloud to one single area (right)

So far vessel rupture and instantaneous release were considered. When the gas is released from a continuous leak, the steady downwind concentration in steady flow in a tunnel tube can be approximately related to source strengths through:
\[ C = \frac{Q}{\rho U A_t} \times 100\% \]  

(1)

where:  
- \( C \) = steady downwind concentration (m³.m⁻³);  
- \( Q \) = leak rate (kg.s⁻¹);  
- \( \rho \) = propane vapour density (1.9 kg.m⁻³);  
- \( U \) = ventilation wind speed (m.s⁻¹) and  
- \( A_t \) = tunnel cross-sectional area (m²)

Referring to the explosion mechanism and the importance of the length of the explosive gas cloud, it is interesting to see at what release- and tunnel conditions explosive clouds can occur that are long enough to enable the deflagration-detonation transition. The data in Figure 2 illustrates the dependency of the length of the explosive cloud on the release rate and the tunnel length.

![Figure 2: Downwind explosive cloud length development for various leak rates in a tunnel of 5 × 14.4 m² cross-sectional area and a 1 m/s ventilation wind speed. The dashed lines are numerical fit curves [2].](image)

INTEGRATION OF MODELS FOR DISPERSION AND PROBABILITY OF IGNITION

Problem definition and assumptions

We consider a tunnel with length \( L_T \), as in Figure 3. Distances in the tunnel are measured on an \( x \)-axis with its origin at the left tunnel exit. In the tunnel a ventilation speed \( U_v \) is present, usually in the direction of the traffic. At location \( x = x_C \) and time \( t = 0 \) an accident takes place with a truck transporting a combustible gas. We focus on the case in which a direct ignition does not take place. From \( t = 0 \) onwards a leakage results in a cloud that will mix with air and move downstream. The number of vehicles per m tunnel is given by the linear density \( \rho(x,t) \). This density can be a function of distance \( x \) and time \( t \).

![Figure 3: Definition of tunnel and traffic](image)

As described in Section 2 we consider both instantaneous and continuous releases. The explosive part of the cloud has a gas concentration between the LFL (Lower Flammability Limit) and the UFL (Upper Flammability Limit); the explosive cloud length is \( L \).

For propane-air mixtures the auto-ignition temperature is 470 °C [6], and the Minimum Ignition...
Energy (MIE) is between 0.25 mJ (Lewis and von Elbe, [10]) and 0.46 mJ (Eckhoff [9]). The auto-ignition temperature is not reached normally in an ordinary combustion engine, but a static discharge easily exceeds the MIE. As a result a static discharge generated by vehicles is the most realistic option. Therefore it is assumed that a possible ignition is dominated by the vehicles.

In conclusion we assume that the ventilation speed is in the direction of the traffic, and that the ignition probability is dominated by vehicles. These assumptions together imply that the accident scenario of a truck driving into a traffic jam is the most relevant to consider. In this case the explosive cloud will potentially meet a large number of vehicles (ignition sources).

**Probability of ignition**

The description of a model which combines the dispersion of a gaseous fuel in a tunnel, the ignition probability of the flammable cloud and the corresponding overpressure is provided in this section. A typical gas concentration profile is presented in Figure 4. This figure also shows the Lower Flammability Limit (LFL) and the Upper Flammability Limit (UFL) of a propane-air mixture at atmospheric pressure. Flammable clouds are thus defined where the gas concentration is between the flammability limits. Considering a ventilation direction downstream, the length of the leading and trailing flammable clouds are defined as $L_{\text{leading}}$ and $L_{\text{trailing}}$, respectively. The total flammable cloud length ($L$) is therefore: $L = L_{\text{leading}} + L_{\text{trailing}}$. As the maximum gas concentration decreases downstream, it is also possible that the leading and trailing flammable cloud merge into a single cloud with length $L$.

![Figure 4 Typical gas concentration profile including the LFL, the UFL and the definition of flammable clouds](image)

Considering a car density $\rho$ in the tunnel we can calculate the number of cars in the flammable cloud(s):

$$n = L\rho = (L_{\text{leading}} + L_{\text{trailing}})\rho$$

$\rho$: car density (cars/m)

$n$: number of cars (cars)

Defining the ignition probability caused by a single car which remains in a flammable mixture for one second as $P_{\text{single car}}$, the ignition probability for a given gas concentration profile is obtained by using the so-called power-up rule for the leading and trailing flammable clouds:

$$P_{j,\text{leading}} = 1 - \left(1 - P_{\text{single car}}\right)^{n_{\text{leading}}}$$

$P_{j,\text{leading}}$: ignition probability of the leading flammable cloud for one time step at time $t_j$

$$P_{j,\text{trailing}} = 1 - \left(1 - P_{\text{single car}}\right)^{n_{\text{trailing}}}$$

$P_{j,\text{trailing}}$: ignition probability of the trailing flammable cloud for one time step at time $t_j$

In the above relation, it is important that the time step used in the simulation corresponds to the definition of $P_{\text{single car}}$, which is in this case one second. To obtain the overall ignition probability at time $t_j$ including the two flammable clouds the following relation is used:
\[ P_j = 1 - \left(1 - P_{j,leading}\right)\left(1 - P_{j,trailling}\right) \]

\( P_j \): ignition probability for one time step at time \( t_j \)

In case the two flammable clouds merge into a single flammable cloud the ignition probability is expressed as:

\[ P_j = 1 - (1 - P_{\text{single car}})^n \]

As the cloud travels along the tunnel, the ignition probability at consecutive time steps must be related (the ignition probability of a car that remains in a flammable cloud for two seconds is larger than if the car enters a flammable cloud twice for one second in each presence). The cumulative ignition probability is hence obtained with the following relation:

\[ P_{\text{cumul}} = 1 - \prod_{j=1}^{m} (1 - P_j) \]

\( m \): number of time steps

\( P_{\text{cumul}} \): cumulative ignition probability

This relation differs from the previous one because \( P_j \) varies at each time step. The cumulative ignition probability provides the probability that the flammable cloud ignites before a given time. In a risk analysis it is of interest to define a representative set of scenarios with their respective probability of occurrence, physical effects, and consequences. In this case, a scenario corresponds to an ignition within a certain time interval (i.e. for a certain flammable cloud length). The probability of the different scenarios is obtained using the cumulative probability versus time:

\[ P_{\text{scenario}} = P_{\text{cumul}}(t + \Delta t) - P_{\text{cumul}}(t) \]

\( P_{\text{scenario}} \): ignition probability at a given time

Note that \( \Delta t \) may be but is not necessarily equal to the time step used in the dispersion and cumulative probability calculation. Also, the Probability Density Function (PDF) is of interest as it can be used to determine some interesting statistical parameters, like the mode and arithmetic mean.

\[ P_{\text{PDF}} = \frac{dP_{\text{cumul}}}{dt} \]

\( P_{\text{PDF}} \): probability density function

An example of a probability density function is shown in Figure 5 with an illustration of the mode, median and mean values. The mode corresponds to the scenario that occurs the most often (maximum of the function). The median refers to the point where half of the scenarios has occurred (where the area under the curve is separated into half). The arithmetic mean is the scenario that occurs on average (sum of the scenario probability divided by the total number of scenarios).

Additionally the following aspects are taken into account:

- After the explosive cloud has reached a location, some time is needed before the combustible gas will be able to disperse into or below a vehicle and as a result ignition can take place. We take this into account by defining a delay time \( t_d \).

- Outside the tunnel (\( x < 0 \), of \( x > L_T \)) the cloud quickly dilutes. Here ignition cannot take place, and there’s no contribution to the ignition probability.
CASE STUDIES

Introduction

Different cases are considered to illustrate the calculation procedure and the resulting ignition probability of a flammable mixture and the corresponding overpressure in a tunnel for a given accident. The considered cases are introduced in Table 2 and the parameters are divided into two categories: the dispersion and probability parameters.

Case 1 refers to an 80% filled 60 m³ LPG tank, from which 50 m³ of LPG is instantaneously released. Assuming a flash fraction of 0.5 and an expansion ratio of 260, the gaseous fuel volume is 6500 m³ which is then free to disperse in the tunnel. Case 2 refers to a nearly empty (1% filled) tank of LPG at its vapour pressure of 730 kPa (at a temperature of 288 K). In this case the volume of the evaporated gas (expanded to ambient pressure) is 438 m³. Case 3 refers to the situation where the 60 m³ LPG tank ruptures partially and the LPG leaks out at a rate of 30 kg/s. Assuming a flash fraction of 0.5 the leaking rate of the gaseous fuel is 15 kg/s until the complete amount of LPG has leaked out.

Table 2  Parameters considered for the three cases.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release type</td>
<td>instantaneous</td>
<td>instantaneous</td>
<td>continuous</td>
</tr>
<tr>
<td>Volume of fuel (m³ gas at ambient conditions)</td>
<td>6500</td>
<td>438</td>
<td>N/A</td>
</tr>
<tr>
<td>Mass of LPG (kg)</td>
<td>N/A</td>
<td>N/A</td>
<td>12 500</td>
</tr>
<tr>
<td>Density of gas fuel (kg/m³)</td>
<td>N/A</td>
<td>N/A</td>
<td>1.9</td>
</tr>
<tr>
<td>LPG leak rate (kg/s)</td>
<td>N/A</td>
<td>N/A</td>
<td>30</td>
</tr>
<tr>
<td>Ventilation velocity (m/s)</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Tunnel cross section (m)</td>
<td>5 x 14.4</td>
<td>5 x 14.4</td>
<td>5 x 14.4</td>
</tr>
<tr>
<td>Tunnel length (m)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Car density (cars/m)</td>
<td>0.05*</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Probability of a single car*</td>
<td>0.001, 0.007</td>
<td>0.001, 0.007</td>
<td>0.001, 0.007</td>
</tr>
<tr>
<td>Ignition delay (s)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

* The ignition probability of a single car which remains in a combustible mixture for one second.
# Arbitrary value

The tunnel size has a cross section of 14.4 m x 5 m and a length of 1 km. The accident takes place at the entrance of the tunnel. A ventilation speed of 2 m/s is considered in the direction of the traffic. The probability parameters are identical for the three cases. A car density of 0.05 car/m (or 5 cars / 100 m) is considered. This is a rather low value which does not reflect the car density in case of a traffic jam. However, this value was chosen in order to illustrate cases with and without ignition in the tunnel. $P_{\text{single car}}$ is defined as the probability of ignition caused by a single car which remains in a combustible mixture for one second. Two values are considered: 0.001 and 0.007. An ignition delay is set at 5 s, which implies that the probability of ignition during this time is null.

The simulation results for the three cases are presented in the following sections. The results consist of the evolution of the gas concentration profile until the cloud exits the tunnel, the flammable cloud length and position, the overpressure in case of ignition, the cumulative ignition probability of the flammable cloud and the ignition probability density function.

Case I: Instantaneous release, filled LPG tank and Case II: nearly empty LPG tank.

In this section both scenarios are presented and discussed in parallel to highlight the differences. The gas concentration profiles at different times after the rupture of the tank are displayed in Figure 6. In this figure the UFL and LFL are also shown as dashed lines. Due to the large amount of fuel released in Case 1, most of the mixture concentration remains above the UFL until it reaches the exit of the tunnel. At any given time, there are therefore two flammable clouds (leading and trailing clouds) where the gas concentration is between the LFL and UFL. For Case 2 only initially there are two flammable clouds, but they merge quickly and a long explosive cloud is formed.
The positions and the length of the flammable clouds are shown in the sets of top two graphs of Figure 7. The cloud position is defined as the centre location of the flammable cloud. Considering Case 1 the flammable cloud length, the trailing and leading flammable clouds start to develop 66 s and 124 s after the rupture of the tank, respectively. The two clouds are not symmetrical due to the presence of the ventilation on the gas dispersion. The leading and trailing flammable clouds exit the tunnel at a time of 454 s and 563 s, respectively. The overpressure corresponding to the flammable cloud length at the different times is shown in the third graph from the top. The maximum overpressure (310 kPa) is reached when the trailing flammable cloud reaches the exit of the tunnel. The cumulative ignition probability of the flammable cloud is presented in the fourth graph from the top for the two values $P_{\text{single car}}$. This graph shows that $P_{\text{cumul}} = 0.5$ when the trailing flammable cloud reaches the end of the tunnel for $P_{\text{single car}} = 0.001$. In this case ignition in the tunnel occurs half of the time. For $P_{\text{single car}} = 0.007$ there is a cumulative probability of 1 that ignition occurs in the tunnel. The probability density function for both profiles is displayed on the bottom graph of Figure 7.

The same information is given for Case 2 at the right hand site of Figure 7. The merging of the two flammable clouds produces a single cloud length of 80 m which coincides with the cloud length that generates a detonation wave. Therefore the overpressure sharply rises to the detonation overpressure when the two clouds merge. The cumulative ignition probability of the flammable cloud and the probability density function are presented in the bottom graphs for the two values $P_{\text{single car}}$.

![Figure 6: Gas concentration profiles at different times. Left: Case 1 (instantaneous release, 500 m$^3$), Right: Case 2 (instantaneous release, 438 m$^3$).](image)

It is possible to divide the complete cloud dispersion into a number of (sub)scenarios. Considering $P_{\text{single car}} = 0.007$ the cumulative ignition probability can be divided into 10 scenarios as shown in Figure 8. Each scenario has an equal ignition probability of 10%. For each scenario the corresponding flammable length of the cloud and the resulting overpressure are taken at the mid-point of the time interval. These results are listed in Table 3 for $P_{\text{single car}} = 0.001$. Some (sub)scenarios result in leading and trailing flammable clouds. For these cases the ignition probability is provided for each individual cloud (leading & trailing clouds, respectively). The similar data for the higher ignition probability $P_{\text{single car}} = 0.007$ is not given in this paper, but also from the data in Figure 7 it is evident that at higher ignition probability shorter clouds are ignited and the probability of a gas explosion increases but the strength reduces.

The probability for the different scenarios in Case 2 are given in Table 4. The results clearly show that the gas explosion risks of an accident with an almost empty vessel is much higher than the accident with the full tank. A striking result that might be counter intuitive, but it is a direct consequence of the size of the explosive cloud that is formed and thus from the release and tunnel conditions.
Figure 7 Flammable cloud position, flammable cloud length, overpressure, cumulative ignition probability and ignition probability density function for Case 1 Left (instantaneous release, 6500 m³). Case 2 Right (instantaneous release, 438 m³)

Table 3: Relative probability for different scenarios; Case 1 (instantaneous release, 6500 m³) and \( P_{\text{single car}} = 0.001 \).

<table>
<thead>
<tr>
<th>( P_{\text{scenario}} ) (10% bins; see Fig.8)</th>
<th>Leading flammable cloud Length (m)</th>
<th>Leading flammable cloud Overpressure (kPa)</th>
<th>Trailing flammable cloud Length (m)</th>
<th>Trailing flammable cloud Overpressure (kPa)</th>
<th>Statistical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>7</td>
<td>52</td>
<td>8</td>
<td>61</td>
<td>mean</td>
</tr>
<tr>
<td>2.6 &amp; 7.4</td>
<td>10</td>
<td>81</td>
<td>19.5</td>
<td>188</td>
<td>mode</td>
</tr>
<tr>
<td>3.1 &amp; 6.9</td>
<td>13</td>
<td>112</td>
<td>22.5</td>
<td>228</td>
<td></td>
</tr>
<tr>
<td>3.4 &amp; 6.6</td>
<td>25</td>
<td>264</td>
<td>27.5</td>
<td>301</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>55</td>
<td>flammable cloud is outside of the tunnel without ignition</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 8 Division of the complete process into 10 (sub)scenarios for Case 1.

Table 4: Relative probability for different scenarios; Case 2 (instantaneous release, 438 m³) and \( P_{\text{single car}} = 0.001 \).

<table>
<thead>
<tr>
<th>( P_{\text{scenario}} ) (10% bins)</th>
<th>Leading flammable cloud</th>
<th>Trailing flammable cloud</th>
<th>Single flammable cloud</th>
<th>Statistical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length (m)</td>
<td>Overpressure (kPa)</td>
<td>Length (m)</td>
<td>Overpressure (kPa)</td>
</tr>
<tr>
<td>0.7 &amp; 9.3</td>
<td>1</td>
<td>4</td>
<td>12.5</td>
<td>106</td>
</tr>
<tr>
<td>3.5 &amp; 6.5</td>
<td>15</td>
<td>134</td>
<td>27.5</td>
<td>301</td>
</tr>
<tr>
<td>4.0 &amp; 6.0</td>
<td>23.5</td>
<td>242</td>
<td>36</td>
<td>442</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

flammable cloud is outside of the tunnel without ignition

Case 3: Continuous release at 15 kg/s

The evolution of the gas concentration for a continuous release of 15 kg/s is shown in Figure 9. Approximately 435 s are required for the complete amount (12 500 kg) of liquid propane to leak out of the tank. Therefore the 100 s and 300 s profiles presented in Figure 9 (right) show the leading edge of the cloud, but it is only with the other profiles (500 s, 700 s and 900 s) that the trailing edge can be observed. The resulting mixture produced by a ventilation of 2 m/s and a liquid propane leak rate of 30 kg/s (or gaseous leak rate of 15 kg/s) is such that the gaseous fuel concentration is 5.4 % which is between the LFL and UFL boundaries. The flammable cloud length is therefore significantly greater than the previous cases and this can be observed in Figure 9. Consequently the cumulative ignition probability increases rapidly and the peak of the probability density function is obtained soon after the start of the gas release.

Results summary

The results of the three cases are summarized in Table 5 where the mode, median and mean overpressure values are provided for both \( P_{\text{single car}} = 0.001 \) and \( P_{\text{single car}} = 0.007 \). For the cases where two flammable clouds co-exist (such as Case 1), the cloud that generates the larger overpressure is considered for the mode, median and mean values. In general the overpressure levels from \( P_{\text{single car}} = 0.007 \) are lower than for \( P_{\text{single car}} = 0.001 \) for the same case. Furthermore the case of a continuous release provides the worst resulting overpressure levels.
Figure 9  (Left) Flammable cloud position, flammable cloud length, overpressure, cumulative ignition probability and ignition probability density function for Case 3 (continuous release at 15 kg/s); (Right) Gas concentration profiles at different times for Case 3 (continuous release at 15 kg/s).

Table 5: Mode, median and mean values for the different cases.

<table>
<thead>
<tr>
<th></th>
<th>P_{single}car</th>
<th>Mode</th>
<th>Median</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 (instant. release, 6500 m³)</td>
<td>0.001</td>
<td>264</td>
<td>N/A</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td>0.007</td>
<td>134</td>
<td>163</td>
<td>169</td>
</tr>
<tr>
<td>Case 2 (instant. release, 438 m³)</td>
<td>0.001</td>
<td>1612</td>
<td>1700</td>
<td>442</td>
</tr>
<tr>
<td></td>
<td>0.007</td>
<td>188</td>
<td>221</td>
<td>256</td>
</tr>
<tr>
<td>Case 3 (contin. release at 15 kg/s)</td>
<td>0.001</td>
<td>1700</td>
<td>1700</td>
<td>1700</td>
</tr>
<tr>
<td></td>
<td>0.007</td>
<td>1290</td>
<td>1678</td>
<td>1700</td>
</tr>
</tbody>
</table>

CONCLUSIONS

A tunnel accident with a transport of combustible liquefied gases may result in a gas explosion after dispersion and delayed ignition. Quantification of the risk of this scenario is important to take informed decisions on tunnel design and routing of dangerous goods. In a risk analysis both the consequences and the probability of occurrence have to be considered. For this reason TNO has
extended its model for dispersion and gas explosion overpressure with an ignition probability model. The model has been illustrated with three case studies. In these case studies it has been assumed that the ventilation speed is in the direction of the traffic, and that the ignition probability is dominated by vehicles. These assumptions together imply that the accident scenario of a truck driving into a traffic jam is the most relevant to consider. In this case the explosive cloud will potentially meet a large number of vehicles (ignition sources). The scenario, in which the traffic dilutes in front of the accident will yield a small (if not zero) ignition probability, and has not been considered.

Case studies with an instantaneous LPG release show that the cloud is initially too fuel-rich to be ignited. Subsequently the gas concentration either remains mostly fuel-rich by the time the cloud reaches the end of the tunnel or falls within the flammability limits before the tunnel exit, depending on the initial amount of fuel released. A case study with a continuous LPG release shows that depending on the release rate and the ventilation speed, the tunnel may be completely filled with a combustible fuel-air mixture. The simulations provide the overpressure for different scenarios linked with their probability of occurrence. A higher basic ignition probability (per car per second), generally leads to lower overpressures. This is caused by the fact that for a higher basic ignition probability the cloud ignites earlier, at a time when the cloud is less developed.

The case studies clearly show the capability to quantify consequences and probabilities for various accident scenarios. The case studies also show that this level of detail is needed to make consistent predictions.

REFERENCES


Rolf Mellum, Head of the Road Department
Accident Investigation Board Norway (AIBN)

Abstract

The paper describes facts, analyses and results of public investigations of four major fires during the period 2011 to 2015 in Norway. These fires occurred in long single tube tunnels. Among these fires are one in a heavy goods vehicle in the Oslofjord tunnel on 23 June 2011 and a fire in a heavy goods vehicle in the Gudvanga tunnel on 5 August 2013. On 15 July 2015 a trailer loaded with petrol caught fire in the Skatestraum tunnel and, and on 11 August 2015 another fire occurred in the Gudvanga tunnel, this time in a tourist coach. Since the investigations of these two most recent fires not are finished, only limited information about these incidents will be provided. Lessons learned and proposals for improvements from these fires are given.

Keyword: Road tunnel, accident investigation, fire.

Introduction

During the period 2011 to 2015, there have been four major fires in long single tube tunnels in Norway. Nobody died in these fires, but many sustained serious smoke injuries. The fact that there were no fatalities can be seen that due to a combination of coincidence and huge efforts by individuals.

The Accident Investigation Board Norway (AIBN) investigate all these four fires. Two of them are complete, and two are still under investigation. The completed one are both heavy goods vehicles, one that started to burn in the Oslofjord tunnel on 23 June 2011 and one in the Gudvanga tunnel on 5 August 2013. Further two that are still under investigation are the one that started on 15 July 2015, a trailer loaded with petrol caught fire in the Skatestraum tunnel and, the one that started in a tourist coach on the 11 August 2015 in the Gudvanga tunnel. This fire occurred in the same tunnel as the heavy goods vehicle in the 2013. Since the investigation of these two most recent fires not are concluded yet, only limited information will be provided about these incidents.

The investigations show the need for, and the importance of, facilitating self-rescue to avoid serious injuries when such tunnel fires occur. The self-rescue principle, i.e. that the tunnel users have to initiate the evacuation themselves, is applied in most road tunnels in the world. When fires occur in long single tube tunnels, it is demanding for the fire brigade to prioritize between evacuation and rescue of road users on the one hand, and extinguishing efforts on the other. This dilemma is highlighted in these investigations. Through methodical analyses of the sequence of events and underlying factors, the AIBN has identified several safety problems related to the cause of fires, and to extinguishing and rescue work.

The sequence of events in the first two fires is first described separately. Some documented and ascertained facts from the two most recent fires that occurred in 2015 are also included. This is followed by a description of the identified safety problems and a presentation of the conclusions and
submitted safety recommendations. Similarities and differences between the fires in the Oslofjord tunnel and the Gudvanga tunnel are then described.

The final part discusses important findings made in both investigations and some reflections concerning the importance of carrying out thorough investigations of such incidents for the purpose of learning and improvement.

ACCIDENT INVESTIGATION BOARD NORWAY

Mandate
The Accident Investigation Board Norway (AIBN) is a public committee of inquiry. The purpose of AIBN investigations is to clarify the sequence of events and factors, which are assume to be of importance for the prevention of transport accidents.

Investigations are regulated by an own legislation, and it is a fundamental aim to contribute to higher safety. The AIBN shall not apportion blame or liability. All persons involved are obliged to give information to AIBN, but also protected against self-incrimination by law. More information about AIBN is to retrieve at our website.

Organisation
The board is multimodal and it is a National Safety Board for aviation, rail, road and marine accidents. It is organized in four Departement’s – one for each transport mode and has a common Director and common administration.

FACTUAL INFORMATION FROM THE FIRES

Fire in a heavy goods vehicle the Oslofjordtunnel June 2011.

The triggering event:
On 23 June 2011, at approximately 14:33, a heavy goods vehicle carrying approximately 22,000 kg of paper drove onto the Rv 23 road and through the western entrance to the 7,2001 m long Oslofjord tunnel. (Figure 1) The driver mainly used the trailer’s retarder to maintain an even speed along the 7% descent to the bottom of the tunnel. The vehicle’s retarder was not connect to the brake lights at the rear of the semi-trailer. The driver therefore touched the brake pedal to warn the vehicles behind with the brakesignals. According to the driver, he held a speed of 70–80 km/t down the 2,500 m long descent to the bottom of the tunnel.

As the heavy goods vehicle entered the dip in the tunnel, the driver accelerated to maintain the flow of traffic and climb the ascent at a higher speed. Some way up the ascent towards the Drøbak side, the driver changed to the sixth gear. Just after, he heard a loud metallic rumbling noise coming from the engine. Shortly after the driver heard the noise and stopped the vehicle.

The driver was then approximately 1,745 m from the tunnel exit on the Drøbak side. He activated the flashing warning lights and applied the emergency brake. The vehicle stopped right next to the door of an emergency phone booth. At the same time, the driver of another heavy goods vehicle came alongside and used the radio to inform the driver of the accident vehicle that that a fire had broken out under that vehicle’s driver’s cabin.

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1 According to the emergency response plan for the tunnel.
2 Retarders are a supplement to the ordinary friction-based wheel brakes and are activated from the driver’s seat. The driver can decide how much braking action to apply.
Extinguishing, evacuation and rescue

At approximately 14:36, the driver left the driver’s cabin on the right-hand side and immediately initiated extinguishing (Figure 2). Despite his persistent efforts, it was not possible to gain control of the fire. He used one fire extinguisher from the vehicle and two from the tunnel (see Figure 2), but they did not have sufficient capacity to extinguish the fire.

The fire ventilation system was activated about 4 minutes after the Road Traffic Centre (VTS) registered the fire in the lorry truck. The ventilation direction was predefined based on the fire department's extinguishing effort, resulting in 5.5 km of the tunnel got filled with thick, black smoke at a speed of 2-3 m/s.

The danger to road users was exaserated by the tunnel's safety equipment and emergency preparedness solution not being sufficiently designed for self-rescue. There was only one escape tunnel (3480 meters away from the location of the fire) in addition to the tunnel exits and no smoke-proof evacuation rooms. In addition, many road users did not receive information from the VTS via radio on time to turn/evacuate before being trapped in the smoke.

The fire brigade extinguishing from the Drøbak side functioned in a satisfactory manner and as expected. Mostly the whole vehicle and trailer burned out, but the brigade extinguished the fire in the some rolls of paper. The rescue effort from the Hurum side encountered major problems due to the smoke development, risk of collisions and the distance to the fire location. 25 of 34 road-users exited the tunnel under own power. Nine road-users got later evacuated from the tunnel by rescue crews. The overview VTS had through CCTV monitoring of the tunnel and direct contact with road users in the SOS boxes, in addition to the emergency services’ fire and rescue efforts, saved lives that day.

Fire in a heavy goods vehicle on the E16 road in the Gudvanga tunnel August 2013 (1)

The triggering event:

At 9:30 on 5 August 2013, a heavy goods vehicle belonging to the Polish transport company P.H.U. KAJ left Bergen bound for Malmø in Sweden. The vehicle did unload goods at Hansa brewery in Bergen, and was returning empty together with another Polish heavy goods vehicle that was also going to Malmø. The drivers of the two vehicles were in radio contact with each other and headed east along the E16. When they approached Vinje, approximately 20 km west of Voss, they stopped because the driver of the heavy goods vehicle that was following the same route as the P.H.U. KAJ vehicle though he saw smoke coming from the other heavy goods vehicle. After a brief stop, they drove on, as they had concluded that what had appeared to be smoke must be steam from the exhaust pipe because the road surface was wet from rain.

When they arrived at Gudvangen, the two heavy goods vehicles stopped at a petrol station near the entrance to the Gudvanga tunnel. There they had a cup of coffee and topped up their water bottles before continuing along the E16 road and into the Gudvanga tunnel in the direction of Aurland.
Approximately six kilometres after entering the tunnel, the driver of the P.U.H. KAJ vehicle noticed that he was losing engine power. After another two kilometres, he had to stop. (Figure 3)

He pulled in to the right, turned on the hazard warning lights and came out of the vehicle. That was when he saw flames below the driver's cabin on the left side (Figure 4). The driver first tried to put out the fire using a 6 kg fire extinguisher that he had in the vehicle, but could not do so before the extinguisher was empty. He then tried to get hold of more fire extinguishers, but none of the other vehicles close by had any available. Nor were there any fire extinguishers in the tunnel near the place where the vehicle had stopped. When interviewed by the police, the driver said that he had asked people in the nearest vehicles to notify the police and the ambulance and fire services.

**Figure 3:** Map showing the incident site.  
*Source: Road map, the NPRA*

**Figure 4:** The heavy goods vehicle in an early phase of the fire. *Photo: Monika Blikås*

**Extinguishing, evacuation and rescue:**
In the AIBN's opinion, regardless of the requirements and guidelines that apply to the tunnel's design, technical installations and their operation, all the factors considered in this main section had an impact on the outcome of the incident in the Gudvanga tunnel on 5 August 2013. There was inadequate fire extinguishing equipment, control faults in a ventilation system that did not work in an optimum manner, and a vulnerable radio communication network without redundancy. Furthermore, there were no possibilities for traffic control in the form of road barriers and signs, no equipment for monitoring and keeping an overview of vehicles in the tunnel, and limited evacuation possibilities. In addition, the possibility of transmitting a radio break-in message to the road users was not used during the fire. In the AIBN's opinion, the NPRA should map the robustness of other tunnels in the event of a fire in light of the weaknesses identified during this investigation.

**The road users' experience of the fire and the evacuation:**
According to the NPRA's traffic account, there were a total of 58 vehicles inside the Gudvanga tunnel at 11:58 – 43 heading towards Aurland and 15 heading towards Gudvangen when the fire start. Neither the police nor the fire or medical services logged the exact number of road users or any exact times during the evacuation of the tunnel. Based on the information AIBN has received, 67 road users could be accounted in the tunnel and that was also the number of persons who was brought to the hospital. When the final search was completed, the fire service had brought out totally 47 people to the Aurland side of the tunnel. The fire service could not get into the tunnel from the Gudvangen side, and the 20 persons who came out on this side rescued themselves.

During the period 12:00–13:20, the various emergency communication centres received several telephone calls and emergency calls from road users, and the first emergency call registered by the police at 12:23 was received was from a German driver accompanied by four passengers, including
children. At 12:53, the police received an emergency call from a caller who was walking along the tunnel wall towards the Gudvangen exit together with a seven-year-old child. The last call (13:20) to the police came from one of the first cars that had managed to turn and exit the tunnel.

Based on the interviews in the investigation the road users' experiences can be divided into three separate periods. In the first period they did not feel any danger, secondary they felt anxious and uncertain and at least they felt that they were in danger and feared for their lives. This illustrates by a couple of examples told from the road users:

One father led his family along with the rest following hand in hand. The father used one hand to feel his way along the tunnel wall while carrying a rucksack in the other. He had several harsh encounters with the tunnel wall. Once, the impact was so hard that he concussed, threw up, became confused and started to walk in the wrong direction.

One foreign family with three children chose to leave their car to evacuate by foot. Just after they left their car, two of the children (13 and 4 years old) disappeared in the smoke, and their mother and father were unable to find them. The parents placed their third child (10 years old) between them and started walking in the direction of Gudvangen. After walking for over one and a half hours, and covering a distance of approximately 8 km in conditions of minimal visibility and dense smoke, they came out of the tunnel in Gudvangen covered by soot and completely exhausted. At the time, they did not know the whereabouts of their two other children or how they had fared. They got information of that the children possibly had come out on the Aurland side of the tunnel and were being looked after at Lærdal Hospital, and later this information luckily got confirmed.

Fire in tank trailer in the Skatestraum tunnel on the Fv 616 road in Bremanger in Sogn og Fjordane county.

On 15 July 2015, a tank trailer loaded with 16,500 litres of petrol came loose from the tractor inside the Skatestraum tunnel, a subsea tunnel in Sogn og Fjordane county. The trailer hit the tunnel wall, creating a hole in one of the tank compartments. The petrol that leaked out ignited, and the fire spread to the whole trailer and large parts of the tunnel. The driver of the tank truck managed to drive the tractor out of the tunnel unharmed, while a passenger car that was evacuated was destroyed by fire. No one was seriously injured in this incident.

The tank trailer hit the tunnel wall approximately 475 meters after it started the ascent from the bottom of the tunnel. This created a hole in the tank on the trailer, from which petrol leaked out and ignited. As the fire developed, it burnt holes in all the tank compartments on the trailer. Large quantities of petrol flowed down to the bottom of the tunnel, both along the road and through the tunnel’s draining system. This caused the fire to spread over a distance of approximately 475 meters.

AIBN has completed a metallurgical examination of the coupler structure. The examination conclude 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.

Further investigation will focus on how the corrosion could develop towards complete failure without being revealed. It will also focus on how the fire developed and expanded to the bottom of the tunnel. It will also focus on how the fire developed and spread to the bottom of the tunnel.

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Information about this fire is derived from the AIBN website
On 11 August 2015, a Swedish tourist coach caught fire approximately 500 metres from the tunnel entrance on the Flåm side of the 11.4 km long Gudvanga tunnel (Figure 6). About 37 people were evacuated from the tunnel, five of them were injured by the smoke, four of them seriously.

The AIBN has gathered most of the relevant information from involved parties, the National road department and Aurland fire brigade Investigations regarding the origin of the fire has had priority, and will be described in the final report. The experience of the road users had will be limited in comparison to the report from last fire in this tunnel.

This investigation will look to the last investigation in the Gudvanga tunnel, described in ROAD Report 2015/02, and safety measures done after the last fire two years ago. Differences from the last fire will also be emphasized.

The investigation has revealed the ventilation system is automatically controlled if the fire extinguisher is taken off the wall. In this fire it resulted in a reversal of the developing smoke direction, and the road users were trapped. 30 minutes later, after a professional evaluation by the fire brigade, the ventilation direction got turned again, to release the road user from the smoke entrapment.

The AIBN means this automatic control mechanism increase the risk for the road users, and has informed the National Public Road Administration (NPRA) and Aurland Fire brigade before the investigation is completed.

Information about this fire is derived from the AIBN website
FINDINGS AND ANALYSIS.

Investigation of the fire in the Oslofjordtunnel 2011:

Through this investigation, the AIBN has uncovered five important safety problems that have contributed to weaken system safety in relation to the Oslofjord tunnel, and which resulted in road-users becoming trapped in the smoke:

Safety issues:

The Oslofjord tunnel’s safety level, through its emergency preparedness solution and safety equipment, was not satisfactory seen in relation to traffic growth and - composition.

The fire and rescue preparedness for the Oslofjord tunnel was not designed, equipped or organised in relation to what can be expected as regards location and size of fires in the tunnel.

Sufficient documentation for use of longitudinal ventilation in tunnel fires and how to effect evacuation when the tunnel is filled with smoke is not available.

The preconditions for the self-rescue principle were not sufficiently present in the Oslofjord tunnel's safety equipment and emergency preparedness solution.

The Norwegian Public Roads Administration's safety management of the Oslofjord tunnel had not captured the relevant risk situation, and the risk-based approach to safety and preparedness was deficient.

Based on this investigation, the AIBN is concerned that the fire risk in single-lane tunnels is only countered with prioritisation, which ensures a minimum safety level. The decision base for what the acceptable safety level is should be based on an assessment of the real risk situation in the specific tunnel and impact analyses of near-fires, in addition to learning from monitoring and supervision.

SAFETY RECOMMANDATIONS

The investigation of this accident has identified several areas in which the AIBN deems it necessary to submit safety recommendations for the purpose of improving road safety.5

Safety recommendation ROAD No. 2013/08T

The investigation into the fire in the Oslofjord tunnel on 23 June 2011 has shown that the preconditions for the self-rescue principle were absent as a result of the tunnel's safety equipment and emergency preparedness solution, resulting in several road-users being trapped in the smoke. The AIBN points out the lack of a comprehensive assessment of the interaction between information to road-users, safety equipment, ventilation solution/smoke control, firefighting and safe road-user evacuation (self-rescue) as a basis for the tunnel's emergency preparedness plan.

The AIBN recommends that the Norwegian Public Roads Administration, along with the Norwegian Directorate for Civil Protection (DSB) and the fire department, reviews and updates the emergency response plans for long single-lane tunnels, including the Road Traffic Centre's routines in the event of fire, to safeguard the preconditions for the self-rescue principle.

5 The investigation report is submitted to the Ministry of Transport and Communications, which will take necessary measures to ensure that due consideration is given to the safety recommendations, cf. the Regulations of 30 June 2005 on Public Investigation and Notification of Traffic Accidents etc. Section 14.
Safety recommendation ROAD No. 2013/09T:
The investigation into the fire in the Oslofjord tunnel on 23 June 2011 has uncovered that the Norwegian Public Roads Administration and DSB lacked a well-developed reporting system for monitoring and controlling fires and near-fires in road tunnels. This has led to missing reports, deficient analyses and an insufficient overview of the real safety level for the Oslofjord tunnel.

The AIBN recommends that the Norwegian Public Roads Administration and DSB establish systems for registrations of fires and near-fires in road tunnels, for use in the systematic safety work.

Safety recommendation ROAD No. 2013/10T:
At the time of the accident (23 June 2011), the safety level for the Oslofjord tunnel was not satisfactory. The AIBN basis for this assertion is the gap between the tunnel’s safety equipment and emergency preparedness solution seen against traffic volume development and composition. The AIBN is of the opinion that this is connected to the Norwegian Public Roads Administration's risk-based approach to safety and deficient emergency preparedness in the tunnel.

The AIBN recommends that the Norwegian Public Roads Administration develop its safety management system further as regards risk-based and pro-active principles to secure a satisfactory safety level for the Oslofjord tunnel and similar road tunnels.

Safety recommendation ROAD No. 2013/11T:
The lorry truck fire in the Oslofjord tunnel on 23 June 2011, with a calculated fire effect of 70 – 90 MW, was extinguished in a satisfactory manner in spite of the tunnel and the capacity of the fire and rescue services only being dimensioned for a fire effect of 50 MW. The investigation has shown that the maximum fire effect for lorry truck fires ranges from 50 to 150 MW, and that rescue efforts in long and steep single-lane tunnels pose great demands on firefighters and the safety equipment of the tunnel. This, and not the dimensioning requirements for the tunnel class alone, should in the AIBN's opinion form the basis for required equipment and emergency preparedness in tunnels.

The AIBN recommends that the Norwegian Public Roads Administration, along with the DSB and the fire department, follows up and dimensions the rescue and firefighting effort to realistic fire effects and the specific design of the tunnel in question.

Investigation of the fire in the Gudvangatunnel 2013

Safety issues:
In the AIBN's opinion, there were failures on four material points when 67 persons were trapped in the smoke in the tunnel and 28 persons sustained acute smoke injuries:

The tunnel was not equipped with any kind of monitoring or device for counting vehicles that could have provided continuous information about how many vehicles were in the tunnel. The Road Traffic Centre (VTS) and the fire service thereby did not have an overview of how many people were on the side of the fire towards which the smoke was ventilated.

No information was given to the road users that immediate evacuation was necessary. Only those in the immediate vicinity of the fire scene or who realised what was happening at an early stage managed to evacuate before the tunnel filled with smoke.

As a result of the pre-defined strategy for fire-extinguishing and rescue work that is set out in the emergency response plan for the tunnel, the Road Traffic Centre, immediately after the fire was reported, routinely starting the fire ventilation, so that the smoke from the fire was ventilated 8.5 km

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6 The direction and speed of the ventilation described in the emergency response plan in connection with ventilation of the tunnel in the event of fire. This definition is also used by the fire service and the Road Traffic Centre.
in the direction of Gudvangen. The smoke blocked the only possible evacuation route for the road users on the Gudvangen side of the fire.

The tunnel design and the tunnel's technical equipment did not adequately facilitate self-rescue.

RECOMMENDATIONS

The investigation of this accident has identified several areas in which the AIBN deems it necessary to submit safety recommendations for the purpose of improving road safety.7

Safety recommendation ROAD no 2015/02T:
The investigation of the fire in the Gudvangatunnelen tunnel on 5 August 2013 uncovered weaknesses in the tunnel's design and safety equipment that had a direct bearing on the rescue work and evacuation of road users. They include under-dimensioned fire extinguishing equipment, a ventilation system with a control fault, a vulnerable communications network without redundancy, inadequate traffic control, monitoring and overview of vehicles in the tunnel, and limited aids for evacuation.

The Accident Investigation Board Norway (AIBN) recommends that the Norwegian Public Roads Administration improve the safety equipment in Gudvangatunnelen tunnel in order to ensure its robustness and satisfy the requisite conditions for self-rescue.

Safety recommendation ROAD no 2015/03T:
The investigation of the fire in Gudvangatunnelen tunnel on 5 August 2013 revealed that road users were not given information that could potentially have helped them in their self-rescue efforts. Information signs and radio alerts were not used. Only those in the immediate vicinity of the fire scene or who realised what was happening at an early stage managed to evacuate before the tunnel filled with smoke. The AIBN believes that giving road users information is essential in order to comply with the self-rescue principle.

The Accident Investigation Board Norway recommends that the Norwegian Public Roads Administration and relevant fire services improve information for road users in the event of a fire in Gudvangatunnelen tunnel. Signs, radio alerts and text message notification should be considered, among other things.

Safety recommendation ROAD no 2015/04T:
The investigation of the fire in Gudvangatunnelen tunnel on 5 August 2013 revealed that five people were severely injured and 23 seriously injured by the smoke. That is much more serious than was first assumed. The smoke injuries are not registered in Statistics Norway's injury statistics for road traffic accidents or in the Norwegian Directorate of Health's register of personal injuries. The AIBN believes that personal injuries in tunnels should be systematically registered, so that this information can be used in connection with preventive work.

The Accident Investigation Board Norway recommends that the Norwegian Public Roads Administration take steps to ensure that Statistics Norway and/or the Directorate of Health include personal injuries as a result of exposure to smoke in connection with tunnel fires in relevant accident statistics.

Safety recommendation ROAD no 2015/05T
In connection with the fire in Gudvanga tunnel on 5 August 2013, the smoke was ventilated from the fire scene towards the tunnel opening in Gudvangen before the road users had a chance to evacuate from the tunnel. This resulted in 67 people becoming trapped in the smoke and 28 people suffering

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7 The investigation report is submitted to the Ministry of Transport and Communications, which will take necessary measures to ensure that due consideration is given to the safety recommendations, cf. the Regulations of 30 June 2005 on Public Investigation and Notification of Traffic Accidents etc. Section 14.
serious smoke injuries. The AIBN believes that the requisite conditions for the self-rescue principle were not met through the pre-defined strategy for fire extinguishing and rescue work as defined in the tunnel's emergency response plan. Corresponding findings were also made in connection with the fire in the Oslofjord tunnel on 23 June 2011.

The Accident Investigation Board Norway recommends that the Directorate for Civil Protection (DSB) and the fire service, in consultation with the Norwegian Public Roads Administration, revise the strategy for fire extinguishing, rescue and smoke control in long single-lane tunnels, so that, as far as possible, the fire ventilation does not come into conflict with the road users possibility of rescuing themselves.

Safety recommendation ROAD no 2015/06T
The investigation of the fire in Gudvanga tunnel on 5 August 2013 shows that the emergency services face challenges as regards notifying, coordinating, leading and cooperating along so many different interfaces in a crisis situation. The cooperation was made even more difficult as a result of the communications network that the emergency services were to use being put out of action and the fire incident commander not being in the command centre. The AIBN has identified a lack of coordination of the emergency services' response plans in the Gudvanga tunnel with respect to ensuring optimal notification, incident site command, information sharing, organisation and dimensioning.

The Accident Investigation Board Norway recommends that the emergency services involved (the fire service, health service, police) in the Gudvanga tunnel coordinate the plans for notification, incident site command, information sharing and for ensuring sufficient resources.

Safety recommendation ROAD no 2015/07T
The investigation of the fire in Gudvanga tunnel on 5 August 2013 has shown that the requisite conditions for self-rescue were not present. The weaknesses are related to inadequate safety follow-up of the tunnel. The tunnel's emergency response plan and the Road Traffic Centre's and fire service's incident response plans/procedures for call-out to the tunnel said little about what was necessary to enable self-rescue and evacuation. Aurland fire service had not prepared an incident response plan for the Gudvanga tunnel. Drills described in HB R511 were not held and the fire service's inspection of the tunnel as a special fire object was inadequate.

The Accident Investigation Board Norway recommends that the Norwegian Public Roads Administration Region West and Aurland fire service cooperate on updating and coordinating the emergency response and incident response plans for Gudvanga tunnel in order to improve the possibility of self-rescue, and carry out inspections and scenario-based drills in Gudvanga tunnel.

The fires that occurred in 2015 in the Skatestraum tunnel and the Gudvanga tunnel in 2015.

The investigation of these fires is not yet concluded, and are not ready for further presentation. Some information can nevertheless be mentioned:

The Skatestraum tunnel:
- The drawbar was ripped off near to where it was fastened to the trailer.
- The driver was very alert and rescued several road users with his behaviour.
- The fire effect was very high, 16,000 ltr of petrol burned out, and the damage to the tunnel was critical.

The Gudvanga tunnel (2)
- The fire was very similar to the fire in the same tunnel in 2013, but the fire energy was probably slightly higher this time.
- The smoke was ventilated the shortest way out of the tunnel this time, and only five persons were injured by the smoke. That was a difference from the fire in 2013.
• The evacuation was prioritized in relation to the firefighting this time.
• The coordination between the emergency services was significantly better than in 2013.

Comparison of the two fires (Oslofjord tunnel and Gudvanga tunnel 1).

Similarities:
• Both tunnels were long single tube tunnels that rise/fall at a gradient, and have no evacuation rooms.
• The fires started in the engine compartment of heavy goods vehicles that stopped inside the tunnel because of this.
• Attempts were made by the drivers of the heavy goods vehicles to extinguish the fires, but neither of them succeeded.
• The drivers managed to evacuate the tunnel without sustaining smoke injuries.
• The smoke was ventilated along the longest route and in the opposite direction to the natural draught, in accordance with a pre-defined procedure.
• The tunnels did not adequately facilitate self-rescue.
• The road users were trapped in the smoke and encountered significant hindrances in their attempts to evacuate.
• The tunnels had no evacuation rooms for road users.
• The same evacuation and rescue strategy was used, and attempts were made to extinguish the fires before the evacuation started.
• A major effort from the local fire service nonetheless helped to ensure that the road users were evacuated and that no one died, but many sustained serious smoke injuries.

Differences:
The Oslofjord tunnel
• The thermal effect of the fire was slightly higher.
• The tunnel had air-filled, smoke-free rooms behind the arch of the tunnel that the road users could get to through the emergency telephone boxes.
• The tunnel was equipped with cameras and better communications equipment, which contributed to reducing personal injuries.

The Gudvanga tunnel
• The tunnel was longer and the road users had a longer evacuation route.
• There were technical faults in the ventilation system.
• Some of the road users (28) were seriously injured.
• There were no cameras or means of communicating with the road users.

SUMMARY AND REFLECTIONS

The AIBN’s investigations of the two fires in the Oslofjord tunnel and the Gudvanga tunnel (1) have shown that there is a huge potential for improving safety in connection with fires in long single tube tunnels. The common learning points can be linked to the following common features in particular:

• The tunnels are not adequately equipped for self-rescue. This concerns several factors:
  o Limited evacuation routes for road users, a lack of evacuation rooms and self-rescue equipment.
  o Vulnerability in connection with faults and lack of redundancy in technical installations
  o Inadequate means of identifying and detecting road users who are inside the tunnels
  o Inadequate means of efficient communication with those involved in the fires
Challenges related to firefighting and evacuation are demanding, and quick decisions must be made concerning:
- Correct smoke ventilation to facilitate the road users’ self-rescue and evacuation efforts
- Flexibility in the choice of solution for evacuation and rescue operations.

Better coordination between the rescue services is essential in order to avoid unnecessary loss of time and ensure optimum solutions for the rescue work.

Reflection about investigating these fires:

Fires in tunnels are very serious incidents with a severe injury potential, and always a traumatic experience for those affected. For many years, the focus on safety in connection with such incidents has varied among other things, because they have involved few deaths compared with road traffic accidents in general.

The fires discussed in this paper have been, and continue to be, the topic of public investigations by the Norwegian Investigation Authority, who has a mandate to perform such investigations. The result shows that the learning potential is considerable, but also that the outcome of the investigations depends on the quality of the work performed. Involve and contribution of all parts and affected parties in the incident is important in to shedding light.

This is challenging work, and can only succeed through carefully and properly managed relations with the affected parties. In order, for society to learn and benefit from the work, it is important that those who can improve safety address the issues in a positive way, and that everyone is able to identify with the descriptions, even if not findings, analysis and conclusions are easy to deal with.

We hope that this paper and the information presented herein can help other nations to see the value of independent, public investigations in the road sector, on a par with those in other transport sectors where international regulations are already in place.

REFERENCES

Statistical Analyses of Breakdowns, Accidents and Fires in Road Tunnels in France

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ABSTRACT

The statistics relating to breakdowns, accidents and fires in road tunnels and the lessons they provide are crucial to the risk analyses for these structures and for research into safety. Therefore, the Centre for Tunnel Studies undertook a project concerning these statistics. In an initial phase, data was collected directly from the tunnel operator’s control centres. In a second phase, incident rates were established. Then, statistical analyses were carried out so as to determine the influence of different parameters on incident rates. Within this project, a specialized multiple regression method was used for the first time in the French road tunnel environment. The CETU called on the consulting firm “BG Ingénieurs Conseils” to contribute to this project, along with the Chair of Statistics of the Federal Polytechnic of Lausanne. The study covered 96 tunnels in France and 25 control centres. Around 25,000 incidents were thus collected for the 2002-2011 period (breakdowns: 79%, damage-only accidents: 17%, personal injury accidents: 3%, fires: 1%). In all 96 tunnels, during the 2002-2011, the overall breakdown rate is 279/108 veh.km, the overall accident rate is 41/108 veh.km, the overall fires rate is 1.1/108 veh.km. More in-depth statistical analyses showed that:

• the urban character, a significant proportion of HGVs or a pronounced upwards gradient increased the high rate of breakdowns.
• a unidirectional traffic flow or a high absolute gradient value resulted in a higher accident rate. the higher the upwards gradient value, the higher the fire rate.

Accident severity (rate of personal injury accidents, injured and killed) in road tunnels is lower than in open-air sections. Deaths following a fire mainly occurred when the fire was the result of an accident. They are therefore the consequence of the accident and not the fire.

KEYWORDS: breakdown, accident, fire, injury and death rates, influencing parameters, simple regressions, multiple regressions.

INTRODUCTION

The statistics relating to breakdowns, accidents and fires in road tunnels and the lessons they provide are crucial to the risk analyses for these structures. They are also a data source for studies and research into safety management and continuous safety improvement.

Numerous countries, including France, are aware of these issues and therefore pay special attention to producing these statistics. Analysing these statistics and in particular seeking influencing parameters is tends to be a common goal for all such work.

It is within this context that the Centre for Tunnel Studies undertook a project intended to fulfil two main requirements.
Firstly, the statistics available in France to date needed to be supplemented and updated and then compared with the statistics for the open air and statistics from other countries.
Secondly, existing studies to determine influencing parameters (especially the 1998 French report) needed to be taken further in-depth, through the unprecedented use of specialized methods in tunnel
statistics. The existing studies in the field sometimes raised doubts and/or contradictions.

The CETU called on the consulting firm “BG Ingénieurs Conseils” to contribute to this project, along with the Chair of Statistics of the Federal Polytechnic of Lausanne for the specialized methods.

Section 1 of the article will describe the scope and procedure for collecting data, notably the work in processing these data. Section 2 will explain the methods used for the statistical analysis of these data. Special attention will be paid to the in-depth analyses based on a specialized method. The statistical sample was diverse enough for the method to be able to isolate and study the influence of certain parameters. The next three sections will focus on the three types of incidents studied: breakdowns, accidents and fires. They will present occurrence rates (number of incidents per vehicle-kilometre), with figures on the severity if appropriate. Relevant comparisons will also be made with the open air. The main results of the statistical analysis will also be presented.

DATA COLLECTION

Collection scope
The data was collected from a panel of 96 tunnels managed from 25 control centres and owned by 21 tunnel operators. Only tunnels with a sufficient level of monitoring to detect incidents reliably were included so as to not introduce any statistical bias. The 96 tunnels included represent approximately 70% of the total length of all the tunnels longer than 300m on the French road network (the only tunnels subject to specific safety regulations). This high number of tunnels was chosen to ensure that the collected data sample allowed reliable statistics at a French level.

Data was collected for incidents that occurred over a ten-year period (2002-2011).

Collection procedure
The project teams collected the data by going to the different control centres in order to exhaustively process the available data and communicate with the operators.

The data regarding approximately 40,000 incidents was collected after a first filtering of several hundred thousand incidents from the incident logs. This filtering enabled the elimination of incidents outside the scope of this study, especially those occurring outside the tunnel and all technical incidents. Factual information regarding the tunnels in question and their environment was also collected.

This data was then processed so as to:
- remove that which contained too much uncertainty or was not representative, (e.g. data on tunnel works during which the tunnel was not operating normally or periods with non-usual operating process).
- re-categorize certain incidents (for example, fires re-categorized to simple smoke release),
- exclude the periods (months or years) with incomplete feedback;

Other French databases regarding personal injury accidents and fires were also used in order to verify the data. 25,000 incidents were finally retained.

The three filters produced a better quality of statistical sample and thus ensured the reliability of all statistics produced on this basis.

STATISTICAL TREATMENT: FORMULA AND METHODS

Rate calculation
The rate was calculated for each type of incident (breakdowns, accidents and fires) for all tunnels.

It was also calculated for every sub-category, with a distinction being made in terms of the urban/non-urban or unidirectional/bidirectional character of the tunnel.
Indeed French regulations differentiate tunnels according to these two characteristics.

The rates given in this article are for the entire period (2002-2011). The various processes applied to ensure the reliability of data meant that in some cases all the incidents in a given year were excluded from the data collected. This was the case, for example, when work had been going on in the tunnel for several years.

For incident type E and period A, the formula used was therefore:

\[
\frac{\sum_{T} \text{NumberOfIncidents}_{E,A,T} \times R_{E,A,T}}{\sum_{T} \text{vehicles} \cdot \text{km}_{A,T} \times R_{E,A,T}}
\]

(1)

with \( R_{E,A,T} \) equal to 0 if period A had been excluded (see collection process), otherwise 1. This calculation principle was applied regardless of the period considered.

**Simplified statistical analysis**

These analyses involved studying the influence of a parameter on the incident rate, by calculating the rate based on its variations. This method is based on simple regressions.

The parameters retained were: length, traffic, type of traffic flow (unidirectional or bidirectional), urban or non-urban, number of HGVs, speed limit, gradient, the tunnel operator's control centre and the number and width of lanes.

This approach has one main limitation.

Certain parameters are inter-correlated, which introduces a statistical bias. The study of rate variations for each parameter studied therefore allows no conclusion to be drawn as to the specific influence of the parameter itself. It is therefore not possible to state that the variation in the rate comes from the parameter studied and not from other parameters with which it is correlated. For example, a tunnel with a speed limit of 50 km/h is often urban, with characteristics specific to this type of tunnel (normally low percentage of HGVs and heavy traffic flow).

Thus, although this method shows an apparent influence of a parameter on an incident rate, it cannot be concluded scientifically that a correlation exists between this parameter and the incident rate.

This simplified approach could thus lead to establishing tunnel typologies that are as homogeneous as possible, with each typology being characterised by a set of inter-correlated parameters.

**In-depth statistical analysis: specialized method**

The in-depth statistical analysis was based on a more sophisticated method and complemented the one used for the simplified statistical analysis. This method is based on multiple regressions. It is confirmed by mathematical theory and use in many fields. It enables several parameters to be studied together (the same as for the simplified analysis). The statistical sample was diverse enough for the method to be able to isolate and study the influence of certain of these parameters.

The method can therefore ensure that there is indeed a correlation between the noted trend (influence on the rate) and the variation in the parameter studied. It can invalidate or confirm the conclusions of the simplified statistical analysis, and even modulate or complete them.

Regression analysis is based on the hypothesis that incidents occur randomly. The number of incidents during a certain period of time can be defined by a random variable \( X \) that follows a law \( L \). Regarding the choice of the law \( L \), for example to model the occurrence of fires, which are the rarest
events, preliminary tests showed that Poisson’s equation was especially suitable. Similarly, these tests showed that the Negative Binomial and Quasi-Poisson models modelled the occurrence of breakdowns and accidents well, given that globally an over-dispersion is noted for these types of incident.

The hypothesis is also made that the average value of the law is defined entirely by the influence parameters adopted, i.e. 

\[ E[X] = f(\text{parameter 1, parameter 2, etc.}) \]

This then involves determining the function \( f \) which, based on each parameter, provides the number of events closest to the number of events actually collected. The characteristics of this function explain the influence of parameters.

Based on [1] and [2], a multiplicative structure was chosen for \( f \).

For fires, for example, this resulted in the average value taking the form:

\[
E[X] = \text{Traffic}^{\beta_{\text{Traffic}}} \times \text{Length}^{\beta_{\text{Length}}} \times \text{SpeedLimit}^{\beta_{\text{SpeedLimit}}} \times e^{\beta_{\text{Gradient}}} \times e^{\beta_{\text{HGVRate}}} \times e^{\beta_{\text{HGVRate}}} \times \prod_{\text{Control Centre}} e^{\beta_{\text{Year}}} \times \prod_{\text{Year}} e^{\beta_{\text{Year}}}
\]

Where,

- Traffic flow: is the number of vehicles passing through the tunnel during the period studied (case of fires),
- Length: is the length of the tunnel,
- SpeedLimit: is the speed limit in the tunnel,
- LaneN: is the number of lanes in each tunnel direction,
- LaneW: is the lane width inside the tunnel.

In this formula,

\[
f = \text{Traffic}^{\beta_{\text{Traffic}}} \times \text{Length}^{\beta_{\text{Length}}} \times \text{SpeedLimit}^{\beta_{\text{SpeedLimit}}} \times e^{\beta_{\text{Gradient}}} \times e^{\beta_{\text{HGVRate}}} \times e^{\beta_{\text{HGVRate}}} \times \prod_{\text{Control Centre}} e^{\beta_{\text{Year}}} \times \prod_{\text{Year}} e^{\beta_{\text{Year}}}
\]

Each coefficient \( \beta_X \) translates the influence of parameter \( X \).

The validity of the model was verified using the Akaike information criterion and the residuals analysis.

In practice, formula (2) gives a very direct view of the influence of the variation in a single parameter on the average number of expected incidents \((E[X])\), once all the \( \beta \) have been estimated. Following preliminary tests, a proportionality link was established between tunnel length and the number of incidents and between the traffic flow and the number of incidents. This link enables a change in rationale, preferring a rate-based rationale to a rationale based on incident numbers.

Initially, all the available parameters deemed relevant in the occurrence of incidents were used, then an iterative approach was applied to select the most relevant parameters.

The method concluded that a parameter has significant influence when it is highly unlikely that the result can be reached by chance. Statistical significance thresholds are used to quantify this notion: 5%, 1% and 1‰. For example, a 5% significance threshold means that the result has a less than 5% possibility of being due to chance. The lower the statistical significance threshold, the greater the credit given to the corresponding result. A result is deemed statistically insignificant if it is higher than the 5% threshold.
Highlighting influencing parameters and combining the two approaches

The simplified analysis was applied first. It highlighted a certain number of parameters which would appear to influence the incident rate.

The in-depth statistical analysis was then applied. It was based on a more sophisticated method than the simplified statistical analysis method. Thanks to a sufficiently diverse statistical sample, it was able to isolate certain parameters and determine their influence. Unlike the simplified statistical analysis, it thus prevented the correlations between parameters from biasing the influence of the parameter in question. The in-depth analysis thus confirmed or invalidated the influence of some of the parameters identified by the simplified statistical analysis. On one occasion, it enabled the identification of new parameters with influence.

The in-depth analysis was used to study the statistical significance of the influence of parameters.

For reasons explained at the end of this article, despite the mathematical rigour of methods used, these results and their analyses must be considered with caution and take into account statistical significance thresholds.

Additional analyses will be performed in France to broaden the understanding of the influence of parameters.

MAIN LESSONS ABOUT BREAKDOWNS

Statistical results

The overall breakdown rate in all tunnels during the 2002-2011 period is 279 breakdowns/10^8 veh.km. The sub-category rates relating to the unidirectional/bidirectional and urban/non-urban parameters are presented in Table 1. French regulations use these two parameters to make a distinction between tunnel types. The corresponding results (see Table 1) must be viewed with caution, as the differences between categories may come from characteristics specific to each parameter.

Table 1- breakdown rate according to unidirectional/bidirectional and urban/non-urban parameters

<table>
<thead>
<tr>
<th>Type of tunnel</th>
<th>Rate [breakdowns/10^8 veh.km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional</td>
<td>267</td>
</tr>
<tr>
<td>Bidirectional</td>
<td>335</td>
</tr>
<tr>
<td>Urban</td>
<td>310</td>
</tr>
<tr>
<td>Non-urban</td>
<td>226</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of tunnel</th>
<th>Rate [breakdowns/10^8 veh.km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban unidirectional</td>
<td>304</td>
</tr>
<tr>
<td>Urban bidirectional</td>
<td>375</td>
</tr>
<tr>
<td>Non-urban unidirectional</td>
<td>183</td>
</tr>
<tr>
<td>Non-urban bidirectional</td>
<td>317</td>
</tr>
</tbody>
</table>

Statistical analyses

The simplified statistical analysis highlighted a certain number of parameters which would appear to have an influence on the incident rate: the unidirectional/bidirectional nature, the urban/non-urban nature, number of HGVs, speed limit, gradient value and alternating types of gradient. The in-depth statistical analysis confirmed this initial analysis for the urban/non-urban nature, number of HGVs and gradient value only. The statistical significance threshold of the influence of each of three parameters is 1‰; this means that there is less than one possibility in 1000 that this influence is due to chance.

The next sections describe the influence of each of the three parameters and present the elements likely to explain these results.

With all other parameters being equal, an urban tunnel would produce a higher breakdown rate than a non-urban tunnel. This result of mathematical methods can be explained in several ways. Firstly, in an urban
environment, there are more speed variations (sometimes abrupt), occasionally sharp braking and changes in direction. The mechanical parts of vehicles (brakes and clutch especially) are therefore used far more intensely than in a non-urban environment for equivalent journey length.

With all other parameters being equal, the higher the HGV rate, the higher the overall breakdown rate (all vehicles). This result can be explained by the fact that HGVs have a breakdown rate 1.4 times higher than that of light vehicles. Their presence therefore increases the breakdown rate mathematically when all vehicles are taken into account. HGVs have a higher breakdown rate as their mechanical parts are under greater load than light vehicles, given that they are heavier and their journeys are longer. In addition, some of them may not be maintained sufficiently well to withstand this heavy load on mechanical parts. The level of maintenance can vary tremendously from one company or from one country to the next.

With all other parameters being equal, the steeper the uphill gradient, the higher the breakdown rate. This result is explained by the fact that the mechanical parts, mainly in the engines, are overall under heavier load going uphill than downhill.

**MAIN LESSONS ABOUT ACCIDENTS**

**Statistical results**

The overall accident rate in all tunnels during the 2002-2011 period is 41 accidents/10^8 veh.km. The sub-category rates relating to the unidirectional/bidirectional and urban/non-urban parameters are presented in Table 2. French regulations use these two parameters to make a distinction between tunnel types. The corresponding results (see Table 2) must be viewed with caution, as the differences between categories may come from characteristics specific to each parameter.

<table>
<thead>
<tr>
<th>Type of tunnel</th>
<th>Rate [accidents/10^8 veh.km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional</td>
<td>44</td>
</tr>
<tr>
<td>Bidirectional</td>
<td>25</td>
</tr>
<tr>
<td>Urban</td>
<td>49</td>
</tr>
<tr>
<td>Non-urban</td>
<td>16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of tunnel</th>
<th>Rate [accidents/10^8 veh.km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban unidirectional</td>
<td>50</td>
</tr>
<tr>
<td>Urban bidirectional</td>
<td>44</td>
</tr>
<tr>
<td>Non-urban unidirectional</td>
<td>19</td>
</tr>
<tr>
<td>Non-urban bidirectional</td>
<td>11</td>
</tr>
</tbody>
</table>

The annual accident victim, injury and death rates for the 2002-2011 period are presented in Figure 1.

**Figure 1- annual victim, injury and death rates for the 2002-2011 period**

The victim rates (injured or killed) are relatively stable in the 2002-2011 period except for the death rates.

The accident severity rates for all tunnels for the 2002-2011 period are presented in Table 3.
In France, during the period 2007-2011, the personal injury accident, injury and death rates are respectively 1.5, 3.7 and 2.4 times higher in the open air than in a tunnel environment (the open-air figures come from [3]). This result can be explained by the fact that the open-air road sections have accident causing or mortality factors that do not exist, or rarely, in a tunnel environment. These factors can be, for example, intersections (including crossroads), bends, access or exit ramps, climatic hazards and unlit areas. In addition, speed limits are higher in the open air than in a tunnel environment (for a given itinerary), which is an additional explanatory element.

Figure 2 shows the accident dispersion between the entry and exit portals (which have a fixed length of 100 m) and the interior zone. For greater clarity, a factor of 1 has been allocated to the interior zone and the factors relating to the portals have been established proportionally.

**Table 3- accident severity rates - period 2002-2011**

<table>
<thead>
<tr>
<th>Rate [accidents with personal injury/10^8 veh.km]</th>
<th>Rate [injured persons/10^8 veh.km]</th>
<th>Rate [deaths/10^8 veh.km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>10.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The statistical analyses highlight a certain number of parameters with an influence on the accident rate: the unidirectional/bidirectional nature, the urban/non-urban nature, number of HGVs, speed limit and the alternating type of gradient. In particular, rates for all urban tunnels are at least twice as high as the rates for all non-urban tunnels, including when the comparison is restricted to unidirectional or bidirectional tunnels.

The in-depth statistical analysis confirmed this first analysis only for the unidirectional/bidirectional parameter. The in-depth statistical analysis has also highlighted an influencing factor not detected by the simplified analysis: the absolute gradient value.

The statistical significance threshold of the influence of the unidirectional/bidirectional parameter is 1%, i.e. there is less than one possibility in 1000 that it is due to chance. The statistical significance threshold of the influence of the absolute gradient value is 1%.

The next sections describe the influence of both parameters and present the elements likely to explain these results.
With all other parameters equal, a unidirectional tunnel would produce a higher accident rate than a bidirectional tunnel. Although this result might seem surprising, it is significant according to the mathematical methods (see above). A bidirectional tunnel is normally considered to be more accident-prone, for example, as there is an additional risk of a frontal collision. In addition, the explanation cannot be found in the other parameters included in the study (notably the speed limit). The method verified that with the statistical sample available, the influence of the unidirectional/bidirectional parameter could be isolated from the other parameters.

The most plausible explanation relates to a principle currently accepted in France in terms of road safety: the car driver adapts his behaviour and driving to the perceived risk. In France, it is not just in a tunnel environment that certain accident statistics have proved surprising. Some crossroads perceived as hazardous by car drivers and which need to be dealt with in priority according to local resident associations or local political representatives have been shown to have a lower than average accident rate. Following on-site analysis of behaviours, it appeared that users were more careful and concentrated at the approach to crossroads deemed hazardous. In France, two motorcyclist fatalities out of three occurred in open countryside whereas a far higher proportion was expected in an urban environment. In seven cases out of ten, these accidents occurred during the day and eight of ten in good weather. The French Directorate for Road Safety and Traffic explains this result by the fact that once in town, the motorcyclist pays more attention to his driving, whilst in the country, out of the traffic, in daylight and on a dry road, he drops his guard (http://www.securite-routiere.gouv.fr/conseils-pour-une-route-plus-sure/le-saviez-vous/le-saviez-vous).

It is thus plausible, given these elements, that a car driver tends to behave more prudently when the traffic is bidirectional. With very few exceptions, bidirectional tunnels only have two lanes (one each way). A car driver travelling in one lane can therefore feel hemmed in by vehicles coming towards him and the side wall. This configuration can therefore give him a feeling of insecurity and encourage him to behave with prudence, thereby lowering the accident rate. Conversely, unidirectional tunnels normally have more than one lane per direction, therefore a wider road area, and no vehicles travelling in the opposite direction. These conditions can increase the risk of an accident as they prompt less vigilance, excessive speeds and even imprudent manoeuvres, for example when changing lane. In particular, it is normally possible to overtake in unidirectional structures whereas this is prohibited in a bidirectional tunnel.

Due to insufficient data, this study was not able to consider actual driver speeds. They could have been useful when analysing the influence of the unidirectional/bidirectional parameter.

Naturally, this influencing factor could not be generalised in the open air where the characteristics inherent to bidirectional roads are very different (overtaking permitted, occasionally very sharp bends, intersections including crossroads, non confined nature, etc.).

With all other parameters equal, a tunnel with a considerable absolute gradient value would have a higher accident rate. This result of mathematical methods can be explained in several ways. Firstly, driving downhill favours faster, even excessive speeds, which is a contributory factor in accidents (due to increased braking distances, degraded mutual perception of users, etc.). Secondly, when driving uphill, the difference in speed between HGVs (with their considerably reduced speed) and light vehicles is greater. This is also a causal factor in accidents.

Interestingly enough, the influence of the urban/non-urban parameter highlighted by the simplified analysis was not confirmed by the in-depth statistical analysis. One possible reason is that the influence of this parameter could not be isolated from certain others linked to it.
MAIN LESSONS ABOUT FIRES

Statistical results
The overall rate of fires in all tunnels is 1.1 fires/10^8 veh.km.
The sub-category rates relating to the unidirectional/bidirectional and urban/non-urban parameters are presented in Table 4. French regulations use these two parameters to make a distinction between tunnel types.

Table 4 - rate of fires according to unidirectional/bidirectional and urban/non-urban parameters

<table>
<thead>
<tr>
<th>Type of tunnel</th>
<th>Rate [fires/10^8 veh.km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional</td>
<td>0.9</td>
</tr>
<tr>
<td>Bidirectional</td>
<td>2</td>
</tr>
<tr>
<td>Urban</td>
<td>0.9</td>
</tr>
<tr>
<td>Non-urban</td>
<td>1.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of tunnel</th>
<th>Rate [fires/10^8 veh.km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban unidirectional</td>
<td>0.9</td>
</tr>
<tr>
<td>Urban bidirectional</td>
<td>0.7</td>
</tr>
<tr>
<td>Non-urban unidirectional</td>
<td>1.2</td>
</tr>
<tr>
<td>Non-urban bidirectional</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Annual fire rates for the 2002-2011 period are presented in Figure 3.

Figure 3- changes in annual fire rates for the 2002-2011 period

The annual fire rate is relatively stable in the 2002-2011 period.

These statistics only take into account confirmed fires, not smoke release.
There is an almost equal share of simple outbreaks and raging fires. It is important, however, to be cautious over this observation. There is in fact no standardised definition of an outbreak of fire and a raging fire. The classification criteria can therefore differ from one control centre to the next, even from one operator to the next, which is therefore likely to bias figures established for each share.

Only 10% of these fires were caused by accidents.

Fires following a personal injury accident caused three deaths, serious injuries to one person and minor injuries to fourteen persons. These victims were mainly the result of the accident and not the subsequent fire.
Fires due to another cause resulted in minor injuries to three persons and two deaths.
Statistical analyses
The simplified statistical analysis highlights a certain number of parameters with an influence on the rate of fires: the unidirectional/bidirectional nature, the urban/non-urban nature, number of HGVs and the gradient value.

The in-depth statistical analysis confirmed this first analysis only for the gradient value. It then showed that this parameter had a significant influence on the rate of fires, with all other parameters equal. The statistical significance threshold of this influence is 5%, which means that there is less than one possibility in 20 that it is due to chance.

With all parameters being equal, if the tunnel has an upwards gradient, the rate of fires will be higher. This result is explained by the fact that the mechanical parts, mainly in the engine, are overall under heavier load going uphill than downhill, which can cause spontaneous ignition of the vehicle.

METHOD LIMITATIONS
Special care was taken in all the statistical analyses performed to limit all bias as far as possible (by cross-checking analyses, purging insufficiently reliable or irrelevant data, etc.). Despite this, the conclusions of this report must be viewed with some caution.

The following biases can be listed non-exhaustively:
- Certain incidents – mainly breakdowns – can be traced in different ways depending on the monitoring centre.
- The incident logs used in this study have the advantage of improving the exhaustiveness of incidents. But they also include uncertainties, mainly when the information they contain which was entered at the time of occurrence was not reviewed or corrected.
- As the period considered in the study is fairly long (ten years), organisational changes made by the Operator may have impacted how the incidents were collected:
  - Change in the actual Tunnel Operator;
  - Change to the Operator's internal organisation;
  - Change in personnel within the operational teams.
  - In addition, many control centres rolled out new tools between 2002 and 2011 to improve feedback quality.
- Many tunnels in France underwent extensive renovations between 2002 and 2011. A bias is introduced in these scenarios as the tunnels were not in the same condition constantly throughout the period studied (for example, lighting renovations, installation of automatic incident detection and/or radars, etc.).
- It became apparent during field surveys that, depending on the Tunnel Operators, incidents and vehicle categories could be defined differently from one control centre to the next. For example, the Operators do not always strictly apply the same criteria to define a Heavy Goods Vehicle (for example buses are sometimes included in the HGV category).
- Exploiting certain databases sometimes required an "interpretation" of part of the information.
- The parameters as considered in this report are sometimes "discretised" in the databases. For example, incident location is sometimes provided to the nearest 100 m, more rarely to the nearest 500 m.

In addition, both results and analyses relate to a French context and no claim is made that they could be applied generally. Some were obtained thanks to the statistical sample and the heterogeneity of the tunnels. This diversity was used in particular to isolate the influence of certain parameters that would not have been possible if the tunnels had had more homogeneous characteristics.
CONCLUSIONS

The study determined the rates of breakdowns, accidents and fires in French road tunnels. These rates were confirmed by a statistical sample of unprecedented robustness (250,000 incidents split between 96 tunnels over a ten-year period). Over this 2002-2011 period and taking into account all 96 tunnels:

- The breakdown rate is $279/10^8$ veh.km,
- The accident rate is $41/10^8$ veh.km,
- The fire rate is $1.1/10^8$ veh.km,

The personal injury accident, injury and death rates are respectively 1.5, 3.7 and 2.4 times higher in the open air than in a tunnel environment over the 2007-2011 period. Deaths following a fire mainly occurred when the fire was the result of an accident. They are therefore the consequence of the accident and not the fire.

The influence of several parameters was studied: tunnel length, traffic, type of traffic flow (unidirectional or bidirectional), urban or non-urban, number of HGVs, speed limit, gradient, the Tunnel Operator’s control centre and the number and width of lanes.

To do this, a "traditional" method of simplified statistical analyses was initially used. It is based on simple regression and therefore involves studying the rates based on each parameter, but without taking into account any links between these parameters.

Another method was used which enabled an in-depth analysis based on multiple regressions. This method is confirmed by mathematical theory and use in many fields, but its use is totally new for French road tunnels.

This method only confirmed the results of the simplified statistical analysis in a few cases, summarised in Table 5 for breakdowns, Table 6 for accidents and Table 7 for fires.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lesson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban/non-urban tunnel</td>
<td>The urban nature generates a higher breakdown rate</td>
</tr>
<tr>
<td>HGV/light vehicles</td>
<td>The type of HGV vehicle generates a higher breakdown rate</td>
</tr>
<tr>
<td>Gradient</td>
<td>The higher the upwards gradient, the higher the breakdown rate The lower the downwards gradient, the lower the breakdown rate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lesson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional/bidirectional traffic</td>
<td>Unidirectional traffic generates a higher accident rate</td>
</tr>
<tr>
<td>Gradient</td>
<td>The higher the absolute value of a gradient, the higher the accident rate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lesson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>The higher the upwards gradient, the higher the fire rate</td>
</tr>
</tbody>
</table>

The study is not totally free of inevitable bias, which means considering results and analyses with caution. These biases are mainly inherent to the data collected that include uncertainties, despite all the precautions taken.

Additional analyses will be performed in France to broaden the understanding of the influence of parameters.
REFERENCES


5. Christophe ZING, Raphaël DEFERT, Christophe WILLMANN, "Pannes, accidents et incendies dans les tunnels routiers; Etude statistique à l’échelle nationale", final draft.
An Experimental Evaluation of the Toxic Gas Emission in Case of Vehicle Fires

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\textsuperscript{1}INERIS, Parc technologique ALATA, France

ABSTRACT

Fire safety in tunnels enables to design safety measures to ensure a people safe evacuation in case of fire. Such an analysis considers the different impacts of fire on people as temperature, visibility but also toxicity. Most of standard curves are based on quite old fire tests without any toxic gas qualification. Very few fire tests were previously achieved in that way. Based on those few tests, some standard fire emission factors were proposed. The objective of this paper is to review those emission factors, not only regarding the nature of toxic compounds generated but also through a carbon monoxide equivalent factor.

To reach this objective, two series of tests were performed. The first concerns individual combustible compounds of a car as plastics, tyres and others. The second focusses on full car burning tests with smoke analysis. Those two series of tests lead to an analysis of the smoke toxicity and a comparison of emission factors with standard ones.

KEYWORD: smoke toxicity, car burning tests

INTRODUCTION

In case of fire in confined space as tunnels or car parks, while heat release is crucial for structure behaviour and aerodynamic, impact on people are mainly due to the smoke toxicity. However, while car fires were largely studied in the past regarding the heat release rate (HRR), few papers focussed on the toxic gases emissions [1]. From those papers, cars were concerned by large evolutions that have induced, as far as the topic of this paper is concerned, a major modification of the quantity of plastic but also some improvements regarding comfort or energy that could clearly impact the potential toxic load of cars.

To evaluate the impact of those evolutions, two major large scale experimental fires campaigns on real cars were achieved. Those tests are divided into several categories of cars. The first is a series of three different recent cars, with several sizes, from small “urban” to large “familial” cars. This first series of tests, compared with existing results in the literature, enables to evaluate the impact of embedded comfort on smoke toxicity. The second series of tests concerns the evolution of the energy carrier using the results from electric cars burning [3]. To enable a more detailed comparison, tests were also achieved on different components individually such as fuels, cables and plastics. Finally, toxicity of the produced smoke is compared based on Fractional Effective Concentration (FEC) and Fractional Effective Dose (FED), depending on the nature of the gases as detailed in [5]. This toxicity is evaluated considering all produced gases, to propose a new evaluation of emission rates to be considered regarding toxicity. Because carbon monoxide is not the only toxic product that is generated in case of fire in tunnels, emissions were, during these tests, characterized using an FTIR (Fourier Transform Infra-Red) spectrometer. Such a system enables to perform a detailed calibration including the concentration in carbon monoxide, but also in acid gases (hydrogen chlorine, hydrogen fluorine, …) or other compounds as carbonates for example. Not only the nature but also the quantity of the gases produced during fire are compared.
Regarding these new experimental calibrations of the smoke potential toxicity in case of car fire, a reflexion is proposed regarding the commonly used standard curves [4]. Of course, it is not relevant to take into account, in a safety study, the large variety of toxic compounds generated, according a simplified manner. To do this, CO equivalent production curves are proposed for tunnel safety evaluation, based on the toxic impact on people [5].

**VEHICLE FIRE SOURCE TERMS AVAILABLE**

**The heat release curves**

Considering that most of the emission factors for fire are given relatively to the HRR, it appears important to consider it. Furthermore, the smoke behaviour in confined or semi-confined infrastructure will highly depend on thermal gradient that governs smoke stratification. Several values are available regarding cars maximum HRR in the literature as detailed in [4] and [7]. Two examples or HRR curves are reproduced hereafter on Figure 1.

![Figure 1: Two examples of HRR curves from French reference documentation [4] (left) and PIARC reference [7] (right).](image)

The first, from [4] indicated a calorific load of 12 000 MJ for a large private car, the second, from [7], indicates a calorific load of 6 000 MJ for a private car, 7 000 MJ for a plastic one. It must be highlighted that the range of values is quite important, not only in terms of maximum HRR but also regarding the fire kinetic. The important issue regarding toxicity is then the relation between the HRR and the emission factor. For quite small cars, the plastic load is not so important but the nature of these plastics is not so different. It is then analysed, in the present paper, the relation between the calorific loading in the car and the emission factor.

**The toxic gases emissions rates**

While some data are available regarding the emission rate of carbon dioxide and carbon monoxide, very few data exists on other toxic compounds that can be found in smoke. One of the most detailed one is [2]. Those tests, achieved in 1999, concern vehicles that are quite old now. First of all, it is important for the following and for the estimation of the current model of smoke toxicity to compare the global emission rate in terms of CO equivalent production. This can be done using the FED and FEC relations detailed in [5] or based on a simpler approach as the one detailed in [17]. This is important to consider that not all gases can be considered in a safety study and that a global approach must be followed. This approach generally consists in modeling the CO transport in the tunnel. It is then obvious that the modeled gas must considered not only the effective CO but the effect of other toxic compounds.

It is then interesting to evaluate the impact of vehicle transformation between previous tests and nowadays in terms of nature of toxic compounds but also through the emission factor.
ANALYSIS OF RECENT FIRE TESTS PERFORMED AT INERIS

Brief description of experimental facilities
Experimental device that was used for the experimental campaign is the INERIS fire gallery. This fire gallery was described in some previous papers [13] but relevant details are given hereafter. This gallery is 50 m long with a 3 m width and 1.8 m height section, that corresponds to a two lanes tunnel at third scale. This fire gallery is equipped with a fan that can be control to manage the air flow in the tunnel. Photography of INERIS fire facilities is presented on Figure 2.

One of the main interests of this installation is the smoke treatment system installed downstream. This system, design as for garbage furnace emissions treatment, enables to capture not only the toxic products as carbon oxides or acid gases but chronic toxic compounds, as dioxin or PAH (Polycyclic Aromatic Hydrocarbons) too [15].

ELEMENTARY TESTS

Before going any further in the description of full scale fire tests on vehicle, it is quite important to analyse the emissions factors for different individuals components of the vehicle. Some data were previously published in the literature regarding this as in [8][9][10][11]. The data presented in these papers were recently published following dedicated fire tests achieved in INERIS [12]. During this experimental campaign, four individual car combustible compounds were burnt : gasoil, plastics, tires and electrical compounds. Those individual compounds were taken from a commercial car to be representative of the real materials used on vehicles. For those tests, plastics and tyres were previously crushed. Main results are summarized in Table 1. For each compound, the total duration of the tests was greater than 3 hours.

<table>
<thead>
<tr>
<th>Mass of product burn [kg]</th>
<th>Gasoil</th>
<th>Plastics</th>
<th>Tyres</th>
<th>electric cables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>131</td>
<td>48</td>
<td>49</td>
<td>36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emission factors [mg/g] or [g/kg]</th>
<th>Gasoil</th>
<th>Plastics</th>
<th>Tyres</th>
<th>electric cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>2823</td>
<td>2034</td>
<td>1469</td>
<td>728</td>
</tr>
<tr>
<td>CO</td>
<td>31</td>
<td>20</td>
<td>42</td>
<td>9,1</td>
</tr>
<tr>
<td>HCl</td>
<td>-</td>
<td>2,2</td>
<td>0,2</td>
<td>2,1</td>
</tr>
<tr>
<td>HF</td>
<td>-</td>
<td>0,014</td>
<td>0,003</td>
<td>0,11</td>
</tr>
<tr>
<td>NOx</td>
<td>1,2</td>
<td>5,0</td>
<td>2,8</td>
<td>2,5</td>
</tr>
</tbody>
</table>
Regarding the products that could generate acute toxicity, it is clear the carbon dioxide is clearly predominant. It represents more than 95% of acute toxic gases production.

FULL SCALE CAR BURNING

Measurements made during the tests are located on the scheme reproduced on Figure 3. It must be highlighted that, because of their importance, carbon oxides and oxygen measuremets were made on several points. The interest was not only in insuring the availability of the measurement but also to demonstrate the correct mixture was reached. Toxic products as acid gases were measured with both an online method, based on a FTIR spectrometer, and with integral method thanks to bubblers.

Figure 3: Probes location in the fire gallery.

Brief description of cars and calorimetric data

During the presently described experimental campaign, two series of cars where used. The main characteristics of those cars are described in Table 2. On top of the car characteristics, this table also provide the basic calorimetric data. In is important to note that some measurements can be influence because of the experimental set up characteristics. Then, while total amount of energy, of toxic gas are probably not significantly influenced bythe experimental set up, the HRR max value is probably overestimated compared to a free bruning because of the confinement. Another impact is the dilution of gas by the ventilation system. This aspect is discussed afterward.

Table 2: Main characteristics of burnt cars.

<table>
<thead>
<tr>
<th></th>
<th>Car 1</th>
<th>Car 2</th>
<th>Car 3</th>
<th>Car 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass before ignition [kg]</td>
<td>936</td>
<td>1 404</td>
<td>1 564</td>
<td>1 501</td>
</tr>
<tr>
<td>Energy carrier</td>
<td>Fuel</td>
<td>Fuel</td>
<td>Fuel</td>
<td>Electricity</td>
</tr>
<tr>
<td>Cathegory</td>
<td>Urban car</td>
<td>Medium class familial car</td>
<td>Upper class familial car</td>
<td>Medium class familial car</td>
</tr>
<tr>
<td>Total mass loss [kg]</td>
<td>192</td>
<td>275</td>
<td>262</td>
<td>278,5</td>
</tr>
<tr>
<td>Mass loss fraction [%]</td>
<td>17</td>
<td>19,6</td>
<td>16,8</td>
<td>18,6</td>
</tr>
<tr>
<td>Peak HRR [kW]</td>
<td>4 900</td>
<td>5 900</td>
<td>7 800</td>
<td>4 500</td>
</tr>
<tr>
<td>Time between ignition and peak HRR [min]</td>
<td>15</td>
<td>18</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>Total energy [MJ]</td>
<td>6 890</td>
<td>10 600</td>
<td>10 000</td>
<td>8 540</td>
</tr>
</tbody>
</table>
Those values have to be compared with the standard ones as those defined in the AIPCR reference document [6] or the CETU French guide [4] summarized in Table 3.

### Table 3: Calorimetric standard values.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Private car</td>
<td>Plastic car</td>
</tr>
<tr>
<td>Peak HRR [kW]</td>
<td>2 500</td>
<td>5 000</td>
</tr>
<tr>
<td>Time between ignition and HRR peak [min]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total energy [MJ]</td>
<td>6 000</td>
<td>7 000</td>
</tr>
</tbody>
</table>

The first comparison shows that the standard values commonly used for car fires are relevant in terms of both HRR peak values and total energy released. While the delay between ignition and HRR peak value appears to be underestimated in the referenced document, it is important to remind the objectives of its. The above given values are used for safety studies where minimizing the delay for fire propagation leads to minimize the available escape time for people and consequently improving safety level. In that sense, it could be considered as relevant.

### Gaseous emissions

Before going into the comparison between vehicles, each toxic compound proportion in gaseous products are summarized on Table 4 for the three common energy carriers.

### Table 4: Gaseous emissions data.

<table>
<thead>
<tr>
<th></th>
<th>Car 1</th>
<th>Car 2</th>
<th>Car 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative emission [% of total]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acid gases</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen chloride (HCl)</td>
<td>0.38%</td>
<td>0.29%</td>
<td>0.33%</td>
</tr>
<tr>
<td>Hydrogen fluorine (HF)</td>
<td>0.12%</td>
<td>0.11%</td>
<td>0.07%</td>
</tr>
<tr>
<td>Cyanhydric acid (HCN)</td>
<td>0.03%</td>
<td>0.02%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>96.54%</td>
<td>96.95%</td>
<td>97.33%</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>2.29%</td>
<td>2.11%</td>
<td>1.94%</td>
</tr>
<tr>
<td>Nitrogen oxide (NO)</td>
<td>0.13%</td>
<td>0.1%</td>
<td>0.15%</td>
</tr>
<tr>
<td>Nitrogen dioxide (NO₂)</td>
<td>0.06%</td>
<td>0.06%</td>
<td></td>
</tr>
<tr>
<td>Sulfur dioxide (SO₂)</td>
<td>-</td>
<td></td>
<td>0.13%</td>
</tr>
<tr>
<td>Total hydrocarbons</td>
<td>0.45%</td>
<td>0.37%</td>
<td>-</td>
</tr>
</tbody>
</table>

First of all, as for individual compounds tests, it must be notice that the carbon dioxide proportion in smoke was higher than 95% for each tests. One of the most important issue when dealing with smoke is the CO/CO₂ ratio that depends on external conditions and mainly the fire ventilation. In the present fire tests, the total ventilation air flow, downstream the fire, is about 25 000 Nm³/h, i.e. 8.97 kg/s of air and, consequently 1.88 kg/s of oxygen. Considering 1 kg of oxygen is required to produced 13.1 MJ, it means that the air flow can generate a 24.7 MW fire by consuming all provided oxygen. Not all the provided oxygen can however be consumed and, a concentration around 13% appears as a minimum. In that condition, the amount of oxygen that can be provided to the fire is about 0.7 kg/s, corresponding to a 9.4 MW fire. Fires were then ventilated enough to prevent under ventilation phenomena.

This is confirmed by oxygen concentration measurement downstream the fire, as plotted on Figure 4.
This curve confirm that, when reaching the maximum HRR, the oxygen concentration is still above 13%. This curve also shows that the oxygen concentration is highly time dependant because of the HRR evolution. Consequently, the CO/CO₂ ratio is also time dependant, this is demonstrated on Figure 5.

This curve highlights that, even considering that the energy release is important compared to the air flow when reaching the maximum HRR, this does not slightly modify the CO/CO₂ ratio that stays under 5% all along the whole fire duration. This value is in accordance with observations made by Tewarson at laboratory scale for different series of well ventilated fires. Identical conclusions were made for the other fire tests.

The other interesting point that has to be discussed is the ratio between acid gases. For each cars, the hydrogen chlorine is the predominant one in terms of total amount released. The evolution of concentration in smoke for those gases along the tests however reveals that the emission dynamic are different in between, Figure 6.
This curve shows that while hydrogen chlorine is produced all along the fire, hydrogen fluorine is mainly produced during a short period. On top of that, regarding acid gases, the total quantity of cyanhydric acid is quite small even a lots of foam are present in the car. Once more, those conclusions are valid for all burnt cars.

It is then interesting here to compare emissions for these compounds with those measured by the past [2]. During tests managed by [2], that concerns 90’s car, carbon monoxide was largely the main compound. During these tests, no HF nor HCN and Nox were measured into the smoke.

**Impact of New Energy Carriers**

Regarding the specific composition of their batteries, electric cars are commonly supposed to produce more toxic gases in case of fire. Data from electric cars burning were previously published [3]. Those tests were achieved in the same installation as the one described in the present paper and it is interesting to give some words about the specificities of those fires. All tests for electric cars published in [3] and mainly the one discussed in the present paper concerns Li-Ion batteries.

Main conclusions that are of interest here concern the heat release rate that is not modified by the battery and the toxic gases production that is also similar between fuel car and electric one. The proportion of toxic products for electric cars are indicated in Table 5.

<table>
<thead>
<tr>
<th>Car 4</th>
<th>Total amount of gas [g]</th>
<th>737 717</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acide gases</td>
<td>Hydrogen chlorine (HCl)</td>
<td>0,30%</td>
</tr>
<tr>
<td></td>
<td>Hydrogen fluorine (HF)</td>
<td>0,23</td>
</tr>
<tr>
<td></td>
<td>Cyanhydric acid (HCN)</td>
<td>0,02</td>
</tr>
<tr>
<td>Carbon and nitrogen oxydes</td>
<td>Carbon dioxide (CO₂)</td>
<td>96,98</td>
</tr>
<tr>
<td></td>
<td>Carbon monoxide (CO)</td>
<td>1,83</td>
</tr>
<tr>
<td></td>
<td>Nitrogen oxide (NO)</td>
<td>0,12</td>
</tr>
<tr>
<td></td>
<td>Nitrogen dioxide (NO₂)</td>
<td>0,05</td>
</tr>
<tr>
<td></td>
<td>Sulfur dioxide (SO₂)</td>
<td>-</td>
</tr>
<tr>
<td>Unburnt</td>
<td>Total hydrocarbons</td>
<td>0,45</td>
</tr>
</tbody>
</table>

*Table 5: Gaseous emissions data.*

The main conclusion of this test is that toxic gases emissions are not affected by the battery.

A detailed analysis shows that the total quantity of HF is multiplied by a factor of about 1.8. However
the emission curve of HF is, in the case of an electric car, not strongly different from a fuel one as plotted on Figure 7.

This comparison clearly shows that, the first HF production is totally independent of battery. The contribution of this element appears on the second part of the fire, after 30 minutes burning. In such a condition, it is clear that this new energy carrier does not affect the smoke toxicicity for people during evacuation.

**Equivalent toxicity**

Because the smoke toxicity is a quite complex problem, mainly due to the relative toxicity of each products and interactions between gases regarding their impact on human beings, a criteria has to be defined for discussing about relative toxicity. Several methods exist to evaluate the relative impact of a toxic gases mixtures as the simple approach that consider all the toxicity as equivalent [17] or the one described in the ISO document 13571 [5] that defines the Fractional Effective Dose (FED) and Fractional Effective Concentration (FEC) and enable considering the difference between gaseous in terms of the nature of human being impact.

The first is based on a simpler approach call the equivalent threshold method described in [17]. This approach consists in defining the equivalent impact, $S_{eq}$, on person without taking into account the toxical nature of the different gases:

$$S_{eq} = \frac{1}{n} \sum_{i=1}^{n} \frac{[P_i]}{S_i}$$

In this relation, $[P_i]$ represents the concentration of product $P_i$ in smoke and $S_i$ the corresponding toxic threshold for that species. While this method is not as accurate as the FED/FEC approach regarding the evaluation of the toxic impact on the person, it enables to evaluate toxic impact during first stage of fire, that corresponds to the evacuation period, in fire safety studies for tunnels because it considers all toxicity, carbon monoxide, gaseous gases and other compounds.

Based on this and considering 10 minutes threshold on persons, it is then possible to build an equivalent CO emission factor. Of course, this factor cannot be constant and is time varying, as showed on Figure 8.
Figure 8: Evolution of CO equivalent emission rate along time, comparison of car 2 and 3, fuel and electric private cars.

This curve shows that, by comparison to existing references for equivalent CO emission factor [4], the actual emission factor can reach twice the standard value. On top of that, it can be produced during the first minutes of the fire, minutes that are crucial for people evacuation but, because the kinetic of the fire is linearized during the first minutes, the standard curve production could still be relevant. In some specific cases, when evacuation safety margin is not so important, some more detailed analysis should be achieved to take into account such specific emission factors.

While the previous method enable to propose an equivalent carbon monoxide source term, it does not enable taking into account the different nature of gases in terms of toxicity. To achieve a toxic evaluation based on the ISO 13571 [5], the important data is the carbon monoxide emission factor, in mg by g of burnt materials, coupled with the ratio between the given species and carbon monoxide, along time. Based on this, a FED/FEC evaluation of toxicity became possible. The simplest way to deal with those quantities consists in using average values detailed in previous tables. It must be however kept in mind that those quantities are not stationary. The example of car 2 is used hereafter to give an illustration of this phenomena. For this car, the averaged heat of combustion is about 38 MJ/kg, this value is the only one considered as constant.
Figure 9: Evolution of CO emission factor in mg of CO by g of material burnt (continuous line) and of the HCl/CO mass ratio (dashed line) and HF/CO mass ratio (grey dotted line).

This curve typically shows that, during the first minutes of the fire, the emission of hydrogen chlorine could be higher than the production rate of carbon monoxide. Then, after about 20 minutes, the production of hydrogen chlorine can be neglected. Such a comparison lets appear the details level requires to consider the separate impact if the toxic different compounds.

CONCLUSIONS

While a lot of data are available in the literature regarding the HRR curve for different cars, most of the reference tests that’s were used to build those curve were measured on 90’s cars and few of them concerns the emission factor. Considering toxicity could be one a the key issues for tunnel fire safety during the ventilation design, this paper presents fire curves and toxic gases production rate for recent car in different categories.

The first important results that appears thanks to those tests is that, while both the total mass of car and plastic fraction were increasing, the maximum HRR value and total energy released given by the standard are still valid. It must be also highlighted that those curve consider a rapid fire growth in the very beginning, such a quick growth was not observed during those tests. This is clearly in favor of tunnel safety regarding the people evacuation.

Regarding toxic gases, carbon dioxide is still the major products that is generated. Other toxic compounds are produced in low proportion compared to that one. Some new gases, as HF, were mainly detected during the different tests, independently of the energy carrier used.

Finally, the emission rate of CO were compared with the standard, based on an equivalent toxicity approach. This comparison shows that, while the fire growth is overestimated in standard curves, the CO equivalent production rate could, in such a case, be higher than the commonly used curve. On top of that, while such an approach is useful to built an equivalent toxic source term, it does not enable to consider the various effect of gases on human beings as the ISO 13571 FED/FEC approach. To enable such an approach, in case of requirement, a detail source term must be consider because of the time variation of the CO production rate but also regarding the variation of each toxic product vs carbon monoxide ratio along time.

To conclude, when toxicity is the design factor for a specific ventilation system, one must consider a more detailed approach based on a realistic source term instead of standard values than can be highly overestimated in the very beginning and underestimated just after when fire propagates to the whole car.
REFERENCES

Integrating Evacuation Research in Large Infrastructure Tunnel Projects - Experiences from the Stockholm Bypass Project

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ABSTRACT
Large infrastructure projects often involve important decision about evacuation safety measures, e.g., emergency exit portals, alarm systems, etc, that need to be taken in spite of limited information and knowledge on the topic. This has been shown to sometimes lead to design mistakes, but these mistakes can potentially be avoided if research is linked to the project at an early stage. This paper discusses how research can be connected to large infrastructure tunnel projects and illustrated the process using the Stockholm Bypass Project as an example. In addition, the results of a research project (linked to the Stockholm Bypass Project) are presented and relevant publications are given.

KEYWORDS: large infrastructure projects, evacuation, experiment, human behaviour in fire, tunnels, design, notification, exit choice, Stockholm Bypass Project.

INTRODUCTION
Large infrastructure projects, such as road and rail tunnel projects, often involve major decisions that need to be made given very limited information and knowledge on the topic. Decisions often relate to issues that have not yet been fully explored in research. These decisions then need to be made based on the best available knowledge, but this can easily result in serious design mistakes [1].

There are illustrative cases where evacuation systems have not worked entirely as intended. One example is the Traffic Information Signs (TIS) for tunnel evacuation in the Southern Link Tunnel in Stockholm [2]. The TISs were configured to display different messages, one of which was “evacuate tunnel” (in Swedish), see Figure 1. Initially, this message was displayed in the affected tunnel section in case of fire and smoke, and the intention was that people would leave their vehicle and evacuate the tunnel on foot. However, a few real fire incidents have demonstrated that people interpret the message differently and some motorists instead drove out from the tunnel through thick smoke [2]. This type of behaviour is potentially dangerous due to the risk of running over people in the smoke filled tunnel.

The Southern Link Tunnel example clearly illustrates that a particular design might not work as intended in spite of the best intentions. The simple evacuation message, i.e., “evacuate tunnel”, seems to make sense, since theory suggests that instructions should be kept simple in stressful situations due to limitations of people’s working memory [3]. However, a risk when making instructions simple is that the context can become more important for decision-making. In the Southern Link Tunnel example, the motorists were presumably in their vehicles with the engine on, and given this context it makes sense to evacuate the tunnel by driving out. This type of context dependent interpretation is arguably difficult for to predict, as it is not easily to adapt the mind-set of a tunnel user.

Incidents, like the one in the Southern Link Tunnel, are not in vain and it is important to learn from
them. TIS messages in the Southern Link Tunnel have since been updated and alternative messages, e.g., “evacuate tunnel” or “stop engine, evacuate tunnel”, are shown in different tunnel sections depending on fire and traffic conditions.

![TIS Messages](image1.png)

*Figure 1. Schematic representation of one of the TIS messages in the Southern Link Tunnel (left) and the Göta Tunnel (right) [translated from Swedish]*

In another tunnel project, namely the Göta Tunnel in Göteborg the TIS message “stop engine, evacuate tunnel” is shown in case of fire or smoke, see Figure 1. This message, although simple, changes the context in which the message is interpreted. From the perspective of a motorist behind the wheel of their vehicle, it is not possible to drive out from the tunnel when the engine is stopped. Therefore, the remaining option is to evacuate on foot. Experiments have also indicated that the TIS design used in the Göta Tunnel performs well and is a much appreciated evacuation system [4].

It could be argued that well-trained experts is the way to avoid design mistakes, but experience shows that even experts are not able to predict the influence of the context on the interpretation of evacuation systems. This is illustrated by an experiment in a smoke filled tunnel, which was performed as part of the METRO project [5]. One of the objectives of the experiment was to study the effectiveness of different emergency exit portal designs. Figure 2 shows one of the tested portal designs, which consisted of a green frame around the door, green and white lights at the bottom part of the frame, a back-lit emergency exit sign above the door and strong illumination on the portal. These features were chosen to resemble the design suggested in Swedish guidelines for tunnels.

![Portal Design](image2.png)

*Figure 2. Schematic representation of the emergency exit portal used in the experiment (left) and the actual exit in the smoke filled tunnel during the experiment (right)*

The portal design was seen by the involved researchers both with and without smoke before the experiment. Although a total of six experienced evacuation researchers examined the portal design, none of them were able to predict how it was going to be interpreted by participants. Post-experiment interviews revealed that some participants interpreted the portal as an oncoming train [5]. This was a surprise to the researchers, who had all failed to recognize the context in which the participants viewed and interpreted the portal. Participants had seen a film of a train ride in Stockholm Metro before they entered the smoke filled tunnel, which presumably made them believe that the focus of the experiment was on rail tunnel evacuation. Therefore, they were probably looking out for potential hazards in the tunnel, e.g., the electrified third rail, other trains, etc, which made them interpret the
emergency exit portal as an oncoming train when viewed through the thick smoke, see Figure 2.

A potential way of minimising design mistakes is to analyse evacuation systems using a framework [1]. One such framework is the Theory of Affordances, which was proposed by Gibson [6] and further refined by Hartson [7]. According to Hartson [7], an object, e.g., an evacuation system can be interpreted in relation to what it offers the user in terms of (1) sensory, (2) cognitive, (3) physical and (4) functional affordance. This approach is hence a way of considering the context in which an evacuation system is perceived, interpreted and used. However, it has been argued that the Theory of Affordance is not a foolproof way of avoiding mistakes, but that it should ideally be used mainly to rule out inappropriate system designs at an early stage [8]. It is instead necessary to perform research aimed at testing system designs in realistic scenarios with representative participants before systems are installed in real tunnels. Failure to do this can lead to costly installations of evacuation systems that only provide very limited benefit.

In order to avoid design mistakes it can be useful to include research as a part of the initial stages of large infrastructure tunnel projects. One example of this is the Stockholm Bypass Project, where research was funded by the Swedish Transport Administration and the EU Trans-European Transport Network (TEN-T). In the following text, research related to design of evacuation safety measures in the 18 km long tunnel section is presented in order to illustrate how research can be used in the initial stages of large infrastructure projects to minimise the risk of design mistakes.

**PROJECT DESCRIPTION**

The Stockholm Bypass Project is an on-going large Swedish infrastructure project (budget: approximately € 3 billion). In the project, the E4 road will be lead around Stockholm, which involves the construction of 21 km of new road. A total of 18 of the 21 km will be located in tunnels, which in this paper is called the Bypass Tunnels. Construction, which was preceded by many years of planning and preparation, was initiated in August 2014 and will continue for another 10 years.

In 2012, the Stockholm Bypass Project applied for funding from the EU Trans-European Transport Network (TEN-T) for project related research. The funding lead to contacts being established with various research institutions around the country. One part of the research was focused on human factors in relation to tunnel use in ordinary and emergency situations.

In 2013, contacts were taken by the Stockholm Bypass Project with the Division of Fire Safety Engineering at Lund University, Sweden. These contacts lead to the creation of a sub-project called “Evacuation route design”, which was subsequently started in July 2013 and finished in February 2015. The research project was performed by Lund University in close cooperation with the Swedish Transport Administration. One unique feature of the project was that the research objectives were formulated in cooperation between the involved parties, and were specifically linked to design issues in the Stockholm Bypass Project and state-of-the-art research knowledge. The objectives of the project were to study:

1. how Traffic Information Signs (TIS) should be designed to effectively inform motorist about fire incidents,
2. what colour and configuration (window – no window) of the emergency exit door in the portal that is most appropriate,
3. how acoustic warning signals should be designed to effectively notify people about a fire emergency and influence them to leave their vehicle,
4. how flashing lights at emergency exit portals should be designed from an evacuation perspective in relation to:
   a. colour of flashing lights
   b. flashing frequency of lights
   c. type of flashing light source
5. what type of configuration of lights that is most appropriate from an evacuation point of view, and
6. how persons can be effectively guided to emergency exit portals from the opposite tunnel wall in a smoke filled tunnel
Some aspects were studied in relation to things that had already been decided in the Stockholm Bypass Project. For example, it had already been decided that emergency exit portals should be green, but such aspects as the colour and appearance of the emergency exit doors had not yet been fixed. Similarly, it was only possible to use two different sizes of TISs – called small and large. Another example was that it had already been decided to use flashing lights at emergency exit portals, but that the position of these installations were limited to three locations, namely one on top of the exit and one on each side. This limited the possible configurations of flashing lights at the portals.

Given all the restrictions imposed by the Stockholm Bypass Project, the objectives above were formulated to further research in the area and at the same time provide the necessary input to the infrastructure project. For example, research on flashing frequency of lights at emergency exit portals was included since this had not been the focus of much previous research and the results would be of benefit for the safety in the Bypass Tunnels during evacuation.

Based on the derived objectives, the research project called “Evacuation route design” was divided into three parts:

- Part 1 – Evaluation of the design of TIS, emergency exit doors, and acoustic warning signals
- Part 2 – Test of way-finding systems at emergency exit portals in Virtual Reality
- Part 3 – Test of way-finding systems in a smoke filled road tunnel

In order to accommodate the needs of the Stockholm Bypass Project, all parts were disseminated in interim reports [9,10,11] and final reports [12,13,14], which were delivered at different stages. The aim of the interim reports was to disseminate research results to accommodate the deadlines of the infrastructure project. Hence, the interim reports [9,10,11] mainly focused the results and associated recommendations. The final reports [12,13,14] included all the parts of the interim reports, but also a discussion of previous research, presentation of experimental procedures, discussions, etc. Hence, the interim reports had more technical focus and the final reports were more scientific.

The different parts of the project were designed to build on each other, although some aspects, e.g., design of acoustic warning signals, were only studied in one of the parts. The following sub-sections describe the different parts on the research project.

**Part 1 – Evaluation of the design of TIS, emergency exit doors, and acoustic warning signals**

Part 1 of the research project addressed objectives 1, 2 and 3 stated above. More specifically, three different evacuation measures for the Bypass Tunnels were evaluated, namely:

1. Traffic Information Signs (TIS)
2. Emergency exit doors
3. Acoustic warning signals

The evaluation was initiated with a thorough literature review to identify previous research on the three measures in the list above. Based on the knowledge gained through the literature review and the restrictions imposed by the Stockholm Bypass Project, a number of concept designs were developed for TISs, emergency exit doors, and acoustic warning signals.

In the selecting of concept designs, the restrictions dictated by the infrastructure project played a major role. One imposed restriction was that only two TIS layouts were possible, see Figure 3 and 4. Both layouts included two LCD displays for text or pictograms, but one configuration included two small displays (Figure 3) and one included a small display and a large display (Figure 4). Both layouts also included three road lane indicators, marked with red X, implying that the lanes are closed for traffic. Other imposed restriction were that only signals, i.e., no voice messages, were allowed as acoustic warning signals, and that emergency exit doors could either have no window or a small port-hole type window.

In total, eleven concept TIS designs, four concept emergency door designs and three concept acoustic warning signals were derived. All these concept designs were then evaluated using a Theory of Affordances approach [12]. According to this approach, the factors influencing sensory, cognitive and physical (if relevant) affordances were identified by the researchers and it was indicated if the factor...
has a positive or negative contribution. Based on these estimates, a qualitative rating of affordances was performed and the best design, i.e., the one with the highest functional affordance, was recommended. This ranking process is described in greater detail in the final report [12].

![Figure 3. Layout 1 – two LCD displays with the same dimension (both 240x90 cm)](image1)

![Figure 4. Layout 2 – two LCD displays with different dimensions (240x170 cm and 240x90 cm)](image2)

Based on the evaluation using the Theory of Affordances approach, it was possible to derive a recommended design from the concept design for both emergency exit doors and acoustic warning signals, see Figure 5 and Table 1. However, it was not possible to identify the best TIS design and additional experiments were therefore performed, namely pairwise comparisons between TIS designs using hypothetical scenario experiments. The experiments were performed in classroom environments where participants sat in front of two screens. A hypothetical tunnel evacuation scenario was then described and the participants are told to imagine the scenario. They were then asked to look at TIS designs displayed on the two screens, namely one on the left screen (A) and one on the right screen (B), as they fill out a questionnaire, see Figure 6. A total of 62 participants took part in the study.

![Figure 5. Recommended emergency exit door design](image3)

<table>
<thead>
<tr>
<th>Table 1. Recommended acoustic warning signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>F_SAW</td>
</tr>
</tbody>
</table>

The questionnaire that was used in the experiments was based on the Theory of Affordances. In the questionnaire, participants were asked to provide their estimate of which of the two systems (A or B) that was best at, for example, catching their attention (sensory affordance) or conveying the message (cognitive affordance). They were also asked to make an overall estimation of which system that would be best for the given scenario (functional affordance). The participants were also asked to explain their choices using their own words. Based on the answers of the participants, a TIS design was recommended for the Bypass Tunnels, see Figure 7.
The results and recommendations of Part 1 were summarised in an interim report [9] that was delivered to fit the deadlines of the infrastructure project. In addition, the work was summarised in a final report [12] and has resulted in one scientific paper [15]. The findings of Part 1 were also used as input in a related study in the TEN-T project using real full graphic LED signs in an outdoor environment [16].

**Part 2 – Test of way-finding systems at emergency exit portals in Virtual Reality**

Part 2 of the research project addressed objectives 4 and 5 stated above, and focused on the evaluation of different emergency exit portal designs. The different portal designs were evaluated by human participants in Virtual Reality (VR) experiments. A total of 5 different variables were included in the study. Table 2 shows the included variables together with information about how these variables were changed in the study. In relation to the type of light source, three configurations called strobe (short light pulse), double strobe (two subsequent short light pulses) and 50/50 on/off light (50% of the time on and 50% of the time off) were used. The variables for door design and layout of lights can be found in Figures 8 and 9.
Table 2. The variables included in Part 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Configurations used in the study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour of flashing light</td>
<td>Green</td>
</tr>
<tr>
<td></td>
<td>White</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
</tr>
<tr>
<td>Flashing frequency of light</td>
<td>0.25 Hz</td>
</tr>
<tr>
<td></td>
<td>1 Hz</td>
</tr>
<tr>
<td></td>
<td>4 Hz</td>
</tr>
<tr>
<td>Type of flashing light source</td>
<td>Strobe</td>
</tr>
<tr>
<td></td>
<td>Double strobe</td>
</tr>
<tr>
<td></td>
<td>50/50 on/off light</td>
</tr>
<tr>
<td>Layout of the flashing lights</td>
<td>3 lights</td>
</tr>
<tr>
<td></td>
<td>1 light</td>
</tr>
<tr>
<td></td>
<td>2 bars</td>
</tr>
<tr>
<td>Door design</td>
<td>Port hole window</td>
</tr>
<tr>
<td></td>
<td>Painted running man</td>
</tr>
</tbody>
</table>

The variables in Table 2 were combined in systematic ways to create 11 different emergency exit portal designs for testing, i.e., 11 scenarios in the experiment. Participants were exposed to a limited number of scenarios to minimize the effect of study fatigue. The total number of participants was 96 and participants took part one at a time.

The experiments were performed in a Cave Automatic Virtual Environments (CAVE) at Lund University. The CAVE is a back projection system with three 4-meter wide screens. In addition, the VR environment is also projected on the floor, see Figure 10. The technology uses stereoscopy with polarized light, which together with polarization glasses creates the impression of being in a three-dimensional environment. Participants navigate the virtual environment using a game control and their position is monitored in real-time with head ultrasound tracking. This creates a strong sense of presence and the user perceives the space approximately on a one to one scale [17].
In the VR experiments, participants were first given general information about the experiment, which was followed by a practice session in the CAVE using a test scenario. This was done to allow participants to familiarise themselves with the CAVE and practice navigation in VR. Participants were then instructed to evacuate a virtual tunnel environment by moving to a place of safety. When they had evacuated from their initial location to the emergency exit portal in the tunnel, they were placed in front of a portal and asked to rank it using Likert-scale (from -3 to +3) type questions based on the Theory of Affordances. More specifically, participants were asked questions connected to sensory, cognitive and functional affordance. The evaluation was repeated six times with different designs, which meant that each participant rated a total of seven different emergency exit portals.

Based on participants’ rating of the different portal designs, it was possible to draw a number of conclusions. Results suggest that green or white flashing lights are better than blue flashing lights at emergency exit portals. Also, a flashing frequency of 1 Hz or 4 Hz was preferred compared to 0.25 Hz. The 50/50 on/off light was better than both single and double strobe lights. Although the three layouts of the lights under consideration performed similarly in the experiments, the use of a higher number of lights was deemed to be beneficial. Finally, no difference could be observed between the two door designs.

The results and recommendations of Part 2 were summarised in an interim report [10] that was delivered to fit the deadlines of the infrastructure project. In addition, the work was summarised in a final report [13] and has resulted in one scientific paper [18].

Part 3 – Test of way-finding systems in a smoke filled road tunnel

Part 3 of the research project addressed objective 6 stated above. More specifically, the objective was to evaluate if the following measures are able to attract people moving along the right-hand wall to an emergency exit at the left-hand wall in a smoke filled tunnel:

1. Acoustic alarm at the emergency exit (signal and spoken message)
2. Signs on the right-hand wall indicating the distance to and location of emergency exits
3. Arrows on the pavement on the right-hand side indicating the location of the exit

The evacuation signs and the arrows on the pavement are shown in Figures 11 and 12. The right sign in Figure 11 was used in all scenarios indicating the location of the exit on the opposite side. Another objective of the study was to test the emergency exit portal design recommended in Part 2. In addition, Part 3 also aimed at collecting new data on movement speed in smoke filled road tunnels.

![Figure 11. Sign with distances (left) and sign indicating the location of the emergency exit on the opposite side of the tunnel (right)](image-url)

In order to test the different measures mentioned above, experiments were performed in a real tunnel, namely the Northern Link Tunnel in Stockholm. Experiments were performed during a period where the tunnel was still not in use, which permitted smoke filling of a 120 meter section of the tunnel. A total of 66 persons were recruited from the general public in Stockholm for the experiments, in which participants walked one at a time through the smoke filled tunnel in search for a safe location, i.e., the emergency exit. The emergency exit recommended in Part 2 was used in the experiments, but participants were exposed to either none, one or a combination of measures mentioned above. In total, five scenarios were included in the experiment, see Table 3.
Table 3. Scenarios used in the experiment in the smoke filled tunnel

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Way guiding systems tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base scenario, i.e., only a sign opposite the emergency exit (Figure 11 - right)</td>
</tr>
<tr>
<td>2</td>
<td>Base scenario + acoustic alarm at the emergency exit</td>
</tr>
<tr>
<td>3</td>
<td>Base scenario + sign with distances (Figure 11 - left)</td>
</tr>
<tr>
<td>4</td>
<td>Base scenario + acoustic alarm at the emergency exit and signs with distance (Figure 11 - right)</td>
</tr>
<tr>
<td>5</td>
<td>Base scenario + arrows on the pavement (Figure 12)</td>
</tr>
</tbody>
</table>

Results from the experiments in the smoke filled tunnel suggest that the tested emergency exit portal design is appropriate. Furthermore, results indicate that people need some form of way-finding information in order to move from the right-hand wall to an emergency exit at the left-hand wall of a tunnel. The signs with distances to emergency exits were seen as valuable by participants and the acoustic alarm also performed well. In addition, the experiments resulted in valuable data on movement through smoke in road tunnels.

The results and recommendations of Part 3 were given in an interim report [11]. In addition, the work was summarised in a final report [14] and has resulted in two scientific papers [19, 20].

CONCLUSIONS
In order to avoid design mistakes in large infrastructure tunnel projects, it is suggested that research is connected to the parts of the project where current knowledge and recommendations are limited. This way, it is possible to test different aspects, e.g., different evacuation system designs, before the tunnel is built. An example of how research can be linked to the specific design problems of a large infrastructure project, namely the Stockholm Bypass Project, was presented in this paper. A unique feature of the discussed research is that the objectives were formulated in cooperation between the involved parties. In addition, results were disseminated in interim reports and final reports, which were delivered in different stages of the research project. Interim reports, which mainly focused on providing results and associated recommendations, were delivered to accommodate the deadlines of the infrastructure project. Final reports included all the parts of the interim reports, but also discussion of previous research, presentation of experimental procedures, discussion of results, etc. In addition to reports, the project also generated scientific papers. It is believed that the described collaboration between researchers and the Stockholm Bypass Project has facilitated the selection of appropriate safety measures in the Bypass Tunnels, and it is argued that similar approaches can be used in the future to connect research to large infrastructure tunnel projects.

REFERENCES
Full Scale Tunnel Evacuation Experiment to Determine Appropriate Emergency Exit Portal Designs in Road Tunnels

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ABSTRACT

In this paper, the execution and results of an evacuation experiment that was conducted in a road tunnel in Stockholm in 2014 is presented. The primary objective of the experiment was to evaluate the effectiveness of different emergency exit portal designs, and other technical installations/aids in the tunnel, during a fire evacuation in smoke. Based on the results, it is concluded that the emergency exit portal design, which was developed and evaluated prior to the experiment, seems appropriate for the intended use. However, in order to increase the portal may be complemented with information signs on the wall opposite to the exit, way-finding signs including distances to the closest emergency exits on both tunnel walls, and a loudspeaker installation that can inform evacuating people about the location of the available exits.

KEYWORD: evacuation, experiment, human behaviour in fire, road tunnel, smoke, emergency exit, design, exit choice

INTRODUCTION

Fires in road tunnels may quickly become devastating in terms of life safety. Due to the confined tunnel environment, the fire development may be very rapid with a prompt deterioration of evacuation conditions. Time is therefore the critical component when assessing the possibilities for a successful evacuation in the case of fire. Because of the confined tunnel environment, it can be assumed that people might be surrounded by smoke very quickly. Previous research has shown that this typically causes them to follow one of the tunnel walls on their way to safety [1-3]. Ideally, people would follow the left hand side of the tunnel, as this typically is where way-finding signs, escape lights and escape routes leading to a parallel tunnel tube are located. However, in many cases, people may be expected to start to move along the right hand side of the tunnel, and then keep to that side. Consequently, there is a risk that they may miss the emergency exits on the opposite side, especially if the smoke is very dense [4].

The present paper presents research results related to way-finding systems in the context of a real world tunnel project, more specifically the Stockholm bypass. The Stockholm bypass will be a 21 km long motorway connection between the southern and northern districts of Stockholm, Sweden. Just over 18 of the 21 km will consist of twin-bore, parallel tunnels, with three lanes in each direction, and an expected travel time of about 15 min. The bypass will be one of the longest motorway tunnels in the world, and including ramp tunnels connecting the main tunnels to the surface road network more than 50 km of tunnels will be built. The motorway aims to divert long-distance transports away from central Stockholm, to ensure smoother traffic flows and to reduce vulnerability in the region’s
transport system.
In 2012, the Swedish Transport Administration and the Stockholm bypass project were granted co-funding for various tunnel safety studies from the European Union through the Trans-European Transport Network (TEN-T). The research was performed during the period 2012-2014, and the scope included in-depth studies of safety measures in order to either prevent or reduce the consequences of accidents in the tunnel system, as well as technical design solutions for an efficient emergency response. One major part was research on human behaviour during accidents and incidents in road tunnels, and included studies on emergency exit portal design, evacuation communication and design of evacuation lighting. In this paper, the parts of the TEN-T funded project relating to emergency response is presented. This includes the use of a theoretical framework, more specifically the theory of affordances (ToA) for the analysis of the appropriate colour scheme of the portals, a Virtual Reality experiment on the design of flashing lights at emergency portals, and a full scale experiment aimed at validating the findings of the preliminary findings. Focus is on the latter, i.e., the experiment in the tunnel, but the presentation below includes a description of the prior steps as they partly defined the designs to be tested in the field.

METHOD

An evacuation experiment involving 66 participants was performed in the Northern Link road tunnel in Stockholm on July 1-3, 2014 (the experiment could not be conducted in the Stockholm bypass, as it had not yet been constructed). In the experiment, the participants individually evacuated a smoke-filled section of the tunnel, while their walking speed, behavior and exit choice was measured and observed. This paper is particularly focused on the part of the experiment related to emergency portal exit design and exit choice (information about the individual walking speeds has been presented in another publication [5]). In this section, a brief presentation is, therefore, provided on the preparatory work which determined the emergency exit portal designs to be tested in the experiment, as well as the evacuation experiment. Parts of the presentation below is based on a more detailed description of the experiment, which is available in another publication [6].

Theory of affordances

A useful framework for the analysis of the design of evacuation systems is the Theory of Affordances (ToA), which was originally developed by Gibson [7]. According to this theory, an object is perceived in relation to what it offers or affords the individual in relation to his/her goal(s). The ToA has been used in a variety of different research fields, including the evaluation of the design of emergency exits [8], and to explain the effectiveness of way-finding systems for evacuation [9].

According to Hartson [10], affordances can be divided into four different categories:

1. Sensory affordance: sensing or seeing
2. Cognitive affordance: understanding
3. Physical affordance: physically doing or using
4. Functional affordance: fulfilment an individual’s goal

The ToA can be used for identifying potential design faults of evacuation systems early in the design process [9]. By systematically exploring the sensory, cognitive, physical and functional affordances provided by an evacuation system, it is possible to identify conflicts and design issues. Hence, the theory can be used to analyse a set of alternative system designs and provide a ranking of their effectiveness. This was utilized in the preliminary phase of the TEN-T research project in order to rank different designs of emergency exit portals, which were subsequently tested in the lab and the field.

Preliminary design evaluation

The evaluation of emergency exit portal design for the Stockholm bypass was done in several steps,
which included:

1. An affordance-based qualitative analysis of the appropriate colour scheme of the portal
2. An affordance-based test performed in immersive Virtual Reality (VR) in order to evaluate flashing lights at emergency exit portals

**Colour scheme of the portal**

Emergency exit portals in road tunnels should be designed in such a way that motorists will notice and use the exits. In this context, colour coding is an efficient tool to enhance cognitive affordance, i.e., it may improve the recognition and understanding of an object given the colour in use [11]. In addition, colour coding can improve sensory affordance, since it can be used to increase the visibility of the emergency exit portals. In order to increase sensory affordance, it is also important to consider the contrast between the emergency exit portal and the colours of the tunnel walls.

Different colour schemes were initially selected for the design of the emergency exit portal intended to be used in the Stockholm bypass project, and they were matched with the design of the tunnel considered in this study (the door design in the Stockholm Bypass project may include a circular window and a light behind the door). Suggested emergency exit door colours were the “safety green”, a “green darker than the safety green”, white or grey. The background colour of the environment was assumed to be grey in line with the standard colour of concrete (see Figure 1).

![Colour schemes](image)

*Figure 1. Schematic representation of four initial possible colour schemes for emergency exit portals.*

Appropriate contrast of colours should be provided in order to increase sensory affordance, and emergency exit doors inside the portal should be easy to notice and distinguish. This issue appears when using the same colour for the portal and the emergency exit door, as in colour scheme 2, or using a door which has the same colour of the light coming from the window, as in colour scheme 3. Green colour is generally associated with safety, and thus, the use of this colour for the door may generate a higher cognitive affordance than the white and grey colour for the door. Since this affordance-based analysis considers only the visual part of the system, no physical affordance was considered in the preliminary design evaluation. Functional affordance is associated with the goals of the tunnel occupants, and it can be derived in this case from the other affordances (sensory and cognitive). The conclusions of this affordance-based analysis was that the recommended colour scheme is colour scheme 1, i.e. safety green for the portal and a “green darker than the safety green” for the door, see Figure 3. For more information on this step, see Ronchi & Nilsson [12].
Flashing lights at emergency exit portal

In order to study the characteristics of flashing lights on tunnel emergency exit portals, a VR experiment was carried out at the Cave Automatic Virtual Environments (CAVE) VR laboratory at Lund University in which participants had to evaluate different exit portal designs using a Likert scale-type questionnaire [13]. The questionnaire was designed using the ToA [7], specifically investigating the affordances associated with different types of flashing lights. The study of the correlation between the different types of affordances was made using a mixed ordered logit model [14], and the differences among designs were evaluated with inferential statistics.

The virtual reality (VR) experiment involved 96 participants. Different variables were investigated, namely (1) colour of flashing lights, (2) flashing rate, (3) type of light source, (4) number and layout of the lights on the portal. The participants were immersed in a VR road tunnel emergency evacuation scenario and they were then asked to rank different portal designs using a questionnaire based on the ToA. Results showed that green or white flashing lights performed better than blue lights. A flashing rate of 1 and 4 Hz performed better than a flashing rate of 0.25 Hz, and a light emitting diode light source performed better than single and double strobe lights. The layout and position of the lights can be either with 1 or 3 lights or 2 bars on the side of the door, i.e., no significant differences were found among different installation setups. Altogether, these and the previously presented results determined the design of the emergency exit portal to be tested in the evacuation experiment in the Northern Link road tunnel.

Experiment

This section includes a description of the field evacuation experiment, including details on: the tunnel; the participants; the procedure; the scenarios; and the documentation of experiment data.

Tunnel

The Northern Link road tunnel consists of two parallel, unidirectional tunnel tubes. Both tubes were used during the experiment in a section corresponding to approximately 400 m in length. However, only a shorter section of about 120 m in one of the tubes were filled with smoke (see Figure 6). This section was physically separated from the other parts of the tunnel with large curtains. During the experiment, the participants individually evacuated from position C to D in Figure 6, i.e., toward the emergency exit portal located on the left hand side in the tunnel. As the focus of this paper is on the part related to exit choice, the description below typically refers to the environment and installations in the smoke-filled section of the tunnel.

The total cross-sectional width corresponded to approximately 8 m (measured from wall to wall) in the smoke-filled section of the tunnel, and the height to approximately 5 m. An asphalt floor material covered the entire tunnel, and already existing lighting fixtures attached to the tunnel floor were used during the experiment. With smoke present, the light levels on average varied between 90-120 lux in the centre of the tunnel, and 70-110 lux on the right side of the tunnel.

A number of technical installations, aids and objects were added to the tunnel prior to the experiment. Some of these are illustrated in Figure 1, which in summary consisted of: an emergency exit portal (EXIT); way-finding signs (not included in Figure 1); cars (car1-car4); a loudspeaker (LS); smoke machines (SM); and extinction coefficient measurement devices (L1-L2). As can be seen in Figure 1, the emergency exit portal was located in the end of the smoke-filled section of the tunnel. The portal is illustrated in Figure 2, in which the main components are highlighted with numbers that are described below. In summary, the entire portal measured 4 x 4 x 0.9 m (w x h x d), and was constructed using expanded polystyrene blocks. The portal door was a replica, which meant that it could not be opened.
In some scenarios, way-finding signs were installed on the right tunnel wall (see Figure 3). The signs were intended to direct the participants towards the emergency exit, and were installed every 8 m at a height approximately 1.2 m above the road. Each sign measured 0.5 x 0.2 m (w x h), and were constructed using laminated cardboard paper. In addition to the way-finding signs, the information sign illustrated in Figure 4 was also used in all experiment scenarios. The purpose was to inform participants on the opposite side of the exit about the presence of the exit. Neither the way-finding signs, nor the information sign, were illuminated by any particular lighting installations other than the lighting fixtures in the roof. Finally, in one scenario, white arrows were painted onto the asphalt on the right side of the tunnel. They were intended to inform the participants about the distance to the emergency exit portal on the opposite side of the tunnel, and are illustrated in Figure 5.

The numbers in Figure 2 corresponds to:

1. A circular window in the upper part of the door (diameter = 0.35 m), illuminated with a LED-list from behind.
2. A backlit emergency exit sign above the door.
3. Three green LED lights (one above, and one on each side of the door) blinking with a frequency of approximately 1 Hz.
4. A loudspeaker centered above the door. When active, it played a combination of an alarm signal and a pre-recorded voice message according to the following principle: alarm signal – pre-recorded voice message – alarm signal. The voice was instructing the participants that the sound was coming from an exit, and that the participants should follow it in order to find their way out.
5. A light installation with information signs above the portal (green running man, fire extinguisher and an emergency telephone).
Four passenger cars were used in all scenarios to represent abandoned vehicles. Their positions are illustrated in Figure 1, which also includes the position of a portable loudspeaker that was used during the experiment. The loudspeaker played a repeated ventilation noise in order to imitate the sound being generated by the smoke exhaustion fans used during a road tunnel fire. Noise levels were measured in different parts of the smoke-filled section of the tunnel, and on average corresponded to approximately 70 dB. The smoke was produced by multiple smoke machines, which were positioned at different locations in the tunnel, see Figure 1. No irritant component, e.g., acetic acid, was introduced in the smoke. On average, extinction coefficients varied between 0.4-1.1 m\(^{-1}\), corresponding to a visibility of approximately 2-4 m (for light reflecting objects), during the time at which the participants were evacuating the tunnel.

**Participants**

The people that took part in the experiment were recruited from the general public. Prior to the experiment, explicit information about the true purpose of the experiment was not given. However, the selected participants learnt that they would have to walk a smoke-filled environment. In total, 66 participants took part, of which 20 were men and 46 were women. A brief summary of their characteristics are included in Table 1, which is based on the answers that the participants provided in a questionnaire survey conducted after the evacuation. A total of 57 participants (86%) held a driver’s license for passenger cars. In addition, 37 participants (56%) stated that they were travelling through road tunnels more than once every month.

**Procedure**

As the participants took part in the experiment individually, and as each evacuation took almost 30 min to complete, the experiment was performed on three separate days. Each day was divided into three hour slots, and in each slot, a group of new participants arrived to the location of the experiment. In Figure 6, a schematic illustration of the different phases of the experiment is illustrated with block letters. These refer to major stages of the experiment, and are described below.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>A summary of the participants’ characteristics.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age [years]</td>
<td>Min 18</td>
</tr>
<tr>
<td>Height [m]</td>
<td>Min 157</td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>Min 50</td>
</tr>
</tbody>
</table>

1. The group of participants arrived to position A in Figure 6. Information about the experiment was repeated, and the participants were then selected one by one to take part.

2. The participant received a protective overall, and was asked to enter a car parked at position B in Figure 6. Inside the car, the participant received information, among other things informing the participant that he/she would be driven into a smoke-filled part of the tunnel and there receive more instructions.

3. The participant was driven to position C in Figure 6, where the car stopped on the right side of the tunnel. The participant received an instruction to evacuate the tunnel in the same direction that the car had been driving. The context was that he/she had been driving the car, that the car had stopped due to congestion, and that smoke eventually had started to fill the tunnel, which required an evacuation.
4. The participant evacuated the tunnel, from position C to position D in Figure 6, while being followed by a fire-fighter who documented the evacuation with a thermal imaging camera. At this time the participant could not see the fire-fighter due to the dense smoke.

5. The participant either found the emergency exit or evacuated to the end of the tunnel. Independent of which, he/she was led out of the tunnel to position E in Figure 6.

6. The participant received instructions to walk as they would in a normal situation from position E to A in Figure 6, i.e., in a smoke-free section of the parallel tunnel tube. When back at position A, the participant took part in a questionnaire study about his/her experiences during the evacuation.

**Scenarios**

A total of five scenarios were included in the experiment in order to study the effects on exit choice. Basically, each scenario was a combination of a particular emergency exit portal design, the presence of the way-finding signs on the right side of the tunnel, and the presence of the painted way-finding arrows on the asphalt on the right side of the tunnel. In Table 2, a description of each scenario is presented, together with the number of participants that took part in that scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Number of participants</th>
<th>Installation on emergency exit</th>
<th>Way-finding signs on right wall</th>
<th>Way-finding arrows on asphalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>X X X X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>X X X X X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>X X X X X</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>X X X X X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>X X X X X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

**Documentation**

Each evacuation was filmed using a thermal imaging camera, which was operated by a fire-fighter who was always present in the tunnel. Figure 7 illustrates a snapshot from one of the video recordings, in which both the participant and two so called heat pads are discernible (the latter were used to mark out pre-defined distances in the smoke-filled environment, and could not be seen through the smoke). During each evacuation, the fire-fighter kept a safe distance to the participant, which meant that the participant could neither see nor hear the fire-fighter during the evacuation. Still, the fire-fighter could intervene in case of an emergency or if the participants wanted to end the experiment. The video recordings enabled an analysis of each participant’s behavior, walking speed and exit choice.

In addition to the video recordings, the participants filled out a questionnaire about his/her experiences during the evacuation after each evacuation had been completed. In total, the questionnaire included 29 questions, which were both open-ended and closed-ended. The questionnaire was divided into four parts, an included questions related to: (1) general information about the participants, such as age, gender, etc.; (2) information about the experiment, and the participant’s behavior during it, such as questions on degree of realism, what type of information the participant had searched for, etc.; (3) information about technical installations, and the perceived benefit of these; (4) the participant’s feelings during the experiment. During the development of the questions, a structured questionnaire was adopted in order to ensure that the topic of each question had been clearly defined, that the questions were relevant to the study, that they were not biased, and
that they would not be misinterpreted [15].

RESULTS

The experiment rendered much data, in particular on individual walking speeds in smoke, typical behaviors in this environment, and on exit choice. The presentation below is particularly focused on aspects related to exit choice and emergency exit portal design. For more information related to individual walking speeds, and for a more thorough presentation of the results, additional information is available elsewhere [5, 6].

Exit choice

In Table 3, the number of participants that found and moved to the emergency exit portal in each scenario is presented. It is concluded that the majority of the participants used used the exit, independent of scenario. However, if compared to the baseline scenario, i.e., scenario 1, the proportion that found and moved to the portal is higher in all other scenarios. The highest proportion was achieved in scenario 2 and 4, i.e., the scenarios in which the loudspeaker installations was active. In fact, only 1 out of 28 participants did not move to the exit considering scenario 2 and 4 together, which indicates that the loudspeaker was the technical installation that contributed most to the increased exit frequency.

Table 3 The number of participants that found and moved to the exit in each scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Participants in scenario [no]</th>
<th>Participants that found and moved to exit [no]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13 (11&lt;sup&gt;a&lt;/sup&gt;)</td>
<td>8 (73%&lt;sup&gt;b&lt;/sup&gt;)</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>15 (100%)</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>13 (87%)</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>12 (92%)</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>8 (80%)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Two participants did not finish the experiment.
<sup>b</sup> Based on the total number of participants that finished the experiment.

After the evacuation, the participants were asked about aspects related to their exit choice, such as if they at all had noticed any of the technical installations/aids during the evacuation, and if so, which. They were also asked about the perceived benefit of some of the technical installations that were active in each scenario. In addition, they were asked about their selected walking route, and why a participant had decided to move in the direction that he/she did during the evacuation. The purpose of these types of questions was to add some explanatory aspects to the numbers presented in Table 3, and on a more general level to support conclusions on which technical installations/aids that are important in terms of a successful road tunnel evacuation.

Noticing installations

If a participant is to benefit from a specific technical installation/aid, he/she must of course first become aware of it, i.e., notice it. In order to make out if and which installations the participants noticed, the participant’s were therefore asked about what they saw during their evacuations in the smoke-filled section of the tunnel. The result is summarized in Table 4.
Table 4 The number of participants (in each scenario) that stated having noticed a particular technical installation/aid.

<table>
<thead>
<tr>
<th>Technical installation/aid</th>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency exit sign</td>
<td></td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Flashing lights</td>
<td></td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Continuous lights</td>
<td></td>
<td>4</td>
<td>6</td>
<td>10</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Illuminated door</td>
<td></td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Way-guidening arrows</td>
<td></td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Alarm signal and/or pre-recorded voice message</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Coloured lights</td>
<td></td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Running lights</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hand-rails (similar to those used in stairs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

A separate question related to the way-finding sign illustrated in Figure 3, and the result is summarized in Table 5.

Table 5 The number of participants (in each scenario) that stated having noticed the way-finding sign illustrated in Figure 3.

<table>
<thead>
<tr>
<th>Noticed way-finding sign in Figure 3</th>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes, immediately</td>
<td></td>
<td>12</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes, after a while</td>
<td></td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td></td>
<td>12</td>
<td>13</td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>No answer/Do not remember</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

In the end of the smoke-filled section of the tunnel, more specifically on the opposite side of the emergency exit portal, an information sign (see Figure 4) was installed in all scenarios. Table 5 summarizes the number of participants in each scenario that stated having noticed the information sign.

Table 6 The number of participants (in each scenario) that stated having noticed the information sign illustrated in Figure 4.

<table>
<thead>
<tr>
<th>Noticed information sign in Figure 4</th>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td></td>
<td>6</td>
<td>5</td>
<td>10</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>No</td>
<td></td>
<td>7</td>
<td>10</td>
<td>5</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>No answer/Do not remember</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Motives for exit choice

In the questionnaire, the participants that found and moved to the emergency exit portal were asked to specify what made them notice it in an open-ended question. The purpose of the question was to examine if, and if so, which, technical installations were important in terms of exit choice. The answers were analyzed, and are summarized in Table 7, which describes the number of participants in each scenario that mentioned one or more motives. Note that these categories do not necessarily have to correlate to the categories mentioned in Table 4, Table 5 or Table 6, as the questions were open-ended.
Table 7: The number of participants (in each scenario) that mentioned one or more motives for becoming aware of the emergency exit portal on the opposite side of the tunnel.

<table>
<thead>
<tr>
<th>Specified motive</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information sign illustrated in Figure 4</td>
<td>6</td>
<td>3</td>
<td>7</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Backlit emergency exit sign above the door</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Way-finding sign illustrated in Figure 3</td>
<td></td>
<td>4</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flashing lights on emergency exit portal</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Distinguished emergency exit portal itself</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alarm signal and/or pre-recorded voice message</td>
<td>13</td>
<td></td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Way-guidening arrows illustrated in Figure 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

As emergency exits typically only are available on one side of a road tunnel, it is important that people evacuating the tunnel along the “wrong” tunnel wall (i.e., the side of the tunnel without any exits) are notified and become aware of the exits on the opposite tunnel wall. In this perspective, technical installations and aids that can support exit choice are particularly important. Based on the answers in Table 7, it is clear that many of the included installations/aids in the experiment affected the participants’ exit choice. In particular, the loudspeaker installation seem to have been very important, as most participants in scenario 2 and 4 specified the combined alarm signal and pre-recorded voice message as a reason for becoming aware of the exit.

Studying the other scenarios (1, 3 and 5), the motives are not as consistent among the participants. In scenario 1, particularly the information sign opposite to the exit seem to have been important. This seems natural, as no other technical installations/aids were available on the right side of the tunnel. Some participants in scenario 1 did, however, notice the emergency exit portal, or parts of it, i.e., the green flashing lights, directly. Still, as almost half of the group of participants specified the information sign as the reason to why they became aware of the exit, it is likely that the absence of such a sign would have led to more people missing the exit.

In scenario 3, the motives are evenly distributed among the information sign, the way-findings signs with arrows and distances, and the green flashing lights installed on the emergency exit portal. As a higher proportion saw the lights in scenario 3 compared to scenario 1, it is not unlikely that the way-finding signs made people look to the left as they approached the exit. Some participants may, for example, have seen the green flashing lights as a result of being aware of the fact that they were closing in on the exit. Such a trend can, however, not be identified for scenario 5, in which most participants mentioned the way-guidening arrows on the asphalt as the reason for becoming aware of the emergency exit portal.

Perceived benefit of technical installations/aids

In all five scenarios, a backlit emergency exit sign above the door was active. The perceived benefit of this installation on a scale 1-7 (in which higher is better) is summarized in Figure 8, which indicates that most participants seem to have appreciated the installation. It should be noted that only those participants that stated having noticed the sign are included in the summary.

In scenario 2 and 4, the loudspeaker installation which played an alarm signal followed by a pre-recorded voice message was active. The perceived benefit divided per scenario is illustrated in Figure 9. As indicated in the previous sections, the results indicate that the majority of participants seem to have appreciated the installation. As an example, 11 of the 14 participants that rated the installation in scenario 2 did so with a “7”, and 1 rated it with a “6”. In addition, 8 of the 12 participants that rated the installation in scenario 4 did so with a “7”, and 3 rated it with a “6”. 

450
In scenario 5, way-guidening arrows had been added to the asphalt on the right side of the tunnel, i.e., the side where the participants were walking. The arrows were available 30 m from the emergency exit portal. In total, 9 of the 10 participants that took part in the scenario rated the installation, of which 8 rated it with a “7”, and 1 with a “6”.

**DISCUSSION AND CONCLUSIONS**

The evacuation experiment that was performed in the Northern Link road tunnel, and which has been presented in this paper, should be treated as a so called “worst credible” fire scenario, in which a fire have occurred that causes smoke to propagate among still-standing cars. Given these circumstances, the following conclusions are drawn, based on the results of the experiment:

1. The emergency exit portal design, which was developed and evaluated prior to the experiment, seems appropriate for the intended use. Independent of scenario, a high proportion of the participants in each group acknowledged and moved to the exit.
2. In order to increase the likelihood of people noticing and using emergency exits in road tunnels, in particular when people are moving on the “wrong” side of the tunnel (i.e., along the side with no emergency exits), the emergency exit portal may be complemented with the following technical installations/aids (prioritized with respect to installation costs and succeeding costs for maintanence):
   a. Information signs opposite to the emergency exit portals, i.e., on the opposite tunnel wall. The purpose is to inform evacuating people that they are located opposite to an emergency exit, which may not necessarily be discerned through the smoke.
   b. Way-finding signs, including distances to the closest emergency exits, on both sides of the tunnel.
of the tunnel. The purpose is to inform evacuating people of the closest exits, and the
direction in which they should walk.
c. Loudspeaker installations attached to the emergency exit portals, which can play a
repeated alarm sound followed by a pre-recorded voice message that informs
evacuees about the location of the exit. The purpose is to direct evacuees to the exits,
utilizing another sense than vision.

The above conclusions are not only based on the frequency of exit usage, but also on the participants
questionnaire answers related to notification of technical installations/aids, motives for the choice of
walking route and exit choice, and finally, the perceived benefits of the different technical
installations/aids.

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Ventilation and Egress Strategies for Passenger Train Fires in Tunnels

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ABSTRACT
If a fire occurs on a passenger train stopped in a tunnel, with passengers on both sides of the fire location, any active ventilation measure will push the smoke towards some of the passengers. Not using the ventilation may expose a different group of passengers to the smoke. Ideally, the ventilation system should be used in such a way as to facilitate egress for as many passengers as possible. This paper investigates whether this is best achieved by using or not using longitudinal ventilation, for three different fire scenarios. The study compares the tenability of the tunnel environment on both sides of a fire on a passenger train, along the length of the egress paths, for the duration of the evacuation process. Tenability conditions, based on a fractional effective dose model, are compared in scenarios using longitudinal ventilation to control smoke, with scenarios using only natural ventilation. The effect of ventilation on fire growth is considered. It is concluded that the use of longitudinal ventilation will rapidly lead to untenable conditions for any passengers downstream of the fire, whereas natural ventilation can allow sufficient time for all passengers, on both sides of the fire, to reach a cross-passage before untenable conditions are generated.

KEYWORD: ventilation, tenability, egress, passenger trains

DISCLAIMER
This paper considers the specific case of emergency egress from a high-speed passenger inter-city style train in a long tunnel with cross-passages. Several assumptions are made. It is important to stress from the outset that the conclusions which will be drawn here relate exclusively to this specific scenario, will depend strongly on the assumptions made, and are therefore not transferrable to other vehicle types or tunnel configurations.

INTRODUCTION
The question under consideration is this: Could there ever be an emergency egress situation in a vehicle tunnel where the appropriate ventilation strategy would be not to use the ventilation system?

In an ideal world, incidents would not occur in tunnels and passenger egress from trains in tunnels would never be required. As this is not an ideal world we need to put systems in place to protect passengers in the event of an incident occurring. In an ideal incident, the driver should retain full control of the train for an extended period of time (current industry standards aim for 15 minutes), and have the ability to bring the train to a controlled stop, either outside of the tunnel, in an emergency station in the tunnel (e.g. Gotthard Base Tunnel), in a designated fire-fighting station (e.g. Channel Tunnel), or with the primary train egress doors aligned with the cross passage doors, so that escaping passengers should spend the minimum time possible between leaving the train and entering the safety of the cross-passage.

Unfortunately, ideal incidents rarely happen. For example, in the recent Channel Tunnel fire in January 2015, the strategy should have been to drive the train to a fire-fighting station or drive the
train out of the tunnel. In reality, neither strategy was possible and the train had to stop at an unintended location in the tunnel. It is clear that fire strategies need to be developed for unplanned and uncontrolled stops of trains in tunnels as well as ‘ideal’ scenarios. For the purposes of this paper, an uncontrolled stop is the situation where the train is unable to stop with the egress doors aligned with the cross passages [1].

**DEFINITION OF THE SCENARIO**

Here we consider a typical, modern, high-speed passenger train. Specific dimensions used in this study are based on French TGV and Eurostar trains, but many other train types have similar dimensions. The envisaged train, see Figure 1, has two locomotives/power cars at the front and the rear (designated PC1 and PC2), two end carriages (designated C1 and C18) and sixteen intermediate carriages (C2 to C17). The train has a length of about 450 m and carries up to 800 passengers (here we will assume 750 passengers).

![Figure 1](image)  
*Figure 1  The front portion of the typical passenger train considered.*

During an emergency fire egress, the strategy considered here is for passengers to make their way, away from the fire, along the train to either carriage C1 or C18, and leave the train through the main exit doors in these carriages. Once in the tunnel the passengers need to make their way to the nearest cross-passage exit.

Spacing of cross-passage exits varies from tunnel to tunnel. In the Channel Tunnel, for example, the passages are 375 m apart, in the Gotthard Base Tunnel, they are 325 m apart. These distances are broadly consistent with the length of typical trains.

In an ideal scenario, the front and rear train exit doors would both align with cross passages to facilitate rapid egress and minimise time in the tunnel environment. If this does not happen, the worst case scenario would be one where the fire is positioned beside a cross passage, rendering that route unavailable. This is the scenario considered in this study. In this scenario, passengers near the fire location would have to walk about 375 m, with part of the route on the train and the remainder of the route in the tunnel environment. The proportion of the distance on the train compared to that in the tunnel will, of course, depend upon the location of the fire on the train. This study considers the tenability of that egress path under different fire and ventilation scenarios.

A fire event could occur on any of the carriages in the train. If the fire occurs on either of the power cars or carriages C1 or C18, all passengers may be taken to be on the same side of the fire and it is clearly appropriate to use the ventilation to blow the smoke away from the passengers. These situations are not considered further in this paper.

The situations considered here are those where there are passengers on both sides of the fire location. For simplicity, only three situations have been considered:

- Fire between C2/C3 (or C16/C17); with 104 passengers on one side of the fire and 646 passengers on the other side of the fire. (The passenger distribution has been based on the passenger distribution on a typical Eurostar shuttle.)
- Fire between C5/C6 (or C13/C14); with 272 and 478 passengers on each side of the fire, respectively, and
- Fire at the mid-point of the train (between C9/C10); with 375 passengers on each side of the fire.
It takes these passengers some time to travel along the train, possibly queue to get through the train exit door, then walk along the tunnel to the cross-passage exit. The primary concern of this study is to investigate the tenability of the tunnel environment during the egress process. This involves a careful study of a number of inter-related factors, which are discussed below.

**CONSIDERATIONS**

In order to adequately answer the question of tenability it is essential to understand the fire behaviour of trains in the tunnel environment, the production of smoke from these fires, the effects of tunnel ventilation on this smoke, the movement of people in this environment, and the effects of smoke on the escaping passengers. Of crucial importance is understanding the interactions between some of these considerations. We will consider these in turn.

**Fire behaviour of passenger trains**

As with all fires, understanding fire behaviour in tunnels involves an understanding of the nature of the fuel, the release and dissipation of the heat produced by the fire, and the movements and interactions of incoming air and outflowing smoke. Vehicle fires in tunnel environments are typically characterised by high heat release rates, fairly rapid fire development and very high temperatures being developed [2].

Only a handful of fire tests involving railway carriages in tunnels have been carried out to date, and none involving current or recent generations of railway rolling stock. Graphs of the heat release rate data from fire tests carried out as part of the EUREKA EU499 Project [3], the Metro Project tests [4] and at Carleton University [5] are shown in Figures 2 to 4, below. Each of these tests are described in more detail by Carvel & Ingason [2] and in the references given above.

The fire behaviour observed in the joined half-carriage test, see Figure 2, was due to a very unusual configuration of fuel, the location of the initial ignition, and abrupt changes in the ventilation flow in the tunnel, thus it is not possible to make any generalisations about rail carriage fire behaviour on the basis of this test.

![Figure 2](image_url)

*Figure 2*  Approximate HRR data from Hammerfest IC train test F11 (solid line), ICE train carriage test FS2 (short dash), joined half-carriage test FA3 (long dash) and subway carriage fire test F42 (double line), adapted from [3].
Figure 3  Approximate representation of HRR data from the Carleton University fire tests. The rail car is indicated by the broken line and the subway car by the continuous line, adapted from [5].

The Carleton fire tests were carried out in a tunnel-like facility, but not a true tunnel. It may be important to note that the ventilation in this facility is generated by exhaust fans, pulling the smoke, not jet fans driving the fresh air. Also, there was no significant length of ‘tunnel’ upstream of the carriage, only a reduced height opening to the open air, see Hadjisophocleous, et al. [5] for details.

Figure 4  Approximate representation of HRR data from the METRO project fire tests. Test 2 is indicated by a solid line and Test 3 with a broken line, from [4].

From the data presented above it is apparent that there are broadly two types of fire behaviour observed:

Type A: Rapid fire growth (only 2-5 minutes duration) to a peak above 30 MW, fairly short duration fire, then a rapid decay as the fire runs out of fuel. This is observed in the EUREKA subway car test, the Carleton subway car test and the two Metro Project tests.
Type B: Slower fire growth (15 to 25 minutes) to a peak of about 10 MW, long duration of burning (hours, not minutes) then a slow decay. This is observed in both the EUREKA railway carriage tests.

The Carleton railway carriage test had aspects of both types of behaviour, but appears more like a Type A fire, but with a slower growth rate and decay.

It is tempting to think that Type A behaviour corresponds to subway carriages and Type B behaviour corresponds to rail carriages, but this may be just coincidence as analysis of other fire test data involving road vehicles and various cargo commodities [2] shows the same two forms of behaviour. The distinction in these instances (as well as in the tests described above) is that Type A behaviour is consistently observed in fire tests with mechanically supplied ventilation (generally above 2 m/s) and Type B behaviour is consistently observed in fire tests with natural ventilation and low flow velocities.

Thus it is clear that a fire on a train carriage subject to mechanically forced ventilation will burn in a different way from a fire on a train carriage under natural or low flow conditions. This observation is incorporated into our study.

It has previously been shown [6] that tunnel fires do not grow in the form of a ‘$t^2$’ fire, which is a common assumption in other fire types in the built environment. Fires in tunnels generally appear to grow in a two-step linear manner, the first stage of which is characterised by slow fire growth, when the fire is smaller than one or two MW, followed by a period of much faster fire growth. The first stage (referred to in the literature as the ‘initial’, ‘delay’ or ‘incipient’ phase) can be as short as one or two minutes and as long as nearly two hours (see, for example, Figure 4). At present, we have no clear understanding of the factors which influence this duration, so for design purposes it should be assumed that this stage is short. In the present study we have assumed that the incipient phase of the fire occurs while the train is in motion, and the more rapid growth phase of the fire development begins as the train comes to a halt. It is also assumed, for simplicity, that this is when passenger egress begins, so the ‘pre-movement’ time of the passengers is taken to be while the train is in motion.

In this study, two fires have been used:

Type A: Linear growth from 0 to 45 MW in 4 minutes, thereafter constant until the end of the egress time (about 22 minutes, see below).

Type B: Linear growth from 0 to 10 MW in 20 minutes, thereafter constant until the end of the egress time.

These fire types conform well to the patterns observed in the data in Figures 2 to 4, erring slightly on the conservative side.

**Passenger egress**

A realistic estimate of passenger egress time is required. This is briefly summarised here, further details can be found in Winkler & Carvel [7]. The calculation considers the rate of flow of people through the train door and their descent onto the pathway. Fridolf [8] shows that the descent distance affects the flow rate through exit doors. However, suitable bridging between the train and the tunnel walkway can often be expected, as for example required in the Channel Tunnel [9]. Therefore a low vertical distance has been assumed in the present study. Once in the tunnel, the passengers walk, through the smoky environment, to the cross passage. The Metro Project [4] recommends an average walking speed of 0.9 m/s in smoke filled environments. This value was determined experimentally in a smoke logged tunnel with visibility ranges from 1.5 to 3.5 m. As it is not guaranteed that a visibility of 1.5m can be maintained, a lower walking speed of 0.5 m/s has been used throughout this analysis.

The egress routes on the ‘left’ of the fire are shown diagrammatically in Figure 5 (note: in each case, the fire is considered to be between carriages, not in the middle of a carriage, as shown) and details of
the distance and calculated duration of egress, for each of the scenarios, are summarised in Table 1.

![Figure 5](image)

**Figure 5**  Schematic of the ‘left side’ egress routes considered for fires on Carriages C2, C5 and C9. The cross passages are indicated by ovals. In each case, the cross-passage nearest the fire is deemed to be inaccessible.

<table>
<thead>
<tr>
<th>Fire location</th>
<th>Egress side</th>
<th>Number of passengers</th>
<th>Maximum travel distance on train</th>
<th>Travel distance in tunnel</th>
<th>Total egress time in tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2/3</td>
<td>Left</td>
<td>104</td>
<td>40 m</td>
<td>335 m</td>
<td>872 s</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>646</td>
<td>320 m</td>
<td>55 m</td>
<td>1361 s</td>
</tr>
<tr>
<td>C5/6</td>
<td>Left</td>
<td>272</td>
<td>100 m</td>
<td>275 m</td>
<td>1077 s</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>478</td>
<td>260 m</td>
<td>115 m</td>
<td>1156 s</td>
</tr>
<tr>
<td>C9/10</td>
<td>Left</td>
<td>375</td>
<td>180 m</td>
<td>195 m</td>
<td>1116 s</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>375</td>
<td>180 m</td>
<td>195 m</td>
<td>1116 s</td>
</tr>
</tbody>
</table>

**Table 1**  Summary of egress travel times and distances used in this study.

Of particular concern in our analysis is the tenability of the tunnel environment, between the train exit door and the cross passage exit, for the duration of the egress process. This has been estimated using computational fluid dynamics (CFD), as discussed below.

**Use of CFD for tenability estimation**

According to Purser [10], several parameters need to be identified to allow an estimation of tenability on the egress route, including: carbon monoxide, carbon dioxide & oxygen concentrations, radiant heat flux, smoke temperature, and optical density of the smoke. Current computer fire models are able to simulate most of these parameters with an acceptable degree of accuracy, given a pre-defined fire scenario [11]. In this study, Fire Dynamics Simulator (FDS, version 6) was used as it has been validated for most of these predictions [12]. However, given the size of the computational domain required here, it was not deemed practical to use sufficiently small computational cells to provide acceptably accurate predictions of CO production and transport, so these data were estimated in post-processing, as described elsewhere [7,13]. The tunnel and train were modelled in FDS using a 0.25 m grid, as shown in Figure 6.

In each instance, the computational domain was defined to be two carriage lengths (i.e. 40 m) longer than the zone of interest, and the simulation was started 60 s before the fire started growing and before the egress began, to allow the flow to become established throughout the domain. The concrete walls were modelled with typical heat loss and roughness properties. In ventilated scenarios, air is supplied at the upstream (right) end of the domain at a rate of 100 m$^3$/s, which is the flow rate used for emergency ventilation in the Channel Tunnel [14].
The FDS simulations provide predictions of CO\textsubscript{2} concentration, oxygen concentration, optical density and temperature throughout the computational domain. In order to estimate CO concentrations, a series of hand calculations have been developed which correlate CO production with CO\textsubscript{2} production, soot production and the local equivalence ratio at the fire location [7,13]. Following this analysis, we have sufficient predictions to estimate the tenability effects in the tunnel environment.

The toxicity model

The effects of the conditions in the tunnel have been assessed using a modified form of Purser’s Fractional Effective Dose (FED) model [10,15]. Two quantities are assessed: the fractional effective dose for asphyxiants (FEC\textsubscript{as}) and the fractional effective dose for heat (FED\textsubscript{heat}). In each case, a value of unity or above would indicate conditions leading to incapacity or fatality for about 50% of a population. FED values above 0.3 can lead to serious consequences for some people [15], so values above this threshold are generally to be avoided, if possible. It should be stressed that the FED predictions made using this model should not be taken as absolute measures of toxicity, but rather to give a relative ranking of scenarios. In any comparison between options, the strategy leading to the lower FED value should always be preferred.

In Purser’s analysis, the fractional effective concentration of smoke (FEC\textsubscript{smoke}) is also assessed to provide an estimate of an occupant’s response to visibility. This has been neglected here as even in low levels of visibility, it may still be possible to navigate along the tunnel wall, indeed in the Channel Tunnel and elsewhere a handrail is provided which may assist egress in low visibility.

The FED model is described elsewhere [7,13]. It can be applied to any evacuee travelling from the exit door of the train to the cross-passage door in the tunnel. For simplicity, characteristic values of each of the quantities of interest are sampled from the FDS results every minute of simulation time and the FED model assesses the toxic effects each minute. As the toxicity model is a cumulative model, the FED for any given evacuee increases with longer exposure times. For simplicity in the results, presented below, tenability will only be presented for the first and last passengers to leave the train.

RESULTS

Figure 7 shows the carbon monoxide concentrations experienced by the first passenger escaping to the ‘left’ in both mechanically and naturally ventilated conditions, for each of the three fire locations considered. Note that the passengers in the case of a C2 fire (where the train exit door is near to the fire and the cross passage door which the fire blocks) spend more time in the tunnel than do passengers from a C5 fire, who likewise spend more time in the tunnel than in the case of a C9 fire, hence the different lengths of the graph lines. Equivalent data for temperature, heat flux, CO\textsubscript{2} concentration, O\textsubscript{2} concentration and optical density were calculated [13], but cannot be presented here due to limitations of space.

From Figure 7 it is immediately apparent that the passengers in the mechanically ventilated case
experience much greater exposure to high levels of CO than passengers in the naturally ventilated case. This is to be expected as the ventilation in this instance is blowing all the smoke towards the passengers considered here. Of course, this observation must be considered together with the fact that there are also many passengers escaping to the ‘right’ in a smoke free environment.

The cumulative effect of exposure to the tunnel environment for the first escaping passenger in each of the scenarios considered is shown in Figures 8, 9 and 10 for fires on C2, C5 and C9, respectively.

It is clear from Figures 8, 9 and 10 that the environment in either direction in a naturally ventilated fire is considerably more tenable for the first escaping passenger than the environment downstream of a ventilated fire. In all instances, the FEDIN of the first escaping passenger exceeds 0.3 before they have reached the cross passage exit, and in the case of a fire in C2 exceeds unity well before the cross passage would be reached.

Thus it would appear that in the case of a fire in C2, using mechanical ventilation to provide fresh air for the majority of passengers (i.e. the 646 passenger to the ‘right’) would result in conditions likely to incapacitate and lead to terminal consequences for all 104 of the passengers to the ‘left’.

Figure 11 shows the FED calculations for the last escaping passenger in natural ventilation conditions, both to the left and right, for all three scenarios. While the FED calculations should not be understood in terms of absolute predictions of toxicity here, it is clear that the predicted FED values for the last escaping passenger in all naturally ventilated scenarios are considerably lower than the predicted values for the first passenger escaping to the left in any of the mechanically ventilated scenarios.
Figure 11 shows the results for the $FED_{IN}$ and $FED_{heat}$ for the last escaping passenger downwind of the fire in the mechanically ventilated scenarios. While it appears that conditions likely to incapacitate the last passenger on the basis of asphyxiating gases might not be reached in the C9 egress scenario, once $FED_{heat}$ predictions are taken into account, it is clear that lethal conditions are attained well within the egress time predicted. Thus it is apparent that in none of the forced ventilation scenarios is the survival of all passengers expected.

If these calculations are deemed reliable, the conclusion of this study is that in any scenario where there are passengers on both sides of the fire, adopting a natural ventilation strategy should allow all passengers to reach the nearest cross passage in smoky but tenable conditions. Using a mechanical ventilation strategy will lead to lethal conditions downstream of the fire before all passengers have safely reached the cross passage exit. In the case of a fire near to the exit door, i.e. a fire on C2, it is not expected that any passengers downwind of the fire would survive.

**DISCUSSION**

Common practice in the event of a fire in a tunnel is to use the ventilation system, if there is one, to blow the smoke away to provide a smoke free egress path for most, if not all, of the escaping people. This strategy was established for use in road tunnels and is now the default strategy in almost all uni-directional road tunnels. In the road tunnel situation the benefits of this strategy are clear; if there is an incident in the tunnel, all vehicles ahead of the incident are unaffected by it and may therefore safely make their own way out of the tunnel. The strategy is designed to protect the queue of vehicles that will undoubtedly form behind the incident. The ventilation should thus be used in the direction of traffic flow. If longitudinal ventilation is not used in this scenario, the smoke would spread in both directions from the fire location, most likely at a velocity faster than walking speed [16], so tunnel occupants in the queue of vehicles would be caught in the smoke.

This line of reasoning has, quite rightly, dominated road tunnel ventilation design for the past few decades, but has also been largely adopted by the rail tunnel industry, despite the considerable differences between the two tunnel types. The crucial difference between the road tunnel scenario and the rail tunnel scenario considered here is that the carriages ahead of the fire incident cannot simply drive away from the fire location.

The question of whether or not longitudinal ventilation should be used to facilitate egress comes down to a question of the location of the fire. If there are passengers on both sides of the fire, and if they are unable to get past the fire to the ‘upstream’ side of it, then any use of ventilation to blow the smoke
longitudinally will enflame the fire and, hence, result in untenable conditions on the ‘downstream’ side of it. As we have shown the conditions may become lethal within a few minutes. Thus if a fire occurs, and its location (relative to the passengers) cannot be precisely identified (e.g. in the Channel Tunnel the smoke and heat detectors are fixed in the tunnel, so cannot precisely locate the fire on a train), the only justifiable course of action is to assume that there may be passengers on both sides of the fire, and control the ventilation appropriately.

Once egress has begun it is important that the ventilation strategy remains the same until all passengers have reached the cross passages as changes in ventilation flow during a fire can have very negative consequences on the fire behaviour and the movement of smoke [17].

While absolute predictions of FED exposure have been made above, it must be stressed that due to the uncertainties in the model, these numbers must be treated with caution. It may be that the conservative assumptions built into the above analysis will tend to overestimate the incapacitating effects of the smoke in the tunnel. In other words, it may be that lethal conditions will not be attained as quickly as predicted above. Nevertheless, the relative values of FED are not subject to such a great uncertainty. Even if the absolute values contain systematic errors, the results clearly indicate that the escape route in both directions in a naturally ventilated tunnel is about ten times more tenable than the environment downstream of a ventilated fire.

The primary factor leading to this outcome is the very rapid growth of the fire when longitudinal ventilation is used. This leads to the situation of a very large fire while the egress process is still ongoing. In the case of a naturally ventilated fire, the fire continues to grow beyond the duration of the egress process, and is relatively small during the evacuation phase.

It is possible to choose between a rapidly growing large fire and a slower growing smaller fire. Using longitudinal ventilation may lead to the former scenario. Using natural ventilation, or using the ventilation system to minimise flow at the fire location will lead to the latter scenario. These effects must be considered as part of any fire strategy decision making.

OTHER SCENARIOS

Another scenario considered during the project is phased evacuation. This scenario, which is based on an existing strategy intended for use in some rail tunnels, uses longitudinal ventilation to clear the egress route of smoke for the majority of passengers, while instructing the remaining passengers on the train, downstream of the fire location, to remain on the train until instructed to exit. The intention is to allow the majority of passengers to get to the cross passage and then, once the first phase of passengers have reached a place of safety, to reverse the ventilation direction, clearing the tunnel of smoke on the other side of the fire, and then instructing the passengers on the train to exit through the tunnel, which is now clear of smoke. As noted above, the egress process for the first phase would take about 22 minutes, then it would take some time to reverse the flow and clear the tunnel of smoke, so the second phase of the evacuation would not begin until at least half an hour after ignition, possibly longer.

Assessing the tenability of the on-train environment requires a number of assumptions to be made about the airtightness of the carriages and the pressure onboard the train. Modern high speed railway carriages are very well sealed and may be pressurised during normal operation. Thus it is to be expected that these would remain air-tight for some time in a phased evacuation setting. However, materials typically used in window seals on such carriages may begin to soften at temperatures above 150°C, which would be generated in the tunnel after only a few minutes of fire growth. It is to be expected that carriages near to the fire location would not remain airtight for as long as half an hour. Indeed, the thermal environment in the tunnel would, most likely, lead to a thermally untenable environment on the train before the window seals would fail.

The final scenario considered is the situation of a controlled stop, that is, where the exit doors are
aligned with the cross passages. This situation leads to a very short egress path in the tunnel environment, so it might be expected that this situation would be tenable, even in a longitudinally ventilated fire scenario. Indeed, calculations show that the $FED_{IN}$ values are very low in all ventilated and natural ventilation situations. However, the $FED_{heat}$ calculations show that the thermal tenability conditions in the tunnel at the egress location deteriorate towards untenable, before all the passengers have evacuated. Table 2 gives the calculated $FED_{heat}$ values for the last passenger escaping from carriage 1, for each of the scenarios considered.

<table>
<thead>
<tr>
<th>Fire location</th>
<th>Ventilation condition</th>
<th>$FED_{heat}$</th>
<th>$FED_{heat,forced}$</th>
<th>$FED_{heat,natural}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2/3</td>
<td>Natural</td>
<td>0.004</td>
<td>7900</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forced</td>
<td>31.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5/6</td>
<td>Natural</td>
<td>0.007</td>
<td>225</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forced</td>
<td>1.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C9/10</td>
<td>Natural</td>
<td>0.017</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forced</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: $FED_{heat}$ calculations for the last escaping passenger in controlled stop conditions

It is clear from Table 2 that conditions of the last escaping passenger are considerably more untenable if forced ventilation is used, relative to natural ventilation. As noted above, the absolute $FED$ values are subject to a lot of uncertainty, but based on the calculations summarised here it is clear that even in a controlled stop situation, unless the fire is far from the exit door, a longitudinal ventilation strategy is not to be recommended.

CONCLUSIONS

An analysis of the tenability conditions in a tunnel on both sides of a fire on a passenger train has been carried out, taking into account changes in fire behaviour due to the ventilation, egress times and fire locations. Scenarios using natural ventilation and mechanically forced ventilation have been compared.

On the basis of this analysis it is predicted that:

- If a natural ventilation strategy is adopted, even if the fire blocks one cross-passage exit, all passengers can make their way to another cross passage exit before conditions in the tunnel become untenable.
- If mechanical ventilation is used, conditions on the downstream side of the fire will become untenable within a few minutes, possibly leading to lethal conditions for all escaping passengers.
- Thus, if there are passengers on both sides of the fire, mechanical ventilation for smoke control should not be used.
- Even in a controlled stop situation, the conditions at the egress door downstream of the fire may become thermally untenable if mechanical ventilation is used.
- A phased evacuation strategy is not recommended due to thermal exposure to the waiting passengers.

These conclusions relate specifically to the studied scenarios, are dependent on the assumptions used, and should not be generalised to any other tunnel fire situations.
REFERENCES

Designing Evacuation for Deep Underground Stations Including Escalators

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ABSTRACT

This paper addresses challenges as adopting existing regulations and standards to fire safety designs in underground station. The key questions in this paper are; when designing evacuation for underground stations including escalators, are considering conventional walking speed or capacity in escalators good enough? Is there a need to consider other issues to ensure an acceptable safety level in the fire safety strategy? There is no clear-cut ready-to-use regulation to be implemented when designing fire safety in deep underground stations today, particularly concerning ascending egress using escalators. The focus of this paper is the usage of escalators as part of the egress strategy for deep underground stations in case of fire or other emergencies. Conclusion drawn from the evaluation in this paper is to update regulations concerning technical aspects with regards to escalators. Pedestrian flow in stopped escalators should vary as a function of the total vertical height rather than being dependant on each individual escalator height.

KEYWORD: deep underground stations, pedestrian flow, fire safety, egress, evacuation, escalators, upward movement, fatigue, fire safety strategy, ascending evacuation, code compliant

INTRODUCTION

There is no recognised regulation, neither international nor national, that has a comprehensive design approach to be implemented when designing fire safety in deep underground stations today. Especially with regards to ascending egress using escalators. Available research and regulations regarding underground stations and egress using escalators is not hitherto compliant for deep underground stations. Furthermore, countries that do not have regulations covering deep underground stations end up with a choice of what design strategy to use. Either the choice is to use the conventional national building code, not applicable to underground stations, or international regulations/standards from other countries, which is not always applicable in a different countries from what the regulation or standard was written for. In addition, a combination of national and international regulations may be chosen.

Presented in this paper is an analysis as a case study using pathfinder [1] to shed light on the identified design aspects. In the field of fire safety it is argued that there are flawed codes covering egress strategy from underground stations. Example, NFPA 130 that do not to properly specify the egress flows in escalators with regards to length of the escalator. Far reaching consequences can be expected due to faulty or inappropriate standards as well as misuse of the standard [2, 3]. This paper addresses such challenges as adopting existing regulations and standards to fire safety designs in deep underground station when designing new stations.
IDENTIFIED DESIGN ASPECTS TO BE EVALUATED

When designing deep underground stations and buildings there are many challenges in developing a fire safety strategy. This is due to the lack of both comprehensive available research as well as standards and regulations, leaving it up to the fire engineer to find a suitable design method for each specific project. Consultants designing deep underground stations often refer to prior work done and regulations used to find support in their design method. This cause problems since it leads to new research findings not being implemented in new design. Through available regulations and the latest research as well as experience the following aspects has been identified as challenges when designing fire safety strategies for deep underground stations:

1. Research indicates that pedestrian flow in stopped escalators due to fatigue is affected by depth of the station (e.g. length of escalators).
2. Designing fire safety strategy without valid or with non-applicable standards and regulations for deep underground stations.
3. Basic prerequisite for design of egress using escalators often recommends blockage of one escalator when calculating egress time. However, there is a risk that more than one may be blocked during maintenance due to escalator configuration.
4. Escalators, being a technical installation, potentially generate additional sensitivity scenarios to be incorporated in the egress analysis such as technical failure.
5. Identified aspects in number 1 – 4 for egress may cause knock-on effects if landings between escalators do not have sufficient area to allow for queuing. Which in some cases can result in a "domino-effect" of people falling backwards in escalators.

EVALUATION OF PROBLEMS THAT IDENTIFIED DESIGN ASPECTS MAY CAUSE

1. Research indicates that pedestrian flow in stopped escalators due to fatigue is affected by depth of the station (e.g. length of escalators)

When available regulations for underground stations was written the research for pedestrian flow in upward or stopped escalators was insufficient and no consideration was taken neither to long transitions upwards or more than one consistent rise. Due to lack of space available for expanding cities there is a need to build deeper underground which results in longer vertical transitions.

New research regarding egress flow in stopped escalators indicates that movement speed upwards is affected by fatigue due to length of the escalators. People’s walking speed in a stopped escalator significantly decreases when the vertical height reaches over 20 – 30 meters. [4, 5]

Standards and regulations today only specifies walking speed and pedestrian flow in vertical transition with no regards to the specific height of one escalator nor any consideration to continued vertical escalator rises [3, 6, 7]. Figure 1 illustrates escalator rise, landing and total vertical height.
In line with available regulations and guidelines today’s egress analysis and evaluations, of pedestrian flow in escalators for of deep underground stations, are assumed based on a single vertical rise in the context of limited amount of vertical movements in each separate vertical height. The assumption means that no adjustment is done in regards to the total vertical height. This results in that fatigue, due to total vertical height transportation during egress, is not accounted for which may lead to flawed pedestrian flows in escalators being used in calculations. Using a higher pedestrian flow in egress calculations may result in designs that are not compatible with real life or best practice in fire safety strategy, where worst case scenario should be considered. Real life egress times may therefore be significantly longer since the specified capacity in one escalator rise used for design does not consider aspects like fatigue as much as actually required. Consequently, movement speed and pedestrian flow in escalators should vary as a function of the total vertical distance.

2. Designing fire safety strategy without valid or with non-applicable standards and regulations for deep underground stations

Since there is no comprehensive international regulation regarding fire safety in deep underground stations, national standards and regulations not intended for these types of facilities might be used due to this lack of guidance when designing fire safety strategies. Example, there is a gap between Swedish national building regulation and Swedish tunnel regulation leaving the interpretation and adoption of guidance, hence level of safety, to be decided by each specific design group [8-11].

Due to lack of national or comprehensive fire codes, for deep underground stations, engineers and project managers might find themselves adapting different approaches when designing fire safety design. This can result in methods such as:

- a pick-and-choose approach, combining whatever they find convenient from different regulations, or
- applies and interprets building standards not valid for deep underground station.
- add-on approach, with excessive fire safety measures to adjust for the uncertainty in lack of guidance.

The different approaches can cause a discrepancy in safety level for different projects where some follow and applies for example NFPA 130 to its full extend even for deep underground stations. The pick-and-choose method can also lure engineers into a false sense of security that consideration has been taken to all aspect regarding fire safety. Whereas an add-on approach can result in complex and unnecessarily expensive designs.

When there is no single regulation to fully comply with there is a risk that the overall fire safety design does not fulfill an acceptable level of safety. As a consequence, the fire safety level might be minimized and based more on cost effectiveness than on an acceptable fire safety level. The partial integration of different standards and regulations could even prove counterproductive for the overall project. Either with an add-on approach resulting in excessive fire safety measures or a stripped design resulting in not enough safety measures.

Furthermore, the funder or client of new underground facilities is not always the same as the owner or organization accountable for building maintenance and operator in terms of fire and safety management. The different organizations being responsible for different phases of the station often have diversely aims with the project. The difference in objective priorities is frequently separated between cost respectively functionality and operability. This may result in a diversion of assumed operation of escalator in the design phase not being implemented in real life operation. The risk is that during normal operation steering of escalator’s direction is reversed for more efficient commute flow resulting in lower egress capacity in escalators than required in the fire safety strategy [12-16].
3. **Basic prerequisite for design of egress using escalators often recommends blockage of one escalator when calculating egress time.**

Maintenance on escalators has to be considered when calculating necessary egress capacity from underground stations. NFPA 130 for an example specifies that at least one escalator should be disregarded due to blockage caused by maintenance when calculating egress capacity. A factor that has a direct effect on number of escalators blocked during maintenance is the available space between escalators. Example, in reality more than one escalator may be blocked during maintenance if there is not enough width between escalators. How many escalators that are blocked during maintenance depends on the manufactures technical requirements on their escalators as well as the escalator configuration [17, 18]. Therefore, it is important to follow up that the fire safety strategy is fully incorporated into the overall design and adopted to the specific escalators used in each project.

NFPA 130 states that one escalator should be considerate as out of service in each rise (level). It is not credible that one escalator in each rise is blocked of during maintenance. Assuming that one escalator in each rise is out of service instead of in just one rise will also bypass the risk and consequence of domino-effect of people falling backwards in escalators. This domino-effect is due to difference in pedestrian flow in the different rises as oncoming escalator to a landing can exceed outgoing escalator from the landing, see Figure 2. The cross indicates an escalator out of service and the arrows indicates directions of escalators prior to evacuation.

![Figure 2. Incoming pedestrian flow to landing is higher than outgoing pedestrian flow from landing.](image)

Hence, a stopped escalator from the landing will cause queuing, on the landing, reaching back towards the upcoming escalators if landings between the escalators do not have sufficient area to allow for queuing. If the capacity to the landing exceeds the capacity from the landing the queue on the landing will increase over time and eventually block people in upcoming escalators. Resulting in people falling backward as there is no way to go on top of the escalator but the escalator continues to bring people to the landing.

4. **Escalators, being a technical installation, potentially generate additional sensitivity scenarios to be incorporated in the egress analysis such as technical failure.**

When designing the fire strategy for deep underground facilities the possibility of failure of technical installation, such as escalators, should be taken into account [19]. Furthermore, NFPA 101 specifies that egress evaluation in buildings should be done with regards to that a technical system could fail during an egress. This is usually interpreted as failure of systems as fire suppression or fire ventilation. Technical system failure in egress analysis should also be interpreted as an escalator could fail during egress. Making sure that the planned egress strategy is fulfilling acceptable fire safety level even if an escalator fails prior to or during egress.

There are other more exceptional scenarios to be considered however more unlikely. For instance due to an accident in an escalator in Stockholm’s subway system all escalators from the same manufacturer where stopped during investigation of the cause [20]. This resulted in several stations where all escalators where stopped. People had no other choice than to walk up the stopped escalators...
as this was the only means of exit. People in wheelchairs are unable to use stopped escalators and are reliant upon access to elevators to be able to evacuate or exit an underground station on their own. Numbers of elevators in underground stations in Stockholm are usually limited to one per each platform entrance, which causes long queuing both during normal usage as well as during egress. To ensure people’s safety in case of a fire and if an elevator would be taken out of service this is often combined with a safe area on the platform where people are supposed to wait for assistance. In case of technical failure or stopped elevator this would mean that people dependent on elevators would have to wait for assistance until the emergency is over. Another risk with people waiting a longer period of time for an elevator or assistance is that they might blocking parts of the required egress width in front of the escalators.

5. Identified aspects in number 1 – 4 for egress can cause knock-on effects which may in turn result in a” domino-effect” with people falling backwards in escalators

The prerequisite in standards and regulations for egress can for deep underground stations result in knock-on effects caused by the aspects described above in number 1 – 4.

If a simplified analysis or hand calculations is used to prove that acceptable fire safety level is reached in design of deep underground stations there is a risk of underestimating queue formations, where people queuing are not standing in an optimized manner.

As an example, unwanted queuing on landings between escalator rises will occur when an escalator from the landing fails and full capacity still proceeds in escalators coming up to that landing. This may result in a domino-effect of people falling backwards onto and in the incoming upwards escalators. The size of the escalator landings between each escalator rise should be designed to prevent this risk of domino-effect. When using standardized values for pedestrian flow in escalator to and from a landing to evaluated dimensions needed for each escalator landing queue formations will be misjudge due to people not standing in an optimized manner.

The effect of people not standing in an optimized matter might also cause longer que times in front of escalators than for example a hand calculation will show. The queuing itself may impede people’s possibilities to reach an escalator since the queuing blocks people loading the escalator. Research done on pedestrian flow in escalators often do not take this into account. When pedestrian flow and walking speed is measured in experiments it is usually during controlled forms with a few volunteers and not with the larger amount of people as stations should be designed for. This should however be taken into consideration since this is an important factor that may affect the real pedestrian flow in the escalators. Additionally, egress flow on pathways tend to be reduced as the density of people increase. Even densities of two people per square meter more than halves the pedestrian flow [21, 22]. This will have an effect not only on the flow in pathways but also on pedestrian flow onto the escalators.

Selected critical key problems

Based on the discussion above the following aspect has been identified as the most critical to analyze since they may lead to consequences in deep underground stations.

a) Lack of comprehensive research coverage of what might affect pedestrian flow in stopped escalator and how this might affect egress capacity in escalators.

b) Risk of domino-effect of people falling backwards in escalators due to not enough area on landings.

Analysis of key problems

Available regulations states that escalators operating in the opposite direction from the egress direction should for evacuation be able to be stopped [3, 6]. This is becoming more and more common to rely upon when designing underground stations due to the possibility of reducing project
construction costs. This as less escalators is needed to reach sufficient egress capacity since people can walk upwards in stopped escalators. When stopped escalators are incorporated in a calculation of egress capacity, limited amount data is used to assume pedestrian flow in stopped escalators. New research findings indicates that pedestrian flow rates used in calculations today for stopped escalators are too high and do not take fatigue into consideration. The latest research available [5] of pedestrian flow in stopped escalators is presented in Table 1.

Table 1. Pedestrian flow rates based on latest available experiment in stopped escalators [5].

<table>
<thead>
<tr>
<th>Height</th>
<th>Pedestrian flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10 m</td>
<td>46 people/min</td>
</tr>
<tr>
<td>10-20 m</td>
<td>23 people/min</td>
</tr>
<tr>
<td>20-30 m</td>
<td>14 people/min</td>
</tr>
<tr>
<td>&gt;30 m</td>
<td>12.5 people/min</td>
</tr>
</tbody>
</table>

Case study – Dimension of landings between escalator rises to prevent domino-effect of people falling backwards in escalators

As the depth of the station increases pedestrian flow rates in stopped escalators decreases due to fatigue of people walking in the stopped escalator. For a required total vertical rise over 30 meter the rise usually has to be divided into two. This to avoid unnecessary high cost due to enlarged construction and installation requirements required for an escalator to manage a long rise.

Since longer vertical rises usually tend to be designed as two escalator rises it is with increased depth more critical to ensure that landings between escalators are designed to prevent domino-effect caused by higher capacity in oncoming escalators than capacity in escalator from that landing. In cases of a difference in escalator capacity in incoming and outgoing escalators the area of the landing in between needs do have sufficient area to allow for queuing. Otherwise, a domino-effect of people falling backwards in escalators can occur. This chapter consists of a case study where egress calculation has been carried out with the latest available research on pedestrian flow rates used in stopped escalators. This to illustrate the required area for landings between escalators to prevent a domino-effect. The purpose of landing spaces is to pull passengers away from escalators to provide a clear landing area for following passengers [7]. Landings are also used to allow queuing area in the event of a system failure because the space provides a reservoir in which passengers can accumulate safely.

One way to determine the required area of a landing is to analyze expected queuing with regards to allowed density of people during a queuing situation. For this case study a density of 3 persons per square meters is assumed when people are queuing on the landing. [6, 21, 22,]

Simulations have been executed to calculate required area to prevent domino-effect [1]. Specified pedestrian flow rates in escalators operating upwards during egress vary between 55 – 120 people/minute*meter dependent on the velocity of the escalator [3, 6, 7, 21, 22]. The average pedestrian flow of 75 people/minute*meter is used for this study [3]. The escalators running in the opposite direction of the egress flow are assumed stopped and the flow rate is set to pedestrian flow as presented in Table 1. Simulations are carried out with three escalators in each rise and both rises has the same height, e.g. same pedestrian flow rate. The total vertical height is divided into two separate escalator lifts with a straight landing in between. In Figure 3 to Figure 5 directions of escalators before evacuation is shown. The right side of the same figures shows which escalators that are stopped, blocked or continued with full capacity during an egress situation. The blocked escalator is not used during egress, but people are assumed to walk in stopped escalators. People are also assumed to walk in an escalator that stops due to technical failure, indicated with a blue arrow in the figures. The escalators that continues to run are assumed to have full capacity. Figure 3 illustrated a scenario where one escalator in the second rise is out of service, one stopped and one with full capacity. Figure 4 illustrates a scenario with technical failure in the second rise where two escalators before egress are operating upwards. Figure 5 illustrates a scenario with technical failure in the second rise where two
escalators are before egress operating downwards. The dotted arrow indicates stopped escalator that people walks upwards in and the bold arrow indicated continued upward operating escalators. In the two scenarios with technical failure, an upwards operating escalator is assumed to fail, indicated with a thin arrow.

Figure 3.  The left side shows the escalator running prior to egress. The right side during egress: Out of service. Bold arrows illustrates moving escalator and dotted indicates stopped escalator. The cross indicates escalator closed off for maintenance.

Figure 4.  The left side shows the escalator running prior to egress. The right side during egress: Technical failure up. Bold arrows illustrates moving escalator and dotted indicates stopped escalator. Thin arrows indicates an escalator that has stopped due to technical failure.

Figure 5.  The left side shows the escalator running prior to egress. The right side during egress: Technical failure down. Bold arrows illustrates moving escalator and dotted indicates stopped escalator. Thin arrows indicates an escalator that has stopped due to technical failure.

Presented in Figure 6 to Figure 8 is the result of the case study, which illustrated the increase in required area to prevent domino-effect due to increase of total vertical rise. In each graph 100 % is based on shortest length of landings commonly used, based on regulation as well as constructional limitation. Technical failure up indicates a higher capacity upwards i.e. there are more ascending escalators than descending prior to egress. Whereas technical failure down indicates the opposite, a higher capacity downwards i.e. there are more descending escalators than ascending, prior to egress.
Figure 6. Increase of required minimum area for queuing on landings* with regards to total escalator rise simulated with 1000 pedestrians

Figure 7. Increase of required minimum area for queuing on landings* with regards to total escalator rise simulated with 1500 pedestrians

Figure 8. Increase of required minimum area for queuing on landings* with regards to total escalator rise simulated with 2000 pedestrians

*Based on minimum 10 meters clear width of landings for pedestrians to queue on
The graphs shows that with increase of total vertical height the required area of the landings to prevent domino-effect due to queuing increases. The slope of the increase differences between scenario with technical failure and out of service. It is also shown that a large impact of the increase of landing area is due to how the escalators are running prior to an evacuation.

In the simulations the escalator rises are the same height whereas in reality the rise usually varies. It is common to design escalator rises from a deep underground station with one shorter rise from the platform and one longer second rise. If the first vertical rise is the shorter one this will require a larger landing area due to the difference in pedestrian flow rates in the two rises.

The possible positive impact on pedestrian flow rate in stopped escalators due to people resting on landings while queuing has not been accounted for in this case study.

**CONCLUSION AND SUGGESTED SOLUTIONS TO IDENTIFIED TECHNICAL ASPECTS**

Standards and regulations internationally for deep underground stations do not have a comprehensive method to be implemented when designing fire safety in deep underground stations today. The egress capacity calculated from pedestrian flow in escalators in underground stations is only valid up to a certain depth.

To prevent domino-effects of people falling backwards in escalators the case study shows that the analyzed size of escalator landing in deep underground stations between each rise is larger than the required size according to today’s available regulations in design of underground stations.

There is a limited amount of research in how fatigue effects the pedestrian flow in stopped escalators. New research indicates that people walking in stopped escalators are affected by fatigue, which will decrease pedestrian flow rates [5]. These new research findings are not today represented in standards and regulations such as NFPA, LU and Singapore code of practice [3, 6, 7]. Furthermore, the research available on this do not represent a higher number of pedestrian. This in turn does also have an effect on pedestrian flow rates in escalators, presumably decreasing the pedestrian flow even further.

In egress analysis, based on available guidance today, and evaluation of safety in underground stations pedestrian flow rates in escalators are assumed based on single vertical height. This pedestrian flow or movement speed is not adjusted according to the total vertical rise even though there might be consecutive escalators. The assumed pedestrian flow rate or movement speed in each separate escalator is based on the vertical height of a specific escalator, regardless of total number of escalators or total vertical height. Since regulations is written in the context of limited amount of vertical movements in each separate vertical height and not according to the total vertical height, it is inappropriate to apply existing codes to deep underground facilities. The pedestrian flow rate or movement speed in stopped escalators should vary as a function of the total vertical distance.

Egress including escalators are dependent on several factors where technical failure and out of service are shown to be two important design aspects for determining the landing sizes between escalators. It is also shown that a large impact of the increase of landing area is due to how the escalators are running prior to an evacuation. Further there is a difference if escalator rises are the same height or if the consecutive rises varies.

Since today’s international and national requirements are inadequate with regard to evacuation incorporating escalators, from deep underground stations, suggestions in Table 2 are to be considered when revising regulations and recommendation when designing safe egress.
<table>
<thead>
<tr>
<th>Design aspect</th>
<th>Suggested requirement</th>
<th>Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Pedestrian flow in escalators affected by fatigue.</td>
<td>Incorporate new research into relevant design codes regarding egress flow in escalators affected by fatigue.</td>
<td>There is only one study carried out with a limited amount of pedestrians.</td>
</tr>
<tr>
<td>B. Pedestrian flow, in escalators, affected by fatigue does not take several rises into account.</td>
<td>Incorporate new research into relevant design codes regarding egress flow, in escalators, affected by fatigue due to total depth of the station and length of escalators.</td>
<td>Lack of research regarding effect of fatigue due to several continued rises.</td>
</tr>
<tr>
<td>C. Some codes specify that egress evaluation should be done with regards to that a technical system could fail during an egress [19].</td>
<td>Escalators, being a technical installation, should generate additional sensitivity scenarios to be incorporated in the egress analysis such as technical failure of an escalator. Incorporate technical failure of an escalator in egress calculations. The risk of someone activating the emergency stop for an escalator should also be considered as a sensitivity scenario.</td>
<td>This may be considered a sensitivity analysis and should be treated as such. Making sure that the planned egress strategy is working even if an escalator is out of service at the same time as an escalator fails is neglected in egress evaluations. The possibility of this happening at the same rise is not small enough to be neglected. Despite this, that aspect is not considered in egress analysis.</td>
</tr>
<tr>
<td>D. Blockage of one escalator due to maintenance.</td>
<td>Incorporate the blockage due to maintenance of one escalator in one rise rather than one in each rise. If an escalator in each level or rise is assumed out of service the risk of domino-effect is not accounted for. This should not be considered a sensitivity analysis and should be incorporated as a design scenario.</td>
<td>There is a risk of more than one escalator being blocked during maintenance depending on type and configuration of escalators. The project should make sure that there is enough space between escalators to allow for maintenance only blocking one escalator at a time.</td>
</tr>
<tr>
<td>E. Required area of landings between escalators.</td>
<td>Designing required area of landing between escalator rises so that the risk of domino-effect of people falling is prevented.</td>
<td>The area is dependent on total vertical height and the relation of vertical height between rises. Furthermore, chosen prerequisites for the direction of operating escalators prior to evacuation in combination with placement of the blocked and/or technical faulty escalator are important factors. Required area are not a fixed value and are required to be analyzed for each specific project.</td>
</tr>
<tr>
<td>F. Refugee area for people dependent on elevators.</td>
<td>In case of failure or stopped elevator people dependent on elevators have to wait for</td>
<td>-</td>
</tr>
</tbody>
</table>
assistance until the emergency has passed. While waiting a longer period of time there is a risk of people dependent on elevators blocking parts of the required egress width in front of the escalators. Specifying refugee area for people dependent on elevators should be incorporated in required area in front of escalators.

| G. Maintenance consideration into the design. | Type and quality of an escalator should be required to be chosen so that the required need for maintenance of the specific type of escalator does not interfere with the assumed prerequisites used in the fire strategy. | The developer of the project is not always the same as the operator. The communication/understanding between the two are important during the design face. |
| H. One can be as accurate as possible in a design. However if the prerequisites used in the design are not considered in the following stages of a project the results will differ. For instance if the entrepreneur choose cheaper technical installations and components not considering the overall fire safety strategy an analyzed and working design may still fail if not considered further along the timeline of the project. | It should be mandatory that the engineer responsible for the design follows it through during the tender and construction face as well as prior to initiating operation. | The constructor, entrepreneurs as well as operators knowledge and understanding of the importance of implementing a fire strategy is crucial to get the required safety level throughout a project. However, this is not always the case and many aspects are lost over time. It is shown that a large impact of the increase of landing area is due to how the escalators are running prior to an evacuation. If this is not implemented in the day to day routine and operation it can have a significant impact on egress. |

**FURTHER STUDIES AND RESEARCH**

Based on the presented suggestions and recommendations in the conclusion the following has been identified as further research needed:

- Develop or update regulations covering deep underground stations as suggested in Table 2, preferably based on a cost-benefit analysis.
- Further studies of fatigue due to long transition in escalators, preferably with larger amount of people.
- Further research regarding effect of fatigue on pedestrian speed and pedestrian flow in stopped escalators using a variation of pedestrians that represent society’s variation.
- Further research regarding effect of fatigue on pedestrian flow in stopped escalators due to several rises of escalators. How the effects of people being able to rest while queuing on the landings impact on pedestrian flow in stopped escalators?
- A holistic approach while developing or rewriting regulations and guideline for design of deep underground stations is crucial. It is otherwise easy to miss important dependencies in prerequisites used. The more complex a design is allowed to be the more likely dependencies
in prerequisites are subject to generate flaws in a regulation and/or design. Hence future work should strive towards keeping complexity in technical systems to a minimum to be able to constructively consider important dependencies.

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Why Pressurized Exits for Transportation Tunnels May Not Make Sense.

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ABSTRACT

Many jurisdictions require a pressurized emergency exit for road and rail tunnels. This derives from the building environment where emergency exits and stairwells are pressurized to keep smoke from the incident floor out of the exit. In contrast, road and rail tunnels rely on emergency ventilation systems within the tunnel to control smoke movement and create tenable environment(s) away from the fire incident. This means the emergency exits that will be used are inherently protected by the tunnel emergency ventilation systems and do not require separate pressurization. In the desire to provide this perceived protection, complex controls are often used that do not work as anticipated when required. Tunnel environments are different than buildings, which is even recognized in the industry standards which allow systems that are harder to operate than buildings. This reality is further evidence that these systems are being imposed into arrangements that are not optimal.

KEYWORDS: exits, tunnel, building, emergency, pressurize

INTRODUCTION

Many jurisdictions require a pressurized emergency exit for road and rail tunnels. This derives from the building environment where emergency exits and stairwells are pressurized to keep smoke from the incident floor out of the exit. However the specific circumstances of road and rail tunnels are quite different from buildings and what seems like a good idea may not even work, be likely to fail even if it could work and cause a significant obstruction to exiting, the exact opposite of its intent.

BASIS OF PRESSURIZED EXITS

Pressurized exits are used in buildings to protect evacuating occupants. The maximum door opening force allowed for buildings based on NFPA 101, the Life Safety Code, is 133 N (30 lb). The required differential pressures in buildings are generally in the range of 12.5 to 25 pa (0.05 to 0.10 in. wc) with a maximum limit of 87.5 pa (0.35 in. wc) for door opening limitations. Pressurized exits are one component of the building fire life-safety design. Building fire design is generally based on the premise that the fire originates on a single floor (incident floor) and mitigations, suppression and containment, are used to confine the fire to that floor. Egress is provided to allow building occupants to evacuate to a point of safety. Pressurization is used to keep egress paths clear of smoke by creating a higher pressure zone in the egress preventing flow of smoke from the incident floor to the egress path. The range of pressure differential is bounded on the low side of that necessary to overcome a smoke pressure and on the high side by the necessary force to be able to open a closed door.

ROAD AND RAIL TUNNEL SMOKE CONTROL DESIGN

Road and rail tunnels are confined spaces where smoke cannot flow out of the space. Some form of ventilation is usually employed to control the smoke flow in the tunnel and allow occupants to move
to either a tenable environment or point of safety. A point of safety is defined as either a location exterior to the facility or a protected space. Protection can be a combination of rated barriers and/or ventilation. A tenable environment is defined as one that permits the self-rescue or survival of occupants. The most common form of smoke control is longitudinal that creates an upstream clear area. In order to accomplish this, sufficient air velocity must be provided to overcome the buoyant forces of the fire plume. This requirement is often referred to as prevention of backlayering and keeps the upstream area clear of smoke and a tenable environment. In contrast, the downstream area is contaminated with smoke and hot gases and untenable. The air flows necessary to create this condition often result in tunnel pressures of 125 pa (0.5 in. wc) and can often rise to 375 pa (1.5 in. wc) if large air flows are required in special sections such as crossovers. These pressures are much higher than seen in the building environment and exceed those door-opening force limitations. The standards for both road and rail tunnels limit maximum door-opening force to 222 N (50 lbf), substantially higher than the 133 N (30 lbf.) allowed in buildings.

BUILDING SMOKE CONTROL

While building smoke control is often used as an example of how beneficial these systems are, there are often complications in more complex and tall buildings. Ferreira (1) describes four particular scenarios that can lead to building smoke control not behaving as expected.

1. Stack effect. For tall buildings, pressures in vertical stairwells and shafts can change dramatically simply because of seasonal temperatures. These changes can cause pressures to exceed door opening forces.
2. Stairwell pressurization. Compensating for high pressures can require barometric dampers, pressure sensors and variable speed drives (VSD) for motors resulting in increased complexity both in commissioning and maintenance.
3. Elevator pressurization. Additional pressure limits are placed on elevators to ensure door-opening is not inhibited by pressure differential.
4. Combined systems. Combinations of elevators, stairs and other areas can create very complex systems, which may not work as desired when needed.

Finally, specific attention is called to test and commission for all conditions that may occur. This would at a minimum include seasonal extremes.

BUILDING SMOKE CONTROL DESIGN

The requirements and details for building smoke control design is given in NFPA 92, Standard for Smoke Control Systems. Building smoke control designs are generally characterized in Figure 1. The space is generally figured to have a slight positive pressure, 13 to 25 pa, in order to prevent ingress of outside air. When an incident occurs, a pressurization system is started that provides sufficient flow to keep a positive pressure differential (13 pa) in the exit so that smoke cannot migrate into it. The maximum airflow is usually based on a number of doors being open. This is at least one incident and exit door for a total of two. Depending on the circumstances, more may be required. Another bounding consideration is the door opening force. This is primarily a function of door area and differential pressure. Figure 1 describes the forces and moments on a door in this situation.

![Figure 1. Exit door arrangement.](image)
Equation 1 gives the force required to open the door.

\[ F_{\text{struc}} = F_r + \frac{W \cdot A \cdot dP_{\text{struc}}}{2 (W - d)} \]  

(1)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Door opening force (N)</td>
</tr>
<tr>
<td>Fr</td>
<td>Residual force to overcome any door closer and friction (N)</td>
</tr>
<tr>
<td>W</td>
<td>Door width (m)</td>
</tr>
<tr>
<td>H</td>
<td>Door height (m)</td>
</tr>
<tr>
<td>A</td>
<td>Door area (m(^2))</td>
</tr>
<tr>
<td>dP</td>
<td>Pressure differential across the door (Pa)</td>
</tr>
<tr>
<td>d</td>
<td>Distance from doorknob to side of door (mm)</td>
</tr>
</tbody>
</table>

Equation 2 solves for the differential pressure across the door for a building location.

\[ dP_{\text{bldg}} = \frac{(Fr_{\text{bldg}} - Fr) \cdot 2 (W - d)}{W \cdot A} \]  

(2)

Using a door of 0.9 m (35 in.) wide by 2.1 m (82 in.) high with handle 75 mm (3 in.) from the edge, and door opening force of 133 N, the maximum differential pressure to keep door opening forces within allowed limits is 130 Pa (0.52 in. wc.). Given the flow and pressure requirements some form of control is necessary to balance these. Figure 2 shows a common approach where pressure differential is used to control a variable speed drive. Another approach is to use a pressure relief damper to vent excess pressure to the outside.

Figure 2. Stairwell pressurization.

TUNNEL SMOKE CONTROL AND EGRESS DESIGN

Tunnel smoke control is characterized by two primary strategies, longitudinal and extraction. Both of these seek to minimize or remove smoke from the immediate incident area. In longitudinal ventilation, the smoke is pushed downstream by a velocity pressure greater than the smoke buoyant pressure as shown in Figure 3.
In extraction, the smoke is removed by a flow rate greater than the smoke generation rate as shown in Figure 4.

A tunnel pressurized egress system must operate against the pressures occurring in the tunnel and still allow door operation. This requires very complex control of flows and pressures. A general description of tunnel egress pressurization system requirements and operation will first be given.

**Tunnel Egress Pressurization Requirements**

Tunnel egress pressurization systems are generally perceived to be similar to those in buildings and are characterized in Figure 1.

Equation 3 is similar to Equation 2 except the higher allowed door-opening forces also allow higher pressure differentials in the tunnel.

\[
dP_{\text{tunnel}} := \frac{(F_{\text{tunnel}} - F_r) \cdot 2(W - d)}{W \cdot A}
\]

In this case the tunnel door opening force of 220 N allows a differential pressure of 215 Pa (0.865 in. wc).

Control can be provided by either a VFD, controlled by pressure differential transmitters or pressure relief damper. Sometimes both of these are used together, which can create some issues when they are compensating for each other. Of more fundamental concern is that tunnel ventilation systems can create positive or negative pressure conditions inside the tunnel. The positive pressure condition conforms to general perception of exits requiring supply air to keep smoke out. It should be noted the pressures are significantly higher which can lead to control complications. The negative pressure condition would require removing air from the system to control exit pressure, i.e. an exhaust fan, which is generally not the practice. Complicating matters is that either condition could exist, depending on the tunnel ventilation mode selected.

In addition, the pressure differential between the egress exit and the external pressure at that location must also be considered. This is most usually an ambient pressure condition. This location may also be an access point for responders, so both tunnel and ambient location doors may be open at the same time.

In an attempt to quantify the description of the issue, some conditional expressions will be developed.
Equation 4 defines the door-opening force pressure limit requirement. The sum of exit pressure plus the tunnel pressure must be less than or equal to the maximum allowed door opening pressure for tunnels.

\[ \text{P}_{\text{exit}} + \text{P}_{\text{tunnel}} \leq \text{dP}_{\text{tunnel}} \]  

Equation 5 defines the tunnel pressure control requirement. The minimum allowed pressure differential to prevent smoke ingress from tunnel to the exit is 12 Pa.

\[ \text{P}_{\text{exit}} - \text{P}_{\text{tunnel}} \geq 12 \text{ Pa} \]  

Equation 6 defines the external or ambient pressure control requirement. The differential between exit pressure and ambient external pressure must be less than or equal to the maximum allowed door opening pressure for tunnels.

\[ \text{P}_{\text{exit}} - \text{P}_{\text{external}} \leq \text{dP}_{\text{tunnel}} \]  

Equation 7 defines the external ambient pressure as atmospheric.

\[ \text{P}_{\text{external}} = 0 \cdot \text{Pa} \]  

Positive Tunnel Pressure

Following conventional practice, exits are positively pressurized since the fire is assumed to be in the tunnel. For a zone where the tunnel is positively pressurized, the exit pressure must be greater than the tunnel pressure, but not so great as to exceed door opening force at the surface exit. For positive tunnel pressure, the governing boundary equations can be consolidated into a maximum exit pressure for tunnels. Equation 8 defines this upper bound of exit pressure and that it must be less than the tunnel pressure plus the positive pressure necessary to keep smoke out.

\[ \text{P}_{\text{exit max}} := \text{dP}_{\text{tunnel}} - 12 \cdot \text{Pa} \]  

This gives a maximum pressure of 203 Pa (0.815 in. wc.) that can occur in the tunnel. Pressure exceeding this will result in a door-opening force at the surface exit that exceeds Standard limits.

Negative Tunnel Pressure

For negative tunnel pressure, the governing boundary equations can be consolidated into a minimum exit pressure for tunnels. Equation 9 defines this lower bound of exit pressure and that it must be less than the surface exit pressure minus the maximum allowed door opening pressure.

\[ \text{P}_{\text{exit min}} := \text{P}_{\text{exit}} - \text{dP}_{\text{tunnel}} \]  

This gives a minimum pressure of -215 Pa (-0.863 in. wc.). Because exits are positively pressurized, they will always be higher than tunnel pressure. Therefore, pressure lower than this will again result in a door opening force at the surface exit that exceeds Standard limits.

TUNNEL VENTILATION SMOKE CONTROL

A common misperception is that tunnels are like horizontal buildings. From a smoke control standpoint this is not accurate. Buildings as shown in Figure 2 can be characterized as multiple
chambers stacked on top of each other with barriers between each of the chambers. These barriers significantly limit smoke spread between the chambers. A key aspect of building smoke control is to confine the fire to the incident chamber (floor) and allow occupants to escape to a protected exit. This exit is protected in two ways, one by separation and second by pressurization to keep smoke from migrating from the incident floor into it. The assumption here is that the exit path is at risk of being contaminated by the smoke products and that it must be protected from this intrusion. This contamination is seen as occurring in the egress path, which must be protected.

Tunnels are fundamentally different. First of all, there are no barriered chambers. The entire facility is open without separation. This lack of separation has led to reliance on ventilation for smoke control. This means that smoke is controlled around the fire such that egress path(s) are maintained in the tunnel itself. Unlike buildings smoke does not intrude into the egress path. Two principle methods of smoke control are used in tunnels, longitudinal and extraction. Both rely on creating smoke-free zones away from the fire incident.

In recognition of this fact, emergency exits are typically spaced around 762 meters (2500 feet) apart, significantly farther than that found in buildings. This further recognizes the reality that once occupants have left the fire incident area, they are protected from smoke by the tunnel ventilation system and that pressurized exits are not necessary.

**Longitudinal Ventilation**

Longitudinal ventilation seeks to create a smoke-free zone behind the fire incident and move the smoke downstream of the incident. Occupants then evacuate upstream. In order to accomplish this, a longitudinal airstream is created with sufficient velocity force to overcome the fire buoyant forces. The velocity necessary to accomplish this is called the critical velocity. Figure 5 shows this. The whole premise of this strategy is that occupants move to the clear area. The downstream area is smoke-filled, but occupants are not in this area. Thus any exits in this area are not being used as exits. In other words, smoke control is provided in the tunnel, not the exit. Therefore, pressurized exits are not necessary for smoke control because there is no smoke where the exits would be used.

![Figure 5. Longitudinal ventilation in a transit tunnel.](image)
Extraction Ventilation

Extraction ventilation works similarly to longitudinal except that the smoke is extracted into a separate duct and tunnel lengths both upstream and downstream of the fire incident are clear. Occupants can evacuate in both directions. Any exits in the tunnel can be used. Similar to longitudinal, smoke control is provided in the tunnel, not the exit. Again, pressurized exits are not necessary for smoke control because there is no smoke where the exits would be used.

DISCUSSION

Many codes and standards require pressurized exits for tunnels. The premise is that these will provide smoke control for occupants evacuating a fire incident in the tunnel, similar to that function performed in buildings. For buildings there is some justification in that smoke from an incident floor can intrude into the exit path, jeopardizing the safe passage of the building occupants. For tunnels, however, the smoke control system in the tunnel is specifically designed to create tenable zones away from the fire incident where smoke cannot intrude. Or to put it another way, the tunnel smoke control system inherently protects the exits from contamination, so no internal protection is necessary.

There are additional complications with pressurized exits for tunnels that make their implementation problematic. Building codes typically require pressure differentials that limit door opening forces to 133N (30 lbf.). Tunnel Standards allow a door opening force of 220 N (50 lbf.), primarily recognizing the higher pressure differentials that are necessary for tunnel ventilation. While these higher forces will work for many tunnel configurations, primarily single track ones, pressures in special sections such as cross-overs, storage tracks, etc. can be much higher because of higher flow rates necessary to handle smoke control requirements in these areas. Also, many agencies require that the design airflow rates be provided with the most critical fan out of service. When all fans are operating, pressures can again get high and exceed the door-opening force pressures.

While some pressure control practices are used to modulate system pressure within the exit stair, there are limits in the allowable pressure range between the tunnel and ambient that are often exceeded primarily by the tunnel smoke control system. In other words, even with a pressure control system, the door operating forces will exceed Standard requirements. These pressure control systems are complex and costly to maintain. That money could be better spent on the components that make a real difference to safety.

Fundamentally, buildings use barrier zoning as a primary means of smoke containment and exit pressurization is only used to protect the exit during evacuation while the barrier to the exit is open. In contrast, tunnels have no barriers and tunnel ventilation is used to control smoke flow. Exits are inherently protected by the tunnel ventilation system, so no additional protection of exits is required.

SUMMARY & CONCLUSIONS

Requirements for pressurized exits derive from the building industry, where fires are separated by barriers and a common exit path is used to allow occupants from the incident space to exit the building. This exit path is protected by a pressurization system that prevents the smoke from the incident space from migrating into the protected evacuation path.

In contrast, tunnels have no occupancy barriers and ventilation systems rather than barriers are used to control smoke spread in the incident space. The exit path is away from the fire in one or two directions and this path is protected by the tunnel ventilation system. There is no need for pressurizing portions of the exit path with separate systems and doing so can create very complex systems that may not even work as intended in an incident.

In the misguided belief that these systems were necessary, many designs have been produced that do not work, result in excessive door opening forces, or require excessive maintenance to keep operational. The barriers that are the primary means of smoke control in buildings do not exist in
tunnels. In contrast, the tunnel ventilation system is the primary means of smoke control in tunnels and exits only need to provide a path to a point of safety. Exits are not a boundary to the incident area.

By not having to maintain a fundamentally flawed system, tunnel operators can focus their resources on measures that provide real benefit rather than measures that don’t.

REFERENCES

Test Method and Performance of Fire Detection Systems in Tunnels

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ABSTRACT

The results of a study carried out for the Swedish Transport Administration on fire detection in road tunnels is presented. Laboratory tests and numerous large-scale tests were carried out in order to verify a proposal for a test method for fire detection systems. The main aim was to investigate possible fire detector systems and to see if they could fulfil the requirement given by the Swedish Transport Administration to detect the fire within 90 seconds. The tests are presented as well as a recommendation for testing detection systems in Swedish road tunnels. In order to perform the fire test, pans of different sizes were tested in order to obtain a reasonable fire size. The method proposed requires the use of three 0.6 m diameter standard pans, each containing eight litres of 95 octane gasoline, and air flow velocities of 2 m/s and 6 m/s. It was found out that using only one 0.6 m pan is sufficient if early warning is required without identifying the position for the fire-fighting system.

KEYWORD: Fire detection, tunnel fire, test method, heat detection, smoke detection, flame detection

INTRODUCTION

Detection of a tunnel fire is usually a challenging task. The detection systems installed can vary in type and performance. The fire growth and size is not the only parameter to consider, but also tunnel height and width as well as flow conditions. There has not been any standardized test method for detection systems in road tunnels available.

The Swedish Transport Administration (STA) has installed several detection systems in different tunnels in Sweden. In a recent tunnel project, the requirement was that the detection system should be able to detect a 3 MW fire within 3 minutes. These requirements were found to be conservative by STA. In preparation for the construction of the “Stockholm bypass” project the STA wanted to investigate new requirements or alternative requirements and appointed SP Fire Research to develop a simple, repeatable and realistic test method for detection systems in road tunnels. The new requirement proposed was that the systems should be able to detect a 0.5 MW fire exposed to 6 m/s lateral wind within a time period of 90 seconds. These requirements may however be too rigid and therefore it was decided to find out what would be realistic requirements for road tunnels with 6 m/s longitudinal flow. Part of the problem is to know what representative fuel to use, what the heat release rates (HRR) the various fuels produce, and what quantity of smoke they release in relation to different air velocities.

It is known that flame detectors react quickly to open flames, that smoke detectors react quickly to fuels that generate large quantities of smoke particles, and that gas detectors are sensitive ‘sniffers’. Camera systems are quick to detect changes in patterns, e.g. stationary vehicles or smoke. It is also recognized that detectors can struggle under certain conditions when conditions around them are not...
optimum. Hidden flames, for example, mean that flame detectors could have a problem. Smoke detectors can have difficulties in detecting smoke from alcohol-based liquids, such as burning methanol or ethanol. Heat detectors are particularly sensitive to tunnel height, in combination with higher air velocities. All these mean that there are many vulnerabilities and characteristics of different types of fires.

The objective of this study was to develop a simple field test method for fire detection systems with a fire source representative of an ordinary fire in a smaller vehicle and investigate the performance of different types of fire detection systems in tunnels.

**EXPERIMENTS**

Prior to the test program, the Swedish Transport Administration had already performed some preliminary tests with diesel and gasoline liquid fuel and different types of pans. The liquid was poured into a steel pan and subsequently ignited to see how large the fire needed to be in order to activate different detection systems. The fire was exposed to different air velocities by controlling longitudinal jet fans in the ceiling. During the tests, it was noticed that the heat release rate (HRR) and smoke production seemed to be lowered when the fire was exposed to a lateral wind.

The test program presented in the following consisted of laboratory tests and full scale tests in real tunnels. A list of all performed tests, dates etc. are given in Table 1.

*Table 1 The list of experiments carried out within the tests program.*

<table>
<thead>
<tr>
<th>Identification of test program</th>
<th>Dates</th>
<th>Test location</th>
<th>Number of tests</th>
<th>Type of tests</th>
<th>Fuel used</th>
<th>Type of detection system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory tests</td>
<td>Oct, 17-18, 2013</td>
<td>SP fire test laboratory</td>
<td>16</td>
<td>Calorimeter tests, open pool fires</td>
<td>Diesel, gasoline, heptane</td>
<td>-</td>
</tr>
<tr>
<td>Test series I</td>
<td>Nov, 21st, 2013</td>
<td>Törnskogs-tunnel</td>
<td>6</td>
<td>Longitudinal ventilation, open pool fires</td>
<td>Gasoline, heptane</td>
<td>Flame, smoke, linear heat detector (LHD)</td>
</tr>
<tr>
<td>Test series II</td>
<td>April, 9-10, 2014</td>
<td>Törnskogs-tunnel</td>
<td>9</td>
<td>Longitudinal ventilation, open pool fires, shielded fires</td>
<td>Gasoline, heptane, PUR/PE, combustible car engine components</td>
<td>Flame, smoke, LHD</td>
</tr>
<tr>
<td>Northern Link</td>
<td>Sep, 16-17, 2014</td>
<td>Northern Link tunnel</td>
<td>16</td>
<td>Longitudinal ventilation, open pool fires</td>
<td>Gasoline</td>
<td>CCTV, smoke, LHD</td>
</tr>
</tbody>
</table>

**Laboratory tests at SP Fire Research**

Prior to the laboratory tests, calculations were made in order to estimate pan size for a 0.5 MW fire (or more). The initial assumption, based on the STA tests mentioned above, was that the HRR would decrease when the wind speed was increased and the pans were therefore designed to produce a slightly higher effect than 0.5 MW at no wind. To get as much wind effect at the fuel surface as possible and to reduce the rim effect, the rim was set to merely 0.04 m for all the liquid pan fires.

The setup consisted of a pool in various sizes, insulation, a wooden pallet and beams for weighing. The tests were carried out under an industrial calorimeter to measure the HRR. The pan was filled with the combustible liquid and as the fuel was burning, the HRR and the weight loss was measured. After the test, the mass loss rate could be associated with the HRR in order to later be able to estimate the HRR when exposed to wind. This was necessary as it was not possible to measure HRRs under the industry calorimeter when exposed to lateral wind.
In order to create the lateral wind conditions above the pan, a fan was placed in front of a 3 m long tunnel with a cross section of 2.4×2.4 m². The tunnel was used to make sure that the pan surface was exposed to a uniform lateral flow. The wind speed at the fuel surface was set to be as close as possible to 6 m/s. The ambient gas temperature within the laboratory during the test time varied between 18.0 – 18.6 °C.

Large-scale test series in Törnskogstunneln, Sollentuna Stockholm
The large-scale tests were performed in a road tunnel (Törnskogstunneln), which is in operation north of Stockholm. The large-scale test series were carried out at two different occasions. The first test series (I) was carried out in November 2013. The second test series (II), which was performed in April 2014, included repetition of the first six tests in test series I, with some additional tests with concealed fires and fires with solid fuels. The tunnel was closed for traffic night-time while performing the tests. In the tunnel, several different detection systems were installed by the different manufacturers.

The setup in the tunnel was similar to the one used in the laboratory tests at SP Fire Research. The pan weight loss was measured during the test and two regular thermocouples and two cable plate thermometers (CPT) were used for temperature measurements. A CPT is a plate thermometer that measures the thermal exposure for a cable and it measures the temperature from a number of different directions. The CPT used in these tunnel tests was designed to simulate a fire detection cable or linear heat detector (LHD), which has a diameter of 4 mm. The other detection systems consisted of two types of flame detectors (F and H) and smoke detectors (S).

The CPT was placed adjacent to the LHD to obtain similar heat exposure for both objects. One CPT was placed as close as possible to the fire and another 5 m downstream. Ordinary welded 0.5 mm K-type thermocouples were used to measure the ceiling temperatures. One centered over the fire and one located 5 m downstream, in accordance with Figure 1.

![Figure 1](image)

*Figure 1 Test setup in the tunnel for temperature measurements above the fire and 5 m downstream (bird’s eye view).*

The placement of the detectors can be found in Figure 2.

![Figure 2](image)

*Figure 2 Placement of smoke and flame detectors upstream and downstream the fire (F and H are flame detectors, and S is smoke detector).*
In test 1, 2, 4, 5 and 7, see Table 4, a square pan with the area 0.35×0.35 m² was used as a container for the liquid fuel. In test 3 and 6 circular pans with radius 0.29 m and 0.25 m respectively was used. The rim height was 4 cm in test 1-5 and it was filled with 3 cm fuel which means that 1 cm remained between the fuel surface and the edge of the rim. In test 6 the rim height was 10 cm with 3 cm fuel which means that the distance between the fuel surface and the rim was 7 cm. The pan weight loss was measured during the test and two regular thermocouples and two cable plate thermometers (CPT) were used for temperature measurements. In Figure 3 the test setup for tests 1-6 are shown.

Figure 3   Test setup for Test 1-6 (here Test 1 at ignition) for test series I and II in Törnskogstunnel.

Large-scale tests in the Northern Link tunnel in Stockholm
In the Northern Link tunnel project an opportunity was given to test the installed detection systems. The tunnel was about to be open for traffic at the time of the tests. It was in September 2014.
The results of the previous tests; Test Series I (2013) and II (2014) in the Törnskogstunnel and tests performed at SP Fire Research laboratory provided information on the test setup design, the choice of fuel and the size of the fuel trays gave the background to how the tests were designed in these large-scale tests. In the following descriptions of test procedures and setup are given.

The test procedure and setup
Two locations were chosen for the test fires in the Northern Link tunnel in Stockholm. The first test series was performed in the part called Roslagstunneln and a second test was performed in a more complex area of the tunnel at a location called Vassen in a part called Gärdestunneln. Detailed descriptions of the test setup are given below.

Large-scale tests in Roslagstunneln
The cross-section at test location was 12 m wide and 6.6 m high. There were different detection systems installed. LHD cables were mounted in the ceiling and on both sides of the tunnel cross-section. A camera system used cameras mounted every 50-60 m (on average). There was a camera installed about 10 m upstream of the test fire. There were also two smoke detectors (S), installed 100 m and 190 m downstream from the fire. These smoke detectors were not permanent but were mounted for the purpose of the tests.

The tests were performed using different numbers of 0.6 m (diameter) circular pans filled with about 8 litres of gasoline (95 octane) each. No water beds were used. The pans were put inside a larger tray of steel which was placed on a set of load cells, used to measure weight loss over a period of time. The weight loss per second correlates to the rate of fuel consumption and ultimately the HRR of the test fires. The exact measure of the radius of the circular pans was 0.288 m and rim heights of the pans were 0.06 m. The fuel depth of the filled pans was 30 mm which corresponds to 7.8 litres of gasoline. The number of pans used in the tests varied from one to four. A total of 16 tests, Table 7, were performed with different number of pans and longitudinal ventilation velocity.

The temperature measurements were performed using ordinary K-type thermocouples and a cable
plate thermometers (CPT). The CPT was placed adjacent to LHD in the cable tray to obtain similar heat exposure for both objects. One CPT was placed as close as possible to the fire on the cable tray and another 5 m downstream the fire. Ordinary welded 0.5 mm K-type thermocouples were used to measure the ceiling gas temperatures beside the CPTs. Further, 0.5 mm K-type thermocouples were used to measure the centerline gas temperatures in the ceiling, 50 mm below the sprinkler pipe (which was about 0.3 m from the ceiling). The distances from the fire location and in the horizontal direction were x=0 m, 5 m, 10 m and 20 m, respectively.

![Figure 4](image.png)

**Figure 4** Test setup for Test 1-16 (here Test 2 at ignition) at the Roslagstunnel test site.

### Large-scale test in Gärdestunneln

The tunnel geometry at the second test location was different than at the first one at the Roslagstunnel. The tunnel was wider and higher and it was connected to two ramps as can be seen in Figure 5. The tunnel cross-section was 15.6 m, and 7.1 m high. This location in the tunnel system was called Vassen. In this test, no temperatures or HRR were measured due to practical reasons. The camera system and the LHD were the only detectors used. The camera positioned closest to the test fire were situated 15 m downstream from it.

### RESULTS AND DISCUSSION FOR FIRE TESTS

In the following the test results based on measured parameters are given. The HRR was determined by measuring the weight loss of the fuel during the test. The weight loss per second in kg/s was multiplied by a value for the heat of combustion. This value was 43.7 MJ/kg for gasoline and 44.3 MJ/kg for heptane.

#### Results from the SP laboratory tests

It was found that gasoline produced the most smoke in relation to the HRR of all fuels tested. Heptane had a more luminous flame than the other fuels. The diesel fuel had a low HRR in comparison with the others, it was also very inconsistent in its HRR due to boiling of the liquid. Gasoline and heptane was selected as the fuels to use in the tunnel tests, mainly due to their relatively high HRR and smoke production. The measured HRR for diesel varied between 1.7 – 2.2 MW/m² with no wind and 1.7 – 2.4 MW/m² with 6 m/s sidewind. The effects of the wind were low. For gasoline and heptane the HRR was 2.0 and 2.9 MW/m², respectively, without wind. With wind of 6 m/s, these numbers could be much higher, 4.1 and 5.2 MW/m². The heptane and gasoline are sensitive to the wind conditions.

#### Results from test series I

Primarily gasoline was used in the tests to get comparable results between the different wind speeds. The HRR decreased significantly when the wind was lowered from 6 m/s to 3.5 m/s. However, when the wind speed is lowered, the measured ceiling temperature increased. In these tests, the ceiling temperature at the cable tray location never increased more than 3°C according to the CPT’s. The linear fire cable detection system (LHD) did not function properly but whether the system would be activated by such a small temperature increase or not depends on operator settings.
In tests 1-5, both the smoke detectors and the flame detectors reacted early. There was a slight difference in reaction time of the different flame detectors even though they were placed in the same area. Test 6 was carried out with a pan having a higher rim, 0.1 m instead of 0.04 m. This particular pan was previously used by the Swedish Transport Administration in their preliminary testing. The results showed that the smoke production was drastically lowered and therefore the smoke detectors did not react as easily as in previous tests. The values registered by the smoke detectors during test 6 might actually be too low to really know if a fire has occurred. In a tunnel there will always be a lot of exhaust gases etc. so the detector used cannot be set to be too sensitive. The flame detectors, however, reacted early despite the higher rim.

The HRR was also lower for the pan with higher rim. It was observed that the gasoline was ignited when the gases above the surface reached the height of the rim, i.e. only fuel molecules and no air was present below the rim height and hence, no combustion could occur close to the fuel surface which led to a less efficient combustion since the process was controlled by the mass transport rate of fuel molecules through the gaseous film above the surface.

**Results from test series I and II**

The purpose of this test series, referred here to as test series II, was to repeat the previous test series I in order to verify the performance of the detections systems. Another aim was to perform some additional tests to improve documentation of the detection system performance.

In tests series I it was found that in the small scale tests the HRR increased when the pool fires were exposed to 6 m/s lateral wind. The smoke production also increased which was not the case in previous tunnel tests performed by the Swedish Transport Administration (carried out prior to test series I). It turned out that the reason that the smoke production and HRR increased, was due to the lower rim height of the fuel pans. In test series I, several fuels were tested in order to choose the ones providing the required HRR and smoke production. The fuels that were found to best fit these requirements were gasoline and heptane. Gasoline had the highest smoke production in relation the HRR. The pan that was found to produce approximately 0.5 MW when exposed to 6 m/s lateral wind, both with heptane and gasoline, had the dimensions of 0.35×0.35 m$^2$, i.e. 4.1 MW/m$^2$ as given in Table 2.

In each of the earlier tests performed, the flame detectors reacted quickly. This was to be expected as the flame was visible and not covered in any way. The smoke detectors performed very well in the first five tests. In the last test, the smoke production was drastically lowered compared to the other tests. The smoke detectors reacted in the last test as well, even though the smoke concentration was far from the values obtained in the previous tests. In Table 3 the test results from test series I have been split up into two time periods. This was done in order to be able to compare the old data to the new data obtained in test series II. The results from test series II is presented in Table 4.
Table 2  Results from test series I in the Törnskogstunnel performed in Törnskogstunnel Nov, 21st, 1913, see Table 1.

<table>
<thead>
<tr>
<th>Test</th>
<th>Pool area (m²)</th>
<th>Fuel</th>
<th>Wind (m/s)</th>
<th>Ambient gas temperature inside tunnel (°C)</th>
<th>Estimated HRR (kW)</th>
<th>HRR¹ (kW) 0.5-1.5 min</th>
<th>HRR¹ (kW) 2-4 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.35×0.35</td>
<td>Gasoline</td>
<td>6</td>
<td>7.0</td>
<td>520</td>
<td>160</td>
<td>488</td>
</tr>
<tr>
<td>2</td>
<td>0.35×0.35</td>
<td>Heptane</td>
<td>6</td>
<td>7.0</td>
<td>490</td>
<td>266</td>
<td>402</td>
</tr>
<tr>
<td>3</td>
<td>π×(0.2875)²</td>
<td>Gasoline</td>
<td>6</td>
<td>7.0</td>
<td>880</td>
<td>371</td>
<td>728</td>
</tr>
<tr>
<td>4</td>
<td>0.35×0.35</td>
<td>Gasoline</td>
<td>3.5</td>
<td>7.0</td>
<td>380</td>
<td>160</td>
<td>364</td>
</tr>
<tr>
<td>5</td>
<td>0.35×0.35</td>
<td>Gasoline</td>
<td>2.7</td>
<td>7.2</td>
<td>310</td>
<td>124</td>
<td>295</td>
</tr>
<tr>
<td>6</td>
<td>π×(0.25)²</td>
<td>Gasoline</td>
<td>6 (high rim)</td>
<td>7.2</td>
<td>490</td>
<td>393</td>
<td>408</td>
</tr>
</tbody>
</table>

In Table 4 the test data from test series II are given. The test sequences for tests 1 – 6 are identical in both series, I and II. This means they are directly comparable, although the ambient temperature varied between the tests.

Table 3  Results from test series II performed in Törnskogstunnel April 9-10, 2014.

<table>
<thead>
<tr>
<th>Test</th>
<th>Pool area (m²)</th>
<th>Fuel</th>
<th>Wind (m/s)</th>
<th>Ambient gas temperature inside tunnel (°C)</th>
<th>HRR (kW) 0.5-1.5 min</th>
<th>HRR (kW) 2-4 min</th>
<th>Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.35×0.35</td>
<td>Gasoline</td>
<td>6</td>
<td>4.9</td>
<td>320</td>
<td>464</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>0.35×0.35</td>
<td>Heptane</td>
<td>6</td>
<td>4.9</td>
<td>155</td>
<td>514</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>π×(0.2875)²</td>
<td>Gasoline</td>
<td>6</td>
<td>4.9</td>
<td>495</td>
<td>819</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>0.35×0.35</td>
<td>Gasoline</td>
<td>3.5</td>
<td>4.9</td>
<td>157</td>
<td>295</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>0.35×0.35</td>
<td>Gasoline</td>
<td>2.7</td>
<td>4.7</td>
<td>127</td>
<td>273</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>π×(0.25)²</td>
<td>Gasoline</td>
<td>6 (high rim)</td>
<td>4.7</td>
<td>459</td>
<td>557</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>0.35×0.35</td>
<td>Gasoline</td>
<td>6</td>
<td>5.0</td>
<td>335</td>
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<td>Yes</td>
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<td>8</td>
<td></td>
<td>Combustible car engine components</td>
<td>6</td>
<td>4.8</td>
<td>2)</td>
<td>2)</td>
<td>Yes</td>
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<tr>
<td>9</td>
<td></td>
<td>PUR/PE</td>
<td>6</td>
<td>4.5</td>
<td>2)</td>
<td>2)</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The temperature due to radiative heat transfer measured by the CPT and the gas temperature measured by thin thermocouples were measured above the fire and 5 m downstream. The result of these measurements is presented in Table 5. Above the fire, mainly radiated heat from the flame was registered by the CPT at an increase above ambient of 1-2°C. Five meters downstream temperature increase at about 1°C was registered by the CPT and TC. Test 3 shows about 1°C higher temperature difference. Due to the inclination of the fire plume by the high wind velocity, see Figure 6, the highest temperature will be registered further downstream the fire at the ceiling. For a 0.5 MW fire placed 6 m below the ceiling with 6 m/s ventilation the highest temperature increases in the ceiling would be around 6°C 15-20 m downstream the fire.

1 Note that here the HRRs are calculated differently compared with previous column, calculation. The time periods are divided up in two, instead of one as in .
2 No HRR were measured and temperature increase was insignificant.
Figure 6  With 6 m/s wind the flame is severely tilted.

It is clear from the analysis of the measured data correlate well but there is a variability of about 100 kW when the tests are repeated. There is tendency that the temperature registered increase with HRR over 600 kW (test 3 which represent the upper right points from series I and II). For lower HRR it is almost the same in both test series. However, note that the gas temperature registered is not the maximum ceiling gas and even not the gas temperature. In most cases, the measured values are only an indication of radiation.

In the following the performance of each detector is given. The data is based on registrations provided to us by the manufacturer or operators of the systems. In Table 5 the detection times are given in minutes from ignition. Since no data from the linear heat detector was available the maximum temperatures at 0 and 5 m downstream the fire with TC and CPT are presented for comparison. The ambient gas temperature inside the tunnel prior to the tests was about 7.0 °C, see Table 3.

In in Table 5 and Table 6 it can be seen that the smoke detectors (S 1 and 2) detect most fires which are large enough, or smoky enough, within 5 min. Detection within 1.5 min was only achieved for Test 3 in both test series and Test 6 in test series II. Note that the smoke detectors were placed 100 m downstream the fire.

The flame detectors on the other hand react on the photons emitted from the flame with the speed of light. The flame detectors detected all fires with a measurable HRR in the test series shortly after ignition. This is valid also for covered fires. Often detection was within 6 seconds from ignition.

The data from the linear fibre optic cable was not available due to technical problems and therefore it is not possible to put the results from that detector into the context of performance in relation to the smoke and flame detectors. The temperature measurements indicates that it may have responded in some of the tests, e.g. test 3, if it is sensitive to temperature increase of 2-3°C in about 5 min. The ambient gas temperature inside the tunnel prior to the tests was in the range of 4.5 – 4.9 °C, see Table 4. Note that the maximum ceiling gas temperature to which the linear heat detector could response is much higher than the one registered. The reasons have been presented previously.

Table 4  Detector performance in test series I, time to detection from ignition (min) and temperature increase (°C). Ambient gas temperature was in range of 7.0-7.2 °C.

<table>
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<tr>
<th>Test</th>
<th>S 1 (mE/m)</th>
<th>S 2 (mE/m)</th>
<th>F 1</th>
<th>F 2</th>
<th>H 1</th>
<th>H 2</th>
<th>AT CPT, 0</th>
<th>AT CPT, 5</th>
<th>AT TC, 0</th>
<th>AT TC, 5</th>
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<tbody>
<tr>
<td></td>
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<td>Smoke (min)</td>
<td>Flame (°C)</td>
<td>Flame (°C)</td>
<td>Flame (°C)</td>
<td>Flame (°C)</td>
<td>Temp (°C)</td>
<td>Temp (°C)</td>
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Table 5  Detector performance in test series II, time to detection (min) and temperature increase (°C). Ambient gas temperature was in range of 4.5-4.9 °C.

<table>
<thead>
<tr>
<th>Test</th>
<th>S 1 (mE/m)</th>
<th>S 2 (mE/m)</th>
<th>F 1 (min)</th>
<th>F 2 (min)</th>
<th>H 1 (min)</th>
<th>H 2 (min)</th>
<th>ΔT CPT, 0</th>
<th>ΔT CPT, 5</th>
<th>ΔT TC, 0</th>
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<tr>
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</tr>
</tbody>
</table>

As the smoke detectors (S) are placed 100 and 200 m downstream the fire it takes at least 16 seconds for the smoke to reach the detector in 6 m/s. Another phenomenon which can be seen is that the smoke becomes more diluted with time. Therefore the signal from S 2 is lower and smoother. If the smoke detectors were placed e.g. 20 meters downstream the fire a faster detection would have been expected. For the fires that reached 0.5 MW in test series II the F1 managed to detect the fire within 90 seconds (Test 3 and 6).

In summary it was observed that the smoke detectors detected a 0.5 MW fire within 90 seconds (i.e. test 3 in both test series and test 6 in test series II that reached above 0.5 MW in 90 seconds) 100 meters downstream the fire. The flame detectors detects all fires larger than 100 kW situated 60 meters from the fire or closer.

Results from the Northern Link tunnel
The first test series was performed in the part called Roslagstunneln and a second test was performed in a more complex area of the tunnel at a location called Vassen in a part called Gärdestunneln.

Results from the large-scale tests in Roslagstunneln
In Table 7 the test results based on the measured parameters are presented. The test set-up and the measured HRR during different time periods after ignition are given. The performances of the camera detection system, the LHD and smoke detector S1 and S2 are also presented. The data is based on registrations provided to SP Fire Research by the manufacturer or operators of the systems.

In Table 7 the data show interesting tendencies about the relation of ventilation velocity, fire size and temperature response. Increasing number of pans means larger HRRs, but it is interesting to note that the HRR is not very dependent on the ventilation velocity. There is, however, a trend that the HRR within the same number of pans, increases with ventilation speed, although this is a relatively vague tendency. It also shows the range of fire sizes tested from 0.5 MW to 3.6 MW. In all tests the LHD detection systems activated with 3-4 pans, i.e. within a range of 2.5 – 3.6 MW, when the velocity was 3 m/s or more. With velocity of 1.5 m/s detection was obtained with only 2 pans. A pre-alarm was obtained with 2 pan or more in most cases. The smoke detectors alarmed in all the tests performed.

In Table 8 temperature measurements are presented. The temperatures are given as the maximum individual temperature increase of each measuring point. The CPT measurements are presented as mean value of the four measurement points on the CPT thermometers. While comparing the rate-of-rise of the temperatures measured by the CPTs to the detection performance of the LHD one could see that detection was achieved only when the CPT showed a rate-of-rise which was higher than 1°C/min and which did not fluctuate too much. When the CPT rate-of-rise did not reach high above 1 °C/min or fluctuated, making the value go below 1°C/min from time to time, there were no detection from the LHD.
Comparing the CPT results with the thermocouples situated next to them made it clear that the CPT was highly affected by radiation from the test fires. This was most obvious for the tests with higher wind speeds where they reached temperature increases several times higher than the corresponding thermocouples. At low wind speeds (1.5 m/s) the convective effects became dominant and the thermocouples increased as much or even more than the CPTs.

### Large-scale test in Gärdestunneln

The test performed at Vassen is presented in Table 9. Only one test was run and the wind speed was lowered during the test. Detection times in cameras and LHD are given in minutes and seconds after ignition.

### Summary of the results of the Northern Link tunnel tests

Large-scale fire tests representing fire sizes with HRRs around 0.5 MW to 3.6 MW were performed in the Northern Link tunnel. The aim of the tunnel tests was to evaluate the fire detector systems and to investigate if they fulfilled the requirement given by Swedish Transport Administration to detect a 3 MW fire within 180 seconds when the traffic is flowing freely. A range of sets of varying numbers of pans were used in order to obtain a range of HRR that could be used for documentation of the detector response in future projects. Three pans appear to give a reasonable fire size to test according to the goal setup by Swedish Transport Administration. The fire growth rate varies, and is very much

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3 Wind speed fluctuated during tests and was measured both with handheld devices and the system installed in the tunnel.

4 Time after ignition

5 These smoke detectors were only mounted there for the tests. The detection time presented is the value given by the manufacturer for when a fire is detected, 30-40 mE/m (milliExtinction/meter). The time which is presented is when the value first enters the mentioned interval. Within brackets the time for a detection limit of 7 mE/m is presented. This value is based on what STA believes could work as a lowest possible limit for fire detection.
dependent on the wind velocity. In the following a short summary of the most important conclusions related to the technical detection system is given.

**CCTV**
In each of the tunnel tests performed, the CCTV were able to detect the fire within 3 minutes of ignition.

**Linear heat detectors**
When using three test pans (2.2 MW) the linear heat detection system alarmed within 2 minutes and the four pan fire (3.6 MW) was detected, causing an alarm, within a minute of ignition. In case of only one pan (about 0.5 MW), the LHD system was not able to detect the fires, causing neither pre-alarm nor alarm except for Test 14 where the wind was kept as low as 1.5 m/s. It also did not detect the fire in Test 12 either, with two pans (1.5 MW) and maximum wind at 7.8 m/s, and reached only pre-alarm levels for the other two pan tests when the wind speed was 3 m/s or higher. However, during the two pan fire test at Vassen the LHD detected heat changes of alarm levels shortly after 4 minutes and had reached pre-alarm levels half a minute earlier. The wind speed was lowered during the test though and the LHD did not alarm until the wind was below 3 m/s.

**Smoke detectors**
The smoke detector placed 100 m downstream of the fire detected all fires within 3 minutes using a threshold value of 30 mE/m, except for Test 8 with no detection (one pan fire and wind of 6 m/s). The smoke detector at 190 m downstream of the fire detected all fires of three pans or more within 3 minutes. The two pan fires were detected just before or after 3 minutes and for the low wind speed (1.5 m/s) tests the smoke should not reach the far smoke detector until more than 2 minutes have passed after ignition.

**Cable Plate Thermometers and LHD**
While comparing the rate-of-rise of the temperatures measured by the CPTs to the detection performance of the LHD one could see that detection was achieved only when the CPT showed a rate-of-rise which was higher than 1°C/min and which did not fluctuate too much. When the CPT rate-of-rise did not reach high above 1°C/min or fluctuated, making the value go below 1°C/min from time to time, there were no detection from the LHD. The value of 1°C/min discussed here is only an indication for detection. Comparing the CPT results with the thermocouples situated next to them made it clear that the CPT was highly affected by radiation from the test fires. This was most obvious for the tests with higher wind speeds where they reached temperature increases several times higher than the corresponding thermocouples. (The thermocouples probably also measured the radiation effect and/or the temperature of fresh air flow heated by the hot tunnel walls). At low wind speeds (1.5 m/s) the convective effects became dominant and the thermocouples increased as much or even more than the CPTs.

**CONCLUSIONS**
Large-scale fire tests have been performed in a road tunnel together with small scale laboratory tests in order to define suitable pan sizes for a 0.5 MW fire. The main aim of the tunnel tests was to investigate possible fire detector systems and to see if they could fulfill the requirement given by the Swedish Transport Administration to detect the fire within 90 seconds.

Answers to the initial questions and more were established during the tests. It was found in the small scale tests that the HRR increased when the pool fires were exposed to a lateral wind. Several fuels were tested in order to choose the ones providing the required HRR and fire behavior, which were finally chosen to be gasoline and heptane. Gasoline had the highest smoke production in relation the HRR. The pan that was found to produce approximately 0.5 MW when exposed to lateral wind, with both heptane and gasoline, had the dimensions 0.35×0.35 m². The tests also showed that the height of the pool rim is an important factor for the fire behavior.
In the tests carried out in the Törnskogstunneln, the linear fire alarm cable did not function properly during the tests, and therefore nothing can be said on their function. However, the CPT at 0 and 5 m downstream registered very low temperature differences during the tests, and it is doubtful if the linear fire alarm cable would have been able to detect the test fires. In each of the tunnel tests performed, the flame detectors situated at 25 or 60 meters from the fire location reacted quickly within 0.5 min, both for covered and uncovered fires with a measurable HRR (>0.1 MW). The smoke detector at 100 m downstream the fire detected 3 out of 4 fires with a 0.5 MW HRR within 90 seconds.

Since no data was available for the linear heat detector nothing can be said about its performance, except that a 0.5 MW fire is a challenging to detect within 90 seconds, but not impossible within 5 min. The temperature increase due to radiative heat transfer is around 2-3°C within 5 min and the expected temperature increase due to convective heat transfer is 6°C within 5 min 15-20 m downstream the fire.

From the tests with covered solid material it is clear that such small fires (< 0.1 MW) are not detected by any of the systems. Covering the liquid fuel with a wheel house did not seem to affect the performance of the flame or smoke detecting system.

The Northern Link tests experiments were carried out at a tunnel section with linear and smoke detection systems, together with visual CCTV monitoring. In addition, the test site was instrumented with cable plate thermometer (CPT) and ordinary gas temperature sensors. The performance specification for the Northern Link tunnel before it could be opened specified that the detection system must be activated within three minutes in response to a 3 MW fire and 2 m/s air flow velocity. The ability of the system to detect a 0.5 MW fire with an air flow velocity of 6 m/s within 90 seconds has also been investigated. Changing the number of 0.6 m gasoline-filled pans from one to four enabled production of HRRs between 0.5 MW and 3.6 MW. A total of 16 fire tests were performed, with the results showing that, in most cases, the CCTV and smoke detection systems responded to a 0.5 MW fire (one dish) within 90 seconds. The linear detectors (heat-sensing) reacted within 90 seconds to a HRR of about 2-2.5 MW, which was equivalent to that from three fuel pans.

RECOMMENDATIONS FOR FUTURE TESTS

A suitable method of testing the performance of flame, smoke, linear and visual fire detection systems in road tunnels requires the use of three 0.6 m diameter standard pans, each containing eight litres of 95 octane gasoline, and air flow velocities of 2 m/s and 6 m/s. One pan is sufficient if early warning is required without identifying the position for the fire-fighting system.

ACKNOWLEDGEMENT

In 2012 the Swedish Transport Administration and the Stockholm bypass project was granted co-funding for various tunnel safety studies from the Europena Union (EU) through the Trans-European Transport Network (TEN-T). The research was performed during the period 2012-2014. The study presented here summarises part of the work carried out within the framework of the EU-project. The sole responsibility of this publication lies with the authors. The European Union is not responsible for any use that may be made of the information contained therein.
Extension of Existing Road Tunnels - Challenges in the Application of Road Tunnel Safety Legislation

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ABSTRACT
When property prices in cities increase in pace with the decreasing available surface for development, the financial incentives increases for covering existing roads and extend existing tunnels to create new surface area for urban development projects. At the same time, extensions of tunnels can cause significant changes in the prerequisites of the safety concept. The safety concept in the existing part of the tunnel might need to be upgraded due to higher requirement of the total tunnel with new length, but also due to an obsolete standard that will affect the conditions in the new part of the tunnel. The interdependencies between the existing and new part of an extended tunnel is complex and crucial to address early in the project. This paper describes how the EU [1] and the Swedish legislation [2, 3, 4] on safety in road tunnels affects a project; when a road tunnel exceeds 500 meters before or after an extension. The paper also describes the process that leads to the approval of the safety concept for tunnels and the deviations which are needed to apply for the existing parts. Large parts of the legislative requirements are applied retroactively on the existing road tunnels, which results in that the formulation of the legislations contains ambiguities. Other problems is that the legislation shows shortcomings in the current situation and fails to provide an acceptable level of safety, for example, the form of acceptance criteria. Furthermore, since the approval and examination of tunnel safety is performed in the last instance of the project. The existing legislative process constitutes a major project risk for a developer who wants to extend an existing tunnel since it involves large uncertainties and unpredictable costs, i.e. both deficiencies and regulatory interpretation by authorities having jurisdiction are discovered too late in the project timeline. Since, these types of problems are a quite new phenomenon and the formulation of legislation contains ambiguities, a compounding problem is that the authority having jurisdiction dealing with these issues are unexperienced. To illustrate and clarify the problem, the paper has used Söderledstunnel, form here on called South route tunnel, in Stockholm as a case study.

KEYWORD: Tunnel safety legislation, approval process, acceptance criteria, holistic approach, robustness.

LEGISLATION
In 2004 the European Parliament and Council approved the directive 2004/54/EC on a minimum safety requirements for tunnels in the Trans-European road Network [1], the TEN road network. The directive applies to tunnels which are longer than 500 meters and are included in the TEN road network. In Sweden, the government chose a national equivalent of the directive to also apply to road tunnels longer than 500 meters which are not included in the TEN road network. The transitional arrangements which were developed in accordance with the legislation describe that the regulations do not apply retroactively to road tunnels which are not included in the TEN road network. The directive and the law are retroactive for all tunnels in the TEN road network, regardless of whether a tunnel during the adoption of the law was in operation, under construction, or in the planning stage.
The Swedish government judged however, that there were no grounds to impose retroactivity on the directive for tunnels outside the TEN road network. But the requirements should apply to tunnels which are longer than 500 meters and planned after the law started to be in effect.

According to an interpretation of the Swedish government bill, 2005/06: 168 [5], it is not appropriate to introduce specific requirement levels or to have specific exceptions for some tunnels. Based on this interpretation, the Swedish Transport Agency has interpreted that the Swedish tunnel legislation [2, 3, 4] applies to the extension of an existing tunnel, which is longer than 500 meters; or to a system where the resulting tunnel and or tunnel system will be longer than 500 meters. The Swedish tunnel legislation is based on the EU directive 2004/54/EC [1]. This means that both new and existing parts of the tunnel will be built according to the new demands. There is no partial application of the law relating to tunnels or specific areas in a tunnel[6]. In other words, it is not possible to split up a tunnel with different legal requirements.

The Swedish Administrative Authority can approve exemption from the prescribed safety measures, if it is motivated by the use of new technologies and if the safety level doesn’t deteriorate compared to the safety level using the prescribed safety measures. The law does not define what new technology entail and can thus be interpreted to be different combinations of safety measures that don’t deteriorate the safety level. Another option is if there are imperative reasons, see below. The Swedish law states the following:

1. limited derogations are allowed using new technologies not to lower the safety level, OR
2. if there are imperative reasons for derogation and if alternative risk mitigation measures are applied that don’t deteriorate the risk level then it’s approved to derogate.

The Directive states in Article 3 with respect to the application for derogation:

“Member States or the Administrative Authority shall send to the Commission information on the following:
– the limited derogation(s) envisaged,
– the imperative reasons underlying the limited derogation envisaged,
– the alternative risk reduction measures which are to be used or reinforced in order to ensure at least an equivalent level of safety, including proof therefor in the form of an analysis of relevant risks.”[1]

It’s unclear why the Swedish law [2] differs from the European Directive in this case. In the Swedish translation of the European Directive “or” has been added between the first and second article in the quote above. By adding the word “or” enables an extension of an existing tunnel if imperative reasons can be used, where derogations from certain legal paragraphs are necessary. Nonetheless, changing the existing infrastructure to fulfill the same prescriptive requirements is often economically and practically impossible.

For example, a requirement on a larger cross-section in the South route tunnel would mean that a completely new tunnel needs to be built, other problem areas such as, changing the number of lanes can result in the closing of an access-ramp, which would result in a huge impact on the overall traffic solution for the city district. In these cases the required derogation will be necessary and compensatory measures shall be introduced.

The Swedish legislation [2, 3, 4] on safety in road tunnels has prescriptive or preformed based legal requirements, some of these legal requirements cannot be derogated from. For example, the requirements considering the design of the safety facilities for tunnel users; emergency stations, signs, lay-bys, emergency exits and radio re-broadcasting. The fact that derogation is allowed and the tunnels safety level are based on a holistic approach makes it unclear if all the legal safety design requirements are functional (i.e. performance based) or not, with the exception to the safety facilities at the disposal of the tunnel users.
The Transport Agency regulations and general advice on safety in road tunnels, etc. [4] states in chapter four, that the Transport Agency can permit derogations, but without further description what this entails, therefore one interpret that derogations is still a possibility.

In comparison to the Swedish building law, the legislative text is binding and can be prescriptive or preformed based. Prescriptive rule can have a general recommending text providing a possibility for a performance based approach. The legislation on tunnel safety however provides possibilities for derogations, but only if a risk analyses have been achieved and safety level doesn’t deteriorate compared to the safety level using the prescribed safety measures.

Because the Swedish tunnel legislation also applies to road tunnels exceeding 500 meters which are not included in the TEN road network, a major project risk regarding the time schedule for projects has been identified. Derogations on tunnels that are not included in TEN road network were supposed to be approved by the EU according to the Swedish legislation. The time delay of such management could thus become very extensive and therefore involve to a major risk for the project since such assessment does not fall within the scope of EU jurisdiction. According to the latest version of the legislation, 01- july-2015 [7]; the Swedish Administrative Authority handles all derogations concerning the safety in non-TEN road network tunnels. This clarification makes it easier for a developer to handle project uncertainties, since they now can be consulted by the Swedish Administrative Authority.

**CASE STUDY**

The South route tunnel is approximately 1.6 km long and is located in the central part of Stockholm[8]. It eases traffic from the surface roads and is a central part in the traffic network for traffic from and to the central parts of Stockholm. The tunnel has two single tubes with two lanes in each direction. Furthermore, the tunnel also unburdens the city district of Södermalm with access and exit ramps at six locations. The entrance and exit ramps are woven into the right hand side of the tunnel, the low speed lane. The tunnel is originally built over a lower excavated road which has turned in to a cut and cover concrete tunnel over time with buildings and roads on top of the tunnel. There are also buildings which connect to the tunnel at road level, beside the tunnel wall. The tunnel network also includes a 110 meter long rock tunnel. The first parts of the tunnel are from the 1940’s but the main part is built in the early 1980’s where the last open air part was covered in the early 1990’s. Since, the total extent of the tunnel was built over a long time period, several tunnel parts are constructed with different methods, hence tunnel height and width varies. Furthermore, each side of the tunnel is connected to bridges and the traffic flow is about 100 000 vehicles per day in each direction, the tunnel was designed for a traffic flow of about 35 000 vehicles per day. The traffic flow is resulting in daily queues at rush hours for several hours.

At a tunnel cross section, the lanes are 3.5 meters wide, but the roadside varies from approximately 0.5 to 2 meters and the inside height of the tunnel tubes varies from 4.5 to 6.5 meters.

Below is a brief description of the main parts of the tunnel's safety concept[9]. Note that the description herein is not intended to be a comprehensive description of the existing tunnel safety concept.

- The tunnel tubes are separated with a concrete wall forming the two tubes, resulting in two different fire compartments, separated in EI 60.
- The speed limit is 70 km/h.
- The construction is designed to withstand a fire according to RABT60 with a cooling phase, which is equivalent to R120.
- The evacuation routes are located between the separate tunnel tubes. The connecting fire partition doors which are rated to EI 60-C, are placed about 70 meters apart with the exceptions at ramps and near tunnel exits.
• Longitudinal smoke and heat ventilation is provided and designed for a 100 MW fire.
• The fire detection system is a linear heat cable, Listec.
• General lighting, entrance lighting and emergency lighting are installed in the tunnel.
• The waste water system is designed as a combined system where all water is collated and then transported to a water treatment plant.
• The tunnel is classified as a category E Tunnel according to the ADR regulations, therefore transportation of dangerous goods is thereby prohibited but dispensation can and are given on a regular basis. The new planned extension of South route tunnel results in an exit ramp extension of approximately 210 meters, this section is further combined with an 80 meter long tunnel which runs under a hotel.

Figure 1: South route tunnel, the marked area 2 is the proposed expansion.

The tunnel which runs underneath the hotel, south end of South route tunnel, is joined together with the South route tunnel south bound tube, marked 1. The new extension is planned to render the development of two new city blocks which would include; shops, offices, hotel, flats, etc., marked 2.

Below selected areas, illustrate the conflicts between the present legislation with its higher requirements and the actual layout of the tunnel.

• Numbers of lanes: according to TSFS 2015:27, chapter 3 § 5, the number of lanes on the main carriageway shall remain unchanged before and inside the tunnel. However, the first about 100 meters of the South route tunnels northbound have a weaving access ramp lane.
• Tunnel geometry; according to TSFS 2015:27, chapter 3 § 8, shall tunnels with slopes higher than 3 % a risk analysis should be carried out to determine if risk mitigation measures shall be taken. South route tunnel has a slope of 4.5 %, a risk analysis has never been undertaken.
• Ventilation; according to TSFS 2015:27, chapter 3 § 16, if a tunnel is designed with longitudinal ventilation, a risk analysis should be carried out to determine if mitigation measures are necessary. However, a risk analysis for South route tunnel has never been undertaken.
• Fire extinguishers and emergency telephones; according to TSFS 2015:27, chapter 3 § 22, tunnels exceeding 500 meters should have two fire extinguishers and one emergency telephone at least every other 150 meters. The South route tunnel has fire hydrants and emergency phones, resulting in that the required equipment and distance is not fulfilled.
• Emergency routes; according to TSFS 2015:27, chapter 3§ 28, tunnels with more than one lane shall have at least 0.8 meter wide walkways on both sides of the lanes. However, South route tunnel does not meet the minimum walkway width requirements.
• Evacuation; according to TSFS 2015:27, chapter 3§ 29, evacuation doors should be easy to maneuver and must open in the direction of escape. In the South route tunnel all evacuation door opens in direction from southbound to northbound.
• Closure of a tunnel; according to TSFS 2015:27, chapter 3§ 44, a tunnel should be able to be closed off for traffic without delay in case of accidents or incidents. In case of South route tunnel, a non-automatic system is in place which renders to long reaction times, further not all entry and exit tunnel points are equipped with traffic booms and or light signals.
PROBLEMS LINKED TO THE PROJECT FOR THE DEVELOPER (THE MUNICIPALITY)

The uncertainties around which measures are needed become a major project risk which consequently leads to a wide range of problems. The fact that the Administrative Authority does not do a partially approval of the tunnels in the planning stage, makes it most difficult for the developer to estimate the costs and risk levels for the project. In a normal building project, the developer is responsible to achieve a balanced project economy. The project normally takes costs in account which are unclear or hard to estimate. For the benefit of the developer, a municipality sometimes has to bluntly accept extra costs, for example when upgrading the safety level in a tunnel. In correlation to the South route tunnel, since the project risk level is deemed to be very uncertain, the project is risking to be stopped because of financial concerns. For the tunnel manager all unforeseen expenditures are important but they also want to have a clear view on extra costs such as additional operation and maintenance costs during the management phase for the existing part of the tunnel.

If the cost balance is negative or otherwise deemed ambiguous, the project tends to lead to a project pause. However, in a city planning perspective, projects which tends to have a strategic urban planning importance usually returns for reactivation with a certain degree of frequency. This is due part of that the municipality has an increasing interest to see the project be fulfilled according to the original set strategic city plan. Hence, the municipality willingness to take greater risk and cost for each time the project is activated. After elections where the political majority is changed the frequency of reactivating projects tend to increase significantly.

APPROVAL PROCESS

Since, there is no process described in the legislation [2, 3, 4] on partial approvals for deviations during either the planning phase, the planning consultation process, or the design of compensatory measures. The existing legislative process constitutes a major project risk for a developer who wants to extend an existing tunnel. But according to directive 2004/54/EC [1], that prescribes a consultation with the safety officer and an approval during the design phase, where the design of the tunnel shall be approved by the authority which has jurisdiction before the construction phase is started. Contrary to Swedish law this is not clearly defined, in which only a description of the contents of the safety documentations in the design phase is defined. Further, the safety documentation shall be sent to the Swedish Administrative Authority before the construction phase is started. One of the parts in the safety documentation is an opinion on all aspects of safety from the inspection entities which for some projects is the Administrative Authority.

The approval of the design, instead of an opinion from the inspection entities, is not described in the Swedish law and the consultation with the safety officer is also excluded in the legislative text. In comparison to the EU directive, where the approval of the design occur in the end of the planning process, which is not the same as the approval of a finalized tunnel, and doesn’t include all the detailed documentation related to the safety design. In the Swedish adaptation of the directive, this design approval does not exist.

It is however unclear how the approval of the design and consultation with the Administrative Authority would be performed. But it should occur in the early planning phase thus reducing the project risks, especially if derogations are necessary. Currently, final approval and examination of the tunnel safety are performed in the last instance; hence deficiencies are discovered much too late in the project timeline resulting in huge costs if something is wrong or in conflict with the opinion with the authorities having jurisdiction.

PROPOSAL FOR AN IMPROVED APPROVAL PROCESS

An extension of an existing tunnel that is not designed according to today's legal requirements leaves the developer with a problematic approval process. The testing and approval of a tunnel (extension) is performed before the opening of the tunnel or at the opening of a new section, thus the trial and
approval arrives much too late in the project timeline. The approval process uses a holistic assessment of the safety measures taken and a process can start to determine if deviations can be approved. In order to provide a clear approval process and reduce the major project risks in the current situation, it’s necessary to introduce consultation with the Administrative Authority in an early stage of the project. This is done in order to guide the developer and or project on the right track. Some projects may be impossible to perform and achieving a high enough safety level whilst others projects can be performed with derogations and compensatory measures of a holistic approach.

In order to allow derogations and introduce compensatory measures following a holistic approach one needs to know the accepted risk level. In Sweden there are no explicit acceptance criteria for the risk level. Instead there is a common practice which governs the level of safety in new tunnels. This level consists of a comparison with the risk level of an open road; a tunnel should have the same or less risk then an open road as prior legal legislation have stated[10]. The risk level for an open road has been reduced over time because of safer cars and better roads are being built. The margins that previously existed for the additional risks in tunnels, due to fire and dangerous goods, has decreased and has become insufficient, resulting to a floating or flexible acceptable level of risk. Based on previous design in tunnels, legal requirements and previous design in tunnels do not take into account, differences in the volume of dangerous goods, size and frequency of traffic jams, general traffic volume, etc. These factors are then left to be evaluated in a risk analyses, followed with the validation of risk reducing measures. The result then becomes an acceptable risk level for the overall design. This overall design then forms the foundation for a discussion regarding the outcome between stakeholders. Without generally accepted and legislated risk criteria, the level of risk will be different from tunnel to tunnel.

One way to solve the problem for an individual tunnel project is to perform a comparative study. In such a risk analysis the legislation is followed strictly and other defining factors such traffic volume, queues, transport of dangerous goods, the environment, etc. is used in the analysis. The resulting conclusion can then be used as an acceptable level of risk. Thereafter, a risk analysis with the needed derogations is performed on the tunnel. The mitigation measures can be analyzed and a comparison can be made. At this point, the project can be continued or abandoned. These comparative risk analyses could be used as a tool in the approval process.

Another way to solve the problem is introduce cost-benefit analysis, considering the value of a human life. The new part of the tunnel will be planned after the demands in the legislation and for the existing tunnel it is suggested that the level of risk should be based on cost, benefit, feasibility of construction technical measures and safety aspects.

Cost and benefit considerations could and should be used to point out individual system or groups of systems used to raise the overall safety in the tunnel system. Examples are a fixed firefighting system and systems to increase evacuation safety. If the benefit in human lives does not outweigh the cost of installation, the balance would be considered negative.

The Swedish building legislation contains a chapter on changes to buildings. This chapter allows customizing the level of requirements for existing buildings and could be used as a basis for similar arrangement for tunnels. In buildings the same legislative text is applied for both the construction of a new building as well as for remodeling. However, the requirements for new constructions are never directly applicable to remodeling. For remodeling the requirements can often be met through other solutions than for the construction of new buildings. I other words, there are different conditions when a new building is being built verses remodeling a building. When remodeling is in effect, the project is based on an existing building and its inherent limitations which can lead to an adaption of the demands, such as; the extent of the remodeling, condition of the building, architectural value and distortion of the design. The requirements when remodeling must always be determined by the current building’s qualities and defects and the specific remodeling situation, but at the same time always meet the minimum accepted level.
The safety requirements in a remodeling project can be restricted to the altered part, the section that is directly or indirectly affected by the measure. For example, in a building where a new door opening is made, the demands on load-bearing verification is only subjected to the actual location of the door, hence surrounding rooms are not subjected to verification. Restricting the verifications to the changed part is not acceptable if the entire building or a significant part of the building is to undergo major remodeling. In that case the requirement for new buildings shall be followed in the entire building.

There is a need for a similar approach for tunnels which are undergoing modifications, the legislation for the remodeling of buildings has evolved under a long period of time, however this legislative adaptation and evolution is judged to be of a greater concern for road tunnels, why the legislation need to give alternative solutions (preformens based legislation).

Another way to fulfill the requirements is to introduce administrative measures where for example heavy vehicles are prohibited during rush hour traffic. This may be difficult to implement in an urban area but would lower the inherent risk of heavy vehicles due to a smaller fire load. Consequently, administrative measures could solve the problem with evacuation and fire safety. If the tunnel system receives a higher level of safety, it should also be considered in the assessment of whether an extension can be allowed or not, when a holistic approach is used. After all, if a tunnel extension would not be built, the risk level would be left unchanged. This type of approach needs some sort of risk criteria when evaluating the benefits of what a tunnel extension provides.

Currently, one can assess that the Administrative Authority does not have the correct and or enough tools to effectively manage the present process. It is further assessed that accurate tools need to be developed in order to evaluate acceptable level of risk with acceptance criteria. However, new assessment tools will only solve the majority of the identified process problems. Other needed actions are a change in the legislation, where it becomes more preformed based. This modification could lead to an easier way to solve and manage future project problems. Further, older tunnels need a different approach as to enhance the overall safety level rather than fulfill all the legislative regulations in detail. Hence, a partial application of the law for existing tunnels could solve this problem.

The described problem seems to exist throughout the EU and similarly problem is recognized [11]. The directive is not constructed to manage the problem when upgrading an existing tunnel to new standards, what should be required is that the same level of safety is achieved as intended in the directive. This on other hands has to be left to the engineer and safety designer and that legal opportunity is not given with acceptance criteria.

The approval process is suggested to follow the following process:
CONCLUSIONS

There is a need to clarify and structure the approval and deviation process for existing tunnels longer than 500 meters or tunnels which will have a total length of 500 meters after an extension in Sweden. The existing approval and examination of tunnel safety are performed in the last instance and the existing legislative process constitutes a major project risk for a developer who wants to extend an existing tunnel. The inherent project risks for tunnel extensions involves large uncertainties and unpredictable costs, i.e. deficiencies are discovered much too late in the project timeline. The current Swedish legislation is not adapted to handle extension of tunnels and is also ambiguous regarding to acceptable deviations. An early consulting and communication process with the Administrative Authority must be required for these types of complex project, such as right track indicators and partial approval in the different project phases.

There is also a need to develop an acceptable level of safety and acceptance criteria for tunnels and tunnel extensions. The authors of this paper suggest that this level should be based on a comparative study or on cost, benefit, feasibility of construction, technical measures and safety aspects. It is judged that the authority which has jurisdiction over the matter does not have the adequate and or enough tools to manage this process. Tools as acceptable risk levels with acceptance criteria are assumed to solve the majority of these problems.

Furthermore, it is suggested that the current legislation should become more preformed based, this change could lead to an easier way to manage this type of complex projects where different risk reducing measures can be balanced to an acceptable level of risk. Existing tunnels are assumed to need a different approach as the overall safety should be enhanced to a higher level compared to the present situation, therefore these types of road tunnels should not be subjected to fulfill the whole legislation and every detailed requirement. Risk reducing measures can consist of construction...
(passive systems), technical systems (active systems) and administrative measures. A holistic approach can ensure the possibility that several different combinations of construction, technical systems and administrative measures can be combined to achieve an acceptable level of safety.

A partial application of the law for existing tunnels could solve this problem when existing tunnels are extended. At present, the legal framework does not allow deviations in the existing tunnels, resulting in major costs and uncertainties in the pre-planning phase.

The tunnel manager, the developer and other parties in this kind of complex project must have a clear process to manage the project so they can foresee the costs and understand what type of uncertainties, they are facing in the project. Excessive project uncertainties will most likely postpone or even eliminate urban planning projects.

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Fire and Life Safety Matters During Tunnel Construction

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ABSTRACT
From our local and overseas experiences on new tunnels, it seems that it is common for projects to focus fire and life safety (FLS) planning and design efforts on the ultimate operational phase of the infrastructure. FLS risk in operating rail and road tunnels is managed to an acceptable level by controlling the hazards and by tempering consequences through active or passive engineering and operational measures. For tunnels under construction, fire still presents a considerable risk to life; however, there are fewer engineering avenues available to the contractor for controlling hazards and for managing that risk. Using selected observations and learnings from recent case studies from Australasia; namely the Waterview Tunnel in New Zealand, and the Legacy Way and Clem7 Tunnels in Australia, as well as from recent European projects, this paper explores a number of important FLS concepts and issues that are relevant to tunnel projects under construction. The objective of this paper is to promote safety in tunnel construction by raising industry awareness of several FLS matters and by suggesting improvements to some current practices which appear to provide limited risk benefit.

KEYWORDS: Tunnel fire and life safety, tunnel construction, tunnel boring machine safety, fire-resistant hydraulic fluid, tunnelling codes of practice, tunnel ventilation, refuge chambers

INTRODUCTION
Long egress distances, limited choice of egress routes, limited smoke management capacity, and lack of fixed tunnel fire suppression systems are universal safety concerns for nearly every tunnel project during its construction phase. These concerns also apply to underground mining operations, and so many parallels can be drawn with that industry. Past tunnel construction incidents known to the authors through discussions with contractors and from the literature [1, 2, 3] include:

- Koralm Tunnel KAT2, Austria 2015 – TBM (Tunnel Boring Machine) diesel generator fire.
- Airport Link, Australia 2011 – small fire caused by welding activity.
- Johnstone’s Hill Tunnel, New Zealand – small hydraulic machine fire.
- Cabin Creek Hydro Tunnel, USA 2007 – cleaning chemicals fire.
- Björnböle Tunnel, Sweden 2006 – drilling rig fire.
- Thames Tunnel, UK 2005 – maintenance train explosion and fire.
- Trojane Tunnel, Slovenia 2004 – diesel-powered compressor fire.
- Gotthard Base Tunnel, Switzerland 2004 – conveyor belt fire and drill rig fire.
- Guadarrama Tunnel, Spain 2003 – fire on worker train.
- Toulon Motorway, France 2000 – construction vehicle fire.
- Zurich-Talwil, Switzerland 2000 – electrical fire.
- Oslofjord Tunnel, Norway 1999 - fire from explosion.
- Store Baelt, Denmark 1994 – TBM hydraulic system fire.
- Los Angeles Red Line, USA 1990 – fire on timber supports.
- Brenner Tunnel, Austria 1989 – fire from explosion of dangerous goods.
- Hex River, South Africa 1980 – electric mucking out machine fire.
- Berlin Metro station, Germany 1976 – fire.
Tyneside Metro, UK 1976 - propane cylinder explosion.
Lötschberg Tunnel, Switzerland 1972 – fire.
Symlar Tunnel, USA 1971 - gas explosion.

Fires in tunnels under construction are rare events. Even though the probability of a fire in a tunnel is exceptionally low, the consequences of such an event may be unacceptably severe. Contractors need to make judgments on risk acceptability on behalf of their workers. Decisions on appropriate FLS measures cannot be solely based on the outcomes of quantitative risk assessments. Considerations must also include judgment of community and workforce acceptability of existing risks, and the reasonableness of adopting or rejecting possible measures to further reduce risk. Common FLS challenges for tunnels under construction are very long egress distances to points of safety, blind headings limiting choice of egress direction, limited opportunities for effective smoke management, and variable work activities and workforce. Facilitating self-rescue is a universal FLS objective in mining, for tunnels under construction, and also for operating tunnels. There are four fundamental aspects of managing FLS during tunnel construction, namely:

1. Planning, monitoring change, training, and exercises;
2. Fire prevention through maintenance, housekeeping, hardening and materials control;
3. Egress, wayfinding and ventilation, and;
4. Response and responder access and communications.

No matter the geographic location or extent of tunneling activity, these are common elements of accepted industry practice as embodied in the various regulations, codes, standards and guidelines.

**Tunnelling is Not Mining**

There are aspects of tunnel construction that are more closely aligned with mining than with surface infrastructure in the built environment. There are numerous mining standards, guidelines and codes of practice, however a construction FLS model that works for a mine may not work with tunnelling crews. Mines typically establish and maintain specialist response teams who are trained for underground emergencies. Response plans and procedures are developed for the long term with assumed continuity in application and appropriate change management. Tunnelling projects are often driven by short-lived contractor organisations with a short term perspective, using a dynamic workforce tailored to the tasks at hand. Tunnelling contractors often engage a multitude of multi-disciplinary and task-specific sub-contractors for which they are responsible for, whereas mines tend to rely on fewer third parties underground and so it is easier to foster a consistent safety culture.

It is interesting to note how common fires are in the mining industry relative to the tunnelling industry, despite the similarities in FLS hazards. To illustrate this point, in the State of New South Wales, Australia, between 2008 and 2012 there were on average approximately 2.7 fire incidents on mechanical plant per underground metalliferous mine per year (based on a survey of 12 mines) [7]. In Sweden between 2001 and 2005 there were on average 35 underground fires per year in mines [4] and in 2012 there were 41 vehicle/plant fires in Sweden in underground mines [5]. Since 1970 there have been approximately 366 fatalities in US mines caused by fire or explosion [6]. On the face of it, the statistics suggest that mining is a much more hazardous industry that tunnelling in terms of FLS.

**SAFETY SPECIFICATION**

As a workplace, tunnels under construction are typically regulated under local workplace health and safety laws and subordinate regulations which outline roles and responsibilities and specific duties of care. Supporting these usual requirements are codes of practice (COP), standards and industry guidelines such as:

- Guide for Tunnelling Work (Safe Work Australia 2013);
- Tunnels Under Construction (New South Wales COP 2006);
- Ventilation in Underground Mines and Tunnels (New Zealand Approved COP 2014);
- Fire or Explosions in Underground Mines and Tunnels (New Zealand Approved COP 2014);
- COP for Health and Safety in Tunnelling in the Construction Industry /British Standard BS 6164:2011);
- Guideline for Good Occupational Health and Safety Practice in Tunnel Construction (ITA Report
001 2008);

- Recommendations for Planning and Implementation of Occupational Health and Safety Concept on Underground Worksites (D-A-CH Guidelines BG Bau Berufsgenossenschaft der Bauwirtschaft 2007), and;

Other related and informative tunnelling documents include:

- Tunnelling Machinery – Safety requirements (European Standard EN 16191 2014);
- Guidelines for the Provision of Refuge Chambers in Tunnels Under Construction (ITA WG5 Report 2014), and;

Application of the codes and accepted practice requires interpretation and a sensible balancing of construction program, and financial and safety objectives. Where codes and standards are specified during a traditional design and construct (D&C) tendering phase, this process can be challenging for contractors because:

1. Risk targets can be different between tendering parties due to differences in culture, familiarity with technical standards, and appetite for risk, resulting in cost differentials;
2. On complex projects it may not always be possible to apply all the ‘standard’ safety measures. Projects become particularly complex from a FLS perspective once the TBM tunnel portals are underground and access to them is gained through a shaft (e.g. Koralm or Semmering tunnels);
3. Probity and time often prevents useful interaction between the tenderers and emergency services (as experienced on nearly all of the Australian tunnels), and;
4. Time and cost pressures of tendering often mean that there is little or no opportunity for developing the fundamental thinking around construction safety. It is normally not possible to detail out all FLS requirements for construction with any useful degree of certainty.

Alliances provide a more forgiving project delivery framework than traditional D&C delivery when there is uncertainty in technical and work program assumptions. Alliance members, including the end client, share the pain of cost overruns necessary for safety management but they also share the gains associated with innovation and cost savings, and non-monetary performance such as safety.

From recent projects in central Europe, it seems that compared to Australasia, clients there are more involved in the detailed construction planning of projects prior to release of tender documentation. Many construction safety requirements are prescribed. This is seen to remove time/cost pressures on contractors, and all parties bid against a similar risk benchmark. The Koralm Tunnel was one of the first tunnels in Europe where the client provided detailed construction safety requirements as part of the tender [11]. Building on that project, safety requirements were then developed for the Semmering and Brenner tunnels [12, 10]. The Semmering Tunnel tender specified a maximum blind heading length of 800 m before a cross passage needed to be available, and also the requirement of providing fire / smoke separation between the two adjacent tunnels [24]. Although this process would appear to be fairer and provide a more certain basis for costing, by restricting the approach to safety it also discourages contractor innovation and potentially removes opportunity for cost saving and safety improvement. The end client also takes on technical and commercial risk that would otherwise be transferred to the contractor(s).

Ideally, tenderers should be asked to submit a fully-detailed safety management plan with their proposal to form part of the tender evaluation so that much of the detailed thinking about safety has to occur prior to project commencement. Submission of safety management plans to the regulator prior to works is common practice in the mining and quarrying industries. When planning the sequence of tunnelling works, egress requirements would need to be considered, for example. This approach will only work if the client is informed and has the technical capacity to be able to critically appraise such a safety management plan. With the timing and probity constraints noted above, the authors are
skeptical about the practicalities of this approach.

The authors suggest that tenderers should be encouraged to apply systematic risk-informed methods for more complex or uncertain issues and then to only adopt prescriptive safety rules where there is a proven knowledge base, experience in application, and robust understanding.

Ultimately the client organisation needs to be responsible for their decision making as the safest proposal may not be the cheapest proposal. If they choose a cheaper option, which is not the safest option, they need to be able to demonstrate to the regulator that their choice has considered all practicable steps when considering FLS.

SAFETY MANAGEMENT PLANNING AND IMPLEMENTATION

Early in the project planning phase there needs to be a focus on ventilation and egress. The first task is to establish a project philosophy on self-rescue and fight or flight requirements. In high risk areas of the tunnel or TBM where there is only one available direction for egress, special precautions may be required to minimise the fire hazard. Refuge chambers should only be relied upon as a last resort.

Response strategies need to be kept simple. Because of variability in fire location and growth rate, construction timing and plant, access to egress points, and in work crews, it is important to ‘unify’ responses as far as practicable to minimise the number of scenarios. Such rationalisation helps to simplify communications and training, providing a greater certainty in response outcome.

Tagging in and out of tunnel personnel is common practice in mining as well as in the tunnelling industry. RFID tagging was used for the Clem7 and Waterview projects. Experience has shown that RFID is not 100% reliable in certain circumstances and so a manual backup system should always be available for deployment. One advantage of RFID is that it removes human error which is a real possibility with traditional manual approaches involving sign-in procedures and turnstiles.

REFUGE CHAMBERS

For the A86 fire in France, 19 TBM crew were able to find refuge in the forward TBM air/man lock. No dedicated TBM refuge chamber was provided. For the Koralm fire incident, a refuge chamber in the front of the TBM backup proved useful in saving lives. The Epping to Chatswood Rail Link Project in Sydney in 2003 [16] was one of the first tunnelling projects in Australia to use refuge chambers. For the Clem7 project in Brisbane in 2007, a guideline issued by the Department of Mines and Petroleum, Western Australia [8] was used to inform the design of the TBM refuge chambers. In Europe, the D-A-CH guideline which addresses refuge chamber requirements, was released in 2007, followed by the update of the British Standard BS6164 in 2011. In May 2014, the ITA guideline was published, and in September the same year, EN16191 came into effect. Table 1 summarises key standalone duration and thermal requirements for refuge chambers.
Table 1. Summary of different life support and thermal requirements for refuge chambers.

<table>
<thead>
<tr>
<th>Document</th>
<th>Publish Year</th>
<th>Standalone breathable air supply (hours)</th>
<th>Standalone power supply (hours)</th>
<th>Minimum ambient air temperature</th>
<th>Maximum allowable internal temperature</th>
</tr>
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<tr>
<td>Western Australia Department of Mines and Petroleum</td>
<td>2005, 2013</td>
<td>36</td>
<td>36</td>
<td>-</td>
<td>(a)</td>
</tr>
<tr>
<td>D-A-CH</td>
<td>2007</td>
<td>min. 24</td>
<td>min. 24</td>
<td>60 °C / 8 hours</td>
<td>&lt; 30 °C</td>
</tr>
<tr>
<td>BS 6164</td>
<td>2011</td>
<td>24 + 4 (b)</td>
<td>30</td>
<td>50 °C</td>
<td>&lt; 28 °C</td>
</tr>
<tr>
<td>ITA WG5</td>
<td>2014</td>
<td>min. 24 (c)</td>
<td>min. 24</td>
<td>-</td>
<td>&lt; 30 °C wet bulb</td>
</tr>
<tr>
<td>EN 16191</td>
<td>2014</td>
<td>4 (d)</td>
<td>min. 24</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(a) Environmental controls are required to address the potential for increasing temperature, humidity and potential heat stress.
(b) Where an external supply cannot be provided, 24 hours from cylinders and 4 hours from the emergency chemical supply.
(c) Duration of use should be assessed on the likely time required to affect a rescue. A minimum of 24 hr is recommended.
(d) Emergency breathing supply independent from any external supply.

**Vertical Location of Refuge Chambers**

It is normally recommended that refuge chambers are located well away from potential sources of ignition and fuel loads (preferably on the tunnel floor or at low level) [12, 8, D-A-CH]. With the chamber located at the floor of the tunnel, local tenability for visibility and temperature for persons accessing the chamber will be improved. The thermal exposure of the chamber will also be reduced.

When it comes to the TBM backup trailer/gantries, this preferred location for refuge chambers is frequently not achieved due to the competing operational requirements for the space and location. Diesel-powered trains or rubber-tired TBM service vehicles travel along the tunnel floor to service the TBM operations. The area directly below the last TBM gantry is normally a very busy space. Floor space forward of the last TBM gantry is usually used for the construction of the tunnel invert and/or to supply, handle and place ring segments. The remaining volumes to the sides of this area are kept clear for logistics, and access and egress paths. With these spatial limitations, the traditional approach for large TBMs with a diameter of greater than 9 m, is to locate refuge chambers on the top/upper deck(s) of the backup trailer/gantries. Project examples of this practice include CLEM7, Airport Link and Legacy Way in Brisbane, and Waterview in Auckland. Locating chambers on the top level of a backup not only complicates access to the chambers when smoke affects the backup, but it also increases the thermal exposure of the chamber(s) when the fire is on, or in close proximity to the TBM. For general tunnelling applications, BS 6164 suggests a steady-state ambient temperature limit of 50°C. The D-A-CH guideline suggests 60°C for a minimum exposure period of eight hours.

Computational Fluid Dynamics (CFD) modeling (i.e. Fire Dynamics Simulator - FDS) was used by the Legacy Way project in Brisbane to assess temperatures at a refuge chamber located high in the tunnel [9]. A fire on a TBM supply vehicle located 100 m behind the TBM was simulated with a peak heat release rate of 15 MW, lasting for a conservative time of 60 minutes. The CFD results for a section of the tunnel with 2% grade up towards the TBM are shown below in Figure 2. The data show that smoke temperatures 2 m above the tunnel floor did not exceed 40°C. Peak smoke temperatures in the crown of the tunnel (10.5 m above floor level) close to the fire exceeded 160 °C for the duration of the fire. While the backup structure itself would have an impact on smoke movement and temperatures, it is likely that the same fire, located closer to the TBM than modelled, would result in temperatures well above 60°C at the higher level refuge chamber on the TBM.

Refuge chambers should be thermally insulated using materials that are non-combustible as per EN 13501-1 Euroclass A1 and fire resistant to REI120 as per EN 13501-2 [10], especially if located on the upper levels of the TBM. Additional thermal protection can be provided using sprinkler systems [D-A-CH], but these rely on an external service which may be subject to failure or damage on the TBM or along the incident tunnel.

Refuge chambers require a cooling system to reject the metabolic heat generated by the chamber occupants. Numerous systems have been proposed for the mining industry [12]. Refuge chamber cooling systems that have been used or proposed for use in the tunnelling industry include:
• ‘Standard’ split system air-conditioner systems. These have been used for cooling on the recent large TBM tunnels in Australia and New Zealand (Clem7, Airport Link, Legacy Way, and Waterview). Batteries can be installed to provide power for standalone operation. This approach removes the risks associated with loss of supply lines. It can be a cost effective solution provided that the chambers are at a location where the ambient temperature during a fire will not exceed the rated design temperature of the air-conditioning system. For most commercially-available split systems, cooling performance is not guaranteed once the ambient air temperature exceeds 45 to 50°C at the condenser. While there are special high-temperature systems available that are designed for operation up to 70°C, the heat rejection performance of all split systems decreases as the ambient air temperature increases.

As shown above, ambient temperatures for a refuge chamber located on the upper level of a TBM backup could possibly exceed 70°C during a fire close to the TBM. To improve the situation, the condenser unit or its air intake duct could be located lower down in the tunnel where the air/smoke temperatures are expected to be cooler. Cooling systems which operate independently of the ambient air/smoke temperature should also be considered.

• Compressed air supply to provide oxygen and cooling effect through gas expansion (or possibly vortex tube). This is particularly suitable for stationary refuge chambers, where a high grade compressed air supply is available like in some mining applications. The fixed air supply has to be adequately protected e.g. by burying it in to the invert. This system presents a challenge for refuge chambers located on TBM backups. Even if the air supply line is perfectly protected in the invert over the full length of the tunnel, a flexible hose is needed to connect the fixed line to the moving TBM. That hose could be easily damaged in a fire involving the rear of the TBM. Also such a supply will have to be systematically interrupted for the extension of the pipes.

• Water supply and heat exchanger. For use with TBM chambers, this system has similar issues as the compressed air supply concept above.

• CO₂ refrigeration. With local liquid CO₂ storage on the TBM, this system can provide standalone cooling that is not affected by the ambient air temperature. For a 24-person chamber with a 36 hour rating and a 90 minute temperature exposure to 300°C, it is estimated that the additional gas storage requirement would add approximately 25% extra length and volume to a standard refuge chamber design [13]. CO₂ cooling was used for the Legacy Way Project in Brisbane as a backup to a traditional split air-conditioning system [14]. It was designed to operate for only a short period of time if the ambient temperature ever exceeded the split system air-conditioner capability. The air-conditioning condensers were also physically protected against high air temperatures. Legacy Way chose this dual-mode cooling system because of spatial constraints on the second hand TBM, as it required less space than a full-duration CO₂ system.

• Thermal mass or phase change. This range of solutions provides cooling to the chamber independent of the ambient air temperature. In this approach, chilled water [15] or ice [12, 16, 17] stored on the chamber could provide occupant cooling by means of heat exchangers. The use of ice as a thermal storage medium could reduce the additional weight to about 20% compared to a water solution. For a 24-person chamber with a 36 hour rating and a 90 minute temperature exposure to 300°C, it is estimated that the additional ice storage requirement would add approximately 10% extra volume to a standard refuge chamber design [17]. An ice-based cooling solution would be simple and resilient to a mechanical or power failure. A system designed to use individual ice blocks and fan-driven air flow through a stack of these blocks could still provide cooling to the chamber even if the fans fail. As long as the individual ice containers are small and can be removed from the freezer unit by hand, they will still provide cooling for the chamber. Also, the water liberated in this process would be available to the occupants for drinking. Where standalone operation of a refuge chamber is required in a high ambient temperature environment, ice-based cooling should be considered as a viable option.

Horizontal Location of Refuge Chambers
Refuge chambers need to be located such that they are readily accessible and not susceptible to the incidents they are provided for. The horizontal location of the chamber(s) on the TBM backup gantries is therefore also important. The ITA guideline suggests that refuge chambers should
be located at the rear end of the TBM backup.

There are important considerations for horizontal positioning. Most people onboard the TBM will work towards the front of the backup. Diesel generators and electrical air compressors will normally be located towards the rear of the backup. Diesel-powered supply vehicles will typically load and unload from beneath the TBM between the middle and rear of the backup. If a fire occurred towards the rear end of the backup on a vehicle or on an emergency generator [2], it would be difficult or even impossible for crew to reach a chamber from the front of the backup. Given that diesel-powered equipment is one of the high hazard elements within the TBM backup area, a chamber location as far forward as practical, ahead of all incoming vehicles, but not in the vicinity of major hydraulic or electric equipment, should be considered. Locating the chamber(s) as far forward as possible will reduce the required distance of travel to the chamber for most of the TBM crew, most of the time.

Figure 2. Modelled smoke temperatures resulting from a 15 MW service vehicle fire located 100 m behind the TBM (Legacy Way) [9], and examples of typical TBM service vehicles (Waterview).

OTHER SAFE EGRESS STRATEGIES

FLS risk at the TBM can be greatly reduced by providing ‘rescue’ vehicles [10], especially if they are equipped like a moving refuge chamber [10, 11, 18, 19]. This would not only allow the crew to evacuate quickly and safely, but it could also provide responding teams with a safe means to return to the incident location for rescue or firefighting activities. The Koralm tender included the requirement for an ‘escape train’ [2]. The Brenner tender included the requirement for an ‘escape vehicle’ [10]. Rescue vehicles are useful so long as people can access them. The authors suggest that a permanent smoke-separated escape ‘tunnel’ built within the TBM at a low level to ensure safe passage past any fire, is a concept that could be considered by TBM manufacturers and contractors. This would entail providing a fully enclosed path along the whole backup, which is supplied with fresh air from the primary ventilation system and self-closing doors. It may also remove the need for a refuge chamber on the TBM. For a fire at the rear of the TBM backup, the crew would be able to evacuate immediately instead of having to be rescued at a later stage from an onboard refuge chamber. While this concept may seem farfetched today, so did the enclosing of hydraulic power packs on TBMs less than 10 years ago. For the most part, that is now standard industry practice.

The Waterview Tunnel in Auckland used a novel approach to facilitate egress from the 300 m to 400 m long tunnel zone behind the TBM backup. The tunnel design incorporated a services tunnel (upturned concrete culvert) in the invert. This was installed, and covered with backfill, as the TBM
progressed. So that the services tunnel could be safely used for egress (or access), joints in the
structure were specially caulked to prevent the potential ingress of fuel from a spill above, and a
ventilation system was installed to prevent smoke ingress. Smoke tests were used to prove the
efficacy of the culvert ventilation system, as well as for assessing smoke spread along the tunnels,
recirculation at the main TBM supply fans, and pressure balancing between the two tubes to minimise
smoke spread through cross passages. A small emergency service vehicle or ‘mule’ equipped with
firefighting equipment, stretchers, and first aids kits was always parked between the end of the
services tunnel and the rear of the TBM. Fire blankets were provided at the rear assembly point of the
Waterview TBM so that crew could safely pass a fire at the tunnel floor behind the backup, and
evacuate via the end of the services tunnel, 300 m further along the tunnel. The culvert concept was
also explored for Clem7, however the potential for fuel spill into the culvert made the idea less
attractive for that project which was being delivered by a traditional D&C.

![Image 1](image1.jpg)
![Image 2](image2.jpg)

Figure 3. Smoke tests in the Waterview Tunnel during construction to test culvert smoke management
(left) and other ventilation issues such as the transport of smoke through open cross passages.

**TBM MATTERS**
Planning and procurement of the TBMs at the front end of projects is normally focused on the
functional requirements of the tunnelling activities (e.g. diameter, thrust, cable lengths, hose lengths),
and not on FLS. There is often cost pressure to just meet client requirements and also time pressure to
sort the TBM order, given the very long lead times for supply. At the time of TBM specification and
procurement, a safety management plan for tunnelling activities is typically not well-developed,
unless the client has previously provided a version of one, or unless a plan was required for the tender.
A number of methods are currently used by contractors to help mitigate fire hazards on the TBM
including the use of on-board suppression systems and fire-resistant hydraulic fluids. It seems that
there has been a move by the industry away from hydraulic to electric drive systems which has helped
lower FLS risk at the TBM. Monitoring and controls are also playing a greater role now in
minimising fire hazards on the TBM, and so are becoming more complex and safety critical.

**‘Fire-Resistant’ Hydraulic Fluid**
Many tunnelling codes and guidelines recommend the use of fire-resistant hydraulic fluids. EN16191
5.11 b) states that only low-flammability hydraulic fluids conforming to EN ISO 12922 shall be used
on TBMs. Apart from high-water containing fluids, fire-resistant hydraulic fluids will still burn under
certain conditions. Low-flammability hydraulic fluids are typically more expensive, and for
Australasia, generally more difficult to source and procure.

Arguably, the ignition of a fluid spray can result in a worse situation than a pool fire. In an atomized
spray form, mineral oil can be readily ignited, but so can fire-resistant hydraulic fluids (with the
exception of glycol/water-based fluids) [20, 21]. The literature suggests that for the worst case
conditions of an atomised spray of hydraulic fluid contacting a high temperature, high energy source,
there is practically no difference between mineral oil and a fire-resistant fluid in terms of ignition of
surrounding combustible materials in the vicinity of the leak. A spray fire may also result in a pool
fire which facilitates spread, however hydraulic equipment used underground should be provided with
fire detection and automatic shutdown facilities to minimise the size of any such pool.

For the Waterview Tunnel, mineral oil was initially selected and installed on the TBM based on perceived performance, including better compatibility with mechanical components. That decision was externally questioned by the local workplace health and safety regulator part way through the tunnelling program. However; there was little justification on FLS grounds for converting the large volume of existing mineral oil-based hydraulic fluid on the TBM to a fire-resistant fluid. Other measures were implemented to compensate for the slightly elevated risk, including installing a holding bund, and also a suppression system at the shield area. There are circumstances during typical tunnel construction operations where fire-resistant hydraulic fluids are not likely to offer any significant safety benefit.

**Water Curtains**

One common fire and life safety feature provided on many TBMs around the world is a manually-activated water curtain (i.e. a vertical spray) at the rear of the backup. The water curtain is supposed to cool the smoke and also provide a barrier to impede the movement of smoke from the TBM along the tunnel. EN 16191 (Tunnelling machinery - Safety requirements) Chapter 5.12 requires a water curtain system to be fitted to the rear of the towed backup equipment.

For a fire on, or within 100 m or so of the TBM, stratification of smoke should help occupants evacuate at low level along the backup and the tunnel. A water curtain would inevitably cause local destratification of smoke at the TBM, and so adversely affect visibility, especially along the backup and at refuge chambers. Unless fire water tanks and pumps are provided on the TBM backup / gantries, the availability of water supply from the surface could also be an issue. During TBM service extensions, fire water may not be available. Flexible lines are required to connect the fixed tunnel supply to the TBM systems. These may be readily compromised during a TBM fire.

The Waterview TBM was designed with manually-activated water sprays also over the backup walkways from front to rear (refer Figure 4), with the intended purpose of providing a safer egress path in the event of a fire. Given that these systems cool and destratify smoke, and reduce visibility, serious consideration should be given to their usefulness in reducing FLS risk.

Water curtains will help cool structures locally and attenuate radiation from a fire on a TBM; however, first-aid firefighting could be hampered and tenability for responders compromised due to the reduced visibility. TBM water curtains appear to be an industry standard and yet there is little evidence in the literature to suggest that they reduce FLS risk. If the cooling and radiation attenuation benefits are considered necessary for emergency response or asset protection, then perhaps a means for remote operation of the water curtain system from the tunnel control could be implemented so they can be initiated after the crew have left the danger area at the TBM.

**Fixed Fire Suppression**

EN16191 5.12.2 stipulates that all key fire risks including major plant on the TBM, are to be equipped with a fire suppression system. The Waterview, Clem7, and Legacy Way projects all installed fire suppression systems on the main hydraulic power units and storage, motor control centers, control room, and emergency generators. The Waterview TBM was an EPB type and so had large electric compressors on the top level of the backup. Suppression systems were fitted to the compressor enclosures sometime after tunnelling had commenced.

The TBM service vehicles (MSVs, mules and service trains) present a serious hazard to the crew of a TBM. These vehicles normally involve diesel and hydraulic power systems which, historically, have been a major cause of fires in mining [7, 22] and general industry. It is very common for vehicle and plant fires to be initiated by liquid fuel/oil sprays onto hot surfaces and also by electrical faults. Fixed fire suppression systems will not control or extinguish every fire. The MSV / train parking area under the rear of the backup is a critical location as vehicles spend quite some time there unloading, and it is below, and typically in close proximity to fuel loads on the backup and also refuge chambers.
The Waterview project installed a manual open-head deluge system over the TBM MSV parking area. Interestingly, this system was not originally specified and procured with the TBM, but was installed after tunnelling had commenced. Its need was determined through ongoing emergency planning and following engagement with the local fire brigade. Legacy Way opted to address vehicle fire hazards within the TBM backup differently using portable 50 L compressed air foam units (CAFS) (RF6 type) located on both the lower and middle decks (shown in the figure to the left). Recognising the importance of first response, over 30% of each TBM crew was instructed in the use of CAFS using live fire training. The units were provided with 15 m long hoses, to reduce the need for man-handling. The units could be easily moved by one person on flat ground but two people were required for stairs. Both Waterview and Legacy Way used portable CAFS at high risk work locations during project finishing and fit-out phases.

**Housekeeping**

Good housekeeping is inexpensive and goes a long way to reduce FLS risk. Contractors must remain vigilant for the project duration as workers and construction activities change as the works progress.

![Figure 4. Waterview TBM air compressors on top level, walkway deluge, and clear egress path (left). Microwave oven 'fire box' as a housekeeping improvement outside a TBM crew cabin (right).](image)

**FIT-OUT OPERATIONS**

Fit-out operations can be undertaken in parallel with, or following, tunnelling activities. Key risk considerations during fit-out activities include higher tunnel occupancies, multiple work parties distributed along the tunnel, use of more standardised construction equipment such as elevated work platforms and utility vehicles, and more third-party contractors. Self-rescuers (re-breathers) are normally carried by workers, or kept in the vicinity of workers, for personal safety during tunnelling operations to provide a 30, 60, or 90 minute egress capability in contaminated atmospheres. However, the devices can be cumbersome for workers when worn on a belt and can be a snagging hazard. Depending on construction sequencing and on the availability of effective smoke management and egress routes, there may be certain finishing and fit-out operations where self-rescuers are impractical and/or provide little to no net safety benefit, especially when relative points of safety can be reached within a few hundred metres.

**TUNNEL VENTILATION ISSUES**

Cross passages are a blessing for access and egress but are a curse for smoke management during construction. It is often not practical or convenient to temporarily close off cross passages affecting construction access, and yet providing smoke separation between tubes decreases FLS risk [24]. Shutting down the temporary construction tunnel ventilation system (normally supply only) during a fire should provide the best tenability for most cases prior to breakthrough [1, 9, 19]. This strategy may also be applicable to phases following breakthrough, as workers will often be distributed along the tunnel and forced longitudinal ventilation during a fire could be unsafe.

**RESPONDER CAPABILITY**

It is important for the contractor to understand the real intervention and search and rescue capabilities of the local response agencies prior to developing emergency plans. One important factor to consider
is the maximum distance that responders can travel into a smoke logged tunnel. Without closed-circuit breathing apparatus (BA) and the associated training, the response distance is often limited to around 100 to 120 m. In a number of recent tunnel projects, the distance from the leading TBM to the first available cross passage has ranged from a few hundred meters to 1.5 km.

Figure 5, extracted from an Austrian fire brigade paper [23], shows the maximum rescue distance into a tunnel for different types of BA. It highlights the need for long duration BA such as the Dräger BG4 closed-circuit unit (shown to the right), which is not usually available to ‘normal’ metropolitan fire brigade teams. BG4s (or similar) are commonly used by mines rescue services in New Zealand, Australia, and Europe.

At the time of construction, the 4.8 km long Clem7 tunnel was the longest road tunnel in Australia and indeed the first ‘long’ tunnel in Brisbane. In order to understand their tunnel response capability, the local fire brigade conducted tests with single cylinder BA, reduced visibility, and hot summer ambient conditions. It was determined that with standard-issue equipment, the maximum safe working distance into a smoke-logged tunnel is 120 m. To facilitate fire brigade intervention, the contractor provided twin cylinder long-duration BA sets at site. A quick refill station was also placed in the tunnel approximately 500 m forward of the last available cross passage, to allow safe access to the TBM. Waterview used the services tunnel for safe access by emergency services to the TBM, so that the maximum distance to an incident was always less than approximately 300 m.

Figure 5. Maximum achievable underground rescue distance with different breathing apparatus and walking speeds [23]. The “Rettungsweg” along the x-axis is the safe working distance to the incident incorporating capacity for returning to the portal. No allowance is made for time at the fire site.

KEY CONCLUSIONS

1. A holistic approach to FLS during construction is needed that can adapt to each stage of the construction sequence and to changes in tunnel occupancy and in the type of plant used. Ideally, preliminary FLS plans for tunnelling and fit-out phases should be developed at the same time as the project program, and well before specifications are written for the significant equipment such as the TBM(s), and the temporary ventilation plant. It is important for the contractor to monitor each construction phase and its core activities to ensure consistency between the FLS measures implemented and the real risks at hand.

2. Safety matters during construction should be thought through by the client at the time of development approval and prior to tender issue. There may be cost and risk benefits in having the client prescribe certain construction safety requirements, as per recent European projects. Alternatively, tenderers could be asked to submit detailed safety management plans with their
proposals. This approach requires an informed client and possibly a relaxing of business-as-usual probity requirements so that the contractor can engage with emergency services during the tender.

3. If refuge chambers are to be considered a primary FLS measure, it would seem reasonable to install them at low level and as far forward as possible on the TBM backup/support gantry to minimise their thermal exposure and to make access to them easier and safer. Ice would make a suitable cooling system for chambers in lieu of more traditional air-conditioning or CO2 systems.

4. Fire-resistant hydraulic fluids offer risk benefits, but it is important to not overestimate those benefits, and also to recognise that their use is not justified in all circumstances.

5. Expectations of emergency services’ capabilities need to be realistic so that effective emergency planning can take place. Response agencies should be engaged in a collaborative way from the outset of the project.

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Memorial Tunnel Test
Why Was 100MW Fire So Different?

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ABSTRACT
After 20 years, the data from Memorial Tunnel Test Program still worth to be re-examined. Why was the critical velocity of 100MW fire so low comparing with the smaller fire sizes tested? Such result had been reproduced more than once during the program, therefore experimental error was not impossible but other explanation may still worth persuit. In the current study, the entire set of longitudinal ventilation data from the test program has been examined on the basis of the recent log-law theory. Unlike the $V_c-Q$ curve in conventional studies for tunnel fire ventilation that shows sudden drop of critical velocity from 50MW fire to 100MW fire, the $Fr-Q'$ data curve based on log-law is continuous and has shown consistent trends over the entire test range. For fire sizes smaller than 20MW, the Froude number $Fr$ increases with fire size $Q'$ as expected in the prevailing cubic root theory. However starting from 20MW, $Fr$ continuously decreases with $Q'$ until the very last data point at 160MW in the test program. The trend line fits the log-law corrected by a loss function accounting the radiative loss of flame. It suggests that the heat loss characteristics of large tunnel fires (>20MW) may be quite different from that of small tunnel fires (<10MW) due to different mean flame temperature. Prediction using log-law with the proposed loss function agrees with the data from the test program.

KEYWORD: large tunnel fire, memorial tunnel, longitudinal ventilation, critical velocity.

NOMENCLATURE

\begin{align*}
A & \quad \text{Tunnel cross section area (m}^2) \\
C_p & \quad \text{Specific heat (J/kg.K)} \\
D & \quad \text{Longitudinal dimension of fire pool (m)} \\
Fr & \quad \text{Froude number} \\
g & \quad \text{Gravity (m/s}^2) \\
h & \quad \text{Specific enthalpy (J/kg)} \\
H & \quad \text{Tunnel height (m)} \\
l & \quad \text{Heat loss of fire flame} \\
m & \quad \text{Mass flow of smoke(kg/s)} \\
Q & \quad \text{Heat release rate of fire (W)} \\
T & \quad \text{Local temperature (K)} \\
u & \quad \text{Local air velocity (m/s)} \\
w & \quad \text{Tunnel width (m)} \\
\rho & \quad \text{Density of smoke (kg/m}^3) \\
\gamma & \quad \text{Dimensionless quantity} \\
f & \quad \text{Property of fuel.} \\
v & \quad \text{Property of ventilation air.}
\end{align*}
INTRODUCTION

Between 1989 and 1995, ASHRAE Technical Committee TC 5.9, authorized by the Federal Highway Administration (FHWA) and the Massachusetts Highway Department (MHD) in the US, had developed a full scale fire ventilation test program in the Memorial Tunnel, West Virginia. The test program has been known as MTFVTP. The six years, US$38 million program has provided a comprehensive set of tunnel fire ventilation data for tunnel designers worldwide.

In total, 98 tests were conducted in the MTFVTP program. 15 of them concerned longitudinal fire ventilation covering the nominal fire sizes from 10 to 100MW. Four steel oil pans lined along the axis of the tunnel were used. Each produced heat release rate approximately 10, 20, 30 and 50MW respectively. Other fire sizes were achievable by different combinations of them. In each test, critical velocity had been measured against the heat release rate of fire.

Figure 1 shows the critical ventilation velocity vs. heat release rate from the 15 tests. The heat release rates $Q$ in Figure 1 are the measured instead nominal values. Thomas' cubic root theory in the form of current design formula recommended by PIARC[1] is also presented in Figure 1 as a continuous curve. Although the theoretical curve has touched almost each group of points, no clear data trend has been shown. In constructing Figure 1, the raw data from the test program has been used. The selected measuring plane was the nearest to the upstream of fire at the time when the measured heat release rate was close to its nominal value and the backlayering was just appearing or disappearing. Every effort has been made to ensure that the data selection is objective and representative to true critical velocity. Although there are certain data points appear to be far from "normal". They have been kept and presented in Figure 1.

The large range of data scattering for 50MW fires and very low critical velocity of 100MW fires have causes serious concern about the error control of the test. PIARC had selectively presented the MTFVTP test data as in Figure 2 and excluded all tests of 100MW fires. The selection was obviously guided by the cubic root theory.

The question to be asked here is the justification of applying cubic root theory to tunnel fires up to 100MW. There are compiling evidences showing that the cubic root curve does not represent the data trend in experiments for large tunnel fires [2, 3 and 4].
The scattering of data and the almost abruptive drop of critical velocity as the nominal heat release rate of fire \( Q \) increases from 50MW to 100MW. Despite the time and money spend and all the measures put in place to control the conditions of the test, experimental error is always a possible explanation for the unexpected results in such full scale tunnel fire tests. However, other possibilities may also be equally worth considering. The current article presents one of them.

**THE DIMENSIONLESS PARAMETERS TO REPRESENT TUNNEL FIRE**

The purpose of studying tunnel fire is for fire protection in tunnel, therefore a tunnel fire discussed here is that under the control of tunnel ventilation. More specifically, the fire would be under the control of longitudinal tunnel ventilation. It differentiates a tunnel fire from a free burning fire by the means of air supply to combustion. It changes both the geometry and dynamics of fire flame. Such consideration had prompted the derivation of the log-law for tunnel fire [5]

\[
Fr^2 = \frac{(1 - l')}{Q'^{-1} + l'} \ln(1 + Q'^{-1})
\]

where the velocity of fuel vapour relative to that of ventilation \( u'_{\dot{f}} \) has been omitted. \( Q' \) and \( Fr \) are dimensionless and defined by

\[u'_{\dot{f}} = \frac{u'_{\dot{f}}}{u'}\]

\[Fr = \frac{2g(\rho - \rho_{\infty})u'^2}{\mu'_{\dot{f}}}
\]
In the above expressions, \( u_c \) is critical ventilation velocity and \( T_e \) is the ambient air temperature.

Theoretically,

\[
l' = \frac{Q_{\text{theor}}}{Q} \frac{h_v}{h_f}
\]

where \( Q_{\text{theor}} = m_f h_f \) is the heat release rate of stoichiometric fuel combustion and \( Q \) is the effective heat release rate of fire. In reality, \( Q < Q_{\text{theor}} \) therefore \( l' \) represents the heat loss of flame. With significant thermal loss, Eq.(1) shows that the effect of \( l' \) on \( Fr^2 \) could be as important as \( Q' \).

Both the theory and existing experimental data have demonstrated that \( Fr \) and \( Q' \) are the variables to be used in revealing the similarity among tunnel fires under the control of longitudinal ventilation.

Based on the log-law, the same data of MTFVTP in Figure 1 can be presented in the \( Fr-Q' \) plane. Unlike in Figure 1, the data points in Figure 2 have displayed a coherent trend. The descending of \( Fr \) can be explained by the configuration of fuel pans according to the definition of \( Fr \) in Eq.(3). In the test program, the lateral dimension of all fuel pans was constantly 2.93m but the total longitudinal dimension of the burning pools (\( D \)) were approximately 1.5m, 3m, 7.6m and 18m corresponding to 10, 20, 50 and 100MW nominal fire sizes. As \( Fr \) is inversely proportional to \( D \), the lower value of \( Fr \) comes with no surprise for large fire size \( Q' \).

![Figure 3 Experimental data from MTFVTP in Q'-Fr plane](image)

**THE HEAT LOSS FUNCTION \( l' \)**

The previous sections have revealed the importance of \( l' \) as a parameter in the log-law governing tunnel fires. From Eq.(1), it can be seen that \( l' \) has to satisfy the following condition

\[
l' < 1.0
\]

In the physical model of log-law, the ceiling layer of tunnel fire is driven by the stagnation of vertical
momentum generated by thermal buoyancy of the flame. Any heat loss of the flame before reaching the ceiling of tunnel reduces the stagnation pressure therefore the magnitude of \( Fr \)\(^5\). In fact, if the ambient air can be treated as ideal gas and the environment is adiabatic, Eq.(4) can be written as

\[
l' = \frac{m_f}{m_v} \tag{6}\]

where \( m_f \) is the mass flow of burning fuel and \( m_v \) is the mass flow of ventilation air. In a nearly critical ventilation condition, \( l' \) would be negligibly small. However, it would be not so small if the heat loss \( Q_{theor} / Q \) becomes large as shown by Eq.(4).

With \( l' \) as a parameter, Eq.(1) represents not one but a cluster of curves in the \( Fr-Q' \) plane \[6\]. For Eq.(1) to be useful in tunnel design, \( l' \) has to be defined in more practical form. In this section, a general form of \( l' \) function is proposed first and applied to the prediction of MTFVTP data shown in the last section. Further consideration for large tunnel fire would be given by taking into account of thermal radiation.

The general function form of \( l' \) has been proposed in \[6\] as

\[
l' = 1 - \eta \left( \frac{w}{D} \right)^\gamma \tag{7}\]

where \( \eta \) and \( \gamma \) are universal constants determined from experimental data. In the current article, both of them are given the value of 0.4.

Previously the log-law of tunnel ventilation had been successfully applied to various sets of laboratory test data\[6 to10\]. The fire sizes in the tests were in kW. However the damaging fire in traffic tunnels are often in 10 or 100s of MW. Could the MW fires behave differently from the kW fires? If they do, what would be the model implication?

Figure 3 shows the same data of MTFVTP as in Figure 2 together with the prediction from Eq. (1) and Eq.(7) for each nominal fire size. The prediction has caught the right trend of the data as the fire size \( Q' \) increases, \( Fr \) decreases. However, over prediction for large fires is also quite clearly shown.

![Figure 4 Prediction and experimental data from Memorial Tunnel Test Program](image-url)
THE IMPORTANCE OF RADIATION IN A LARGE TUNNEL FIRE

Although the current prediction has caught the trend of MTFVTP data as shown in Figure 4, a closure look of the test data reveals that for each nominal fire size there may be a range of Fr values instead of just one as predicted in Figure 4. It is quite obvious in the case of 50MW fires that certain influential factors have been missed. What could it be? Answering this question requires further purposely designed experimental investigation that is out of the scope of the current study.

Based on the trend of MTFVTP data, the current authors would like to postulate one missing factor as the thermal radiation. From the postulation, $Q$ in Eq.(4) should be proportional to $T^4$. Normalising $T$ by $T_v$ and assuming air is ideal gas, then

$$\frac{T}{T_v} = Q' + 1$$

It leads to the following form of flame heat loss function to be proposed

$$I'' = 1 - \eta'(Q' + 1)^4 \left(\frac{W}{D}\right)^\gamma$$

(8)

where $\gamma$ is the same as in Eq.(7) and $\eta' = 3.6$ is a new constant in the place of $\eta$.

What needs to be pointed out is that the function $(Q' + 1)^4$ would not be effective if $Q'$ is much smaller than 1.0, therefore $I''$ is only applicable to large tunnel fire. The physical implication is that flame heat loss due to radiation is only significant in a large tunnel fire because of its high average temperature and large surface area. Figure 12 shows the prediction from Eq.(1) and Eq.(8) for all data points of MTFVTP where the solid symbols represent the test results and the open symbols are that from the prediction. As $Q'$ for 10 and 20MW fire are small, $I'$ instead of $I''$ had been used.

![Figure 5 The prediction of MTFVTP data with $I''$](image-url)
DISCUSSION

The similarity of tunnel fires

Based on the field test data of MTFVTP, the current article has demonstrated the similarity among tunnel fires with different fire sizes $Q'$ and the Froude number $Fr$ defined by Eq.(3). Close correlation between the two parameters has been clearly recognised with all data of longitudinal fire ventilation tested in MTFVTP.

The flame heat loss function $l'$

The effect of flame heat loss on critical velocity in a tunnel fire has been presented in previous experimental data but not considered significant. As a matter of fact, in the well controlled laboratory tests such as that by Oka[2] and Wu[3], the variation of $u_c$ or $Fr$ was up to 30% for the same heat release rate $Q$. In the log-law theory, the variation has been understood as a contribution of flame heat loss, denoted by $l'$. Being a parameter, $l'$ identifies individual curve with distinctive loss characteristics from the cluster of $Fr$-$Q'$ curves.

In [6], a function for $l'$ has been proposed so that field engineers can apply the log-law in tunnel ventilation design. The function is based on existing experience accumulated in the laboratory tests. By implementing the function of $l'$ in the current log-law, quantitatively accurate predictions against laboratory data have been achieved. In the case of field test, the prediction has consistently shown the trend of decreasing $Fr$ with increasing fire size $Q'$, which has been rather incomprehensible from MTFVTP test data up to now.

The large tunnel fire

How a tunnel fire should be sized and what can be called a large tunnel fire have been discussed in [9] and [10]. Here the focus is on the behavior of large tunnel fire.

Based on the prevailing understanding, it is clear that when the size of a tunnel fire increases, its behavior starts changing at certain point. It has been consistently shown in the laboratory test results that the turning point is around $Q'=1.0$ on the $Fr$-$Q'$ plane[7]. However, in the test data from MTFVTP as shown in Figure 5, the point appears much earlier and the change is more traumatic comparing with the laboratory test data[5, 6]. Even though, the log-law, together with the proposed heat loss function $l'$, has predicted both sets of measured data reasonably well. In the case of MTFVTP test data, the prediction has been further enhanced by considering $l''$, the hypothetical heat loss of flame due to radiation. The hypothesis has been based on the fact that a large tunnel fire posses high average temperature and large flame surface. Further experimental study is required to prove the effect of radiation in a large tunnel fire.

CONCLUSION

The significance of the log-law is showing the turning point of the $Fr$-$Q'$ curve where $Fr$ reaches its maximum value ($<0.8$). Further increase of fire size, $Fr$ either stays the same or more likely starts decreasing. Translating it into practical term means that a large tunnel fire does not necessarily require large ventilation capacity.

From the log-law, it can be speculated that for the same heat release rate, the ventilation requirement for the fire from a stack of solid fuel can be very different from that due to diesel spill. Over a larger spill area, less air momentum would be needed to control the fire. It is to be proved in further experimental study and a point to be considered in large fire test design.

Flame heat loss, particularly loss through radiation, means the increase of thermal load of tunnel structure. As the ventilation requirement decreases along the $Fr$-$Q'$ curve shown in Figure 3, the
requirement of structure protection will increase. In other words, after the turning point of $Fr-Q'$ curve, the focus of tunnel fire safety design should be shifted towards structure protection.

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Development of Tunnel Ventilation System’s Strategy and CFD Analyses Results for Ottawa LRT Project - Rideau Station

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ABSTRACT
Numerical modeling and analysis for the design of the tunnel ventilation system of Segment 2 of the Ottawa Light Rail Transit (OLRT) project is currently progressing. Segment 2 is mainly underground beneath Ottawa’s downtown core and includes three underground stations, two portals and the connecting tunnel. The tunnel section comprises approximately 2.5 km of twin-track tunnel. The Tunnel Ventilation System (TVS) is comprised of tunnel ventilation fans, jet fans (at portals), and ventilation shafts, which extract contaminated air from the underground system to grade during a fire incident. Based on both specific project requirements and NFPA130 requirements, the mechanical ventilation systems for the underground transit stations are to be designed to ensure a tenable environment is provided for the specified egress period. This paper summarizes the efforts to develop the tunnel ventilation system (TVS) strategy and Computational Fluid Dynamic (CFD) modeling and analysis to assess the duration for which tenability of the egress routes can be maintained by operation of the TVS for one of the underground station of the OLRT project: Rideau Station. The CFD analysis is used to determine the Available Safe Egress Time (ASET). This may then be compared with the time required to evacuate persons from the station, i.e. the Required Safe Egress Time (RSET).

KEYWORDS: Tunnel Ventilation, Ventilation Shafts, Underground Station Ventilation Design, CFD analyses.

INTRODUCTION
Project Background and Info
The Ottawa LRT (OLRT) Project, involves converting a portion of the existing BRT system into a LRT system. The Project includes upgrades at some existing stations, construction of new stations, construction of portions of new track not within the existing BRT infrastructure, tunnelling through the downtown core and the construction of a new Maintenance and Storage Facility (MSF). The project is divided into five segments; Segment 2 is the underground portion and is indicated in black in Figure 1 below.
Segment 2 is mainly tunnelled beneath Ottawa’s downtown core and includes three underground stations (Rideau, Lyon, and Parliament), two portals and approximately 2.5 km of twin-track tunnel. The running tunnel is being constructed by the sequential excavation method, primarily using large-scale road-headers. The geology of Segment 2 consists of relatively high quality limestone formations overlain by weathered sedimentary rock formations, in turn overlain by soil deposits. The vast majority of the tunnel construction will be within the limestone formations.

There are portals at the east and west ends of the tunnel, which transition the underground segment to the adjacent at-grade segments.

The three underground stations, Rideau, Parliament, and Lyon are all to be constructed as mined structures, using the same heavy road-headers as for the tunnel. The stations share a common configuration: a concourse level above 120 m long side platforms, with ventilation shafts provided at each end of the station, terminating at grade.

**Tunnel Ventilation Background**

Sub-surface transportation infrastructure requires ventilation due to its enclosed, inherently hazardous nature. The applicable legislation and standards, in particular NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems (2014), provide a framework for assessing the ventilation requirements, which in turn drives the selection of the design solution. For the Segment 2 tunnels and stations, a mechanical tunnel ventilation system is required.

A mechanical TVS may follow one of several configurations. For Segment 2 of OLRT a longitudinal ventilation design has been selected, comprised of ventilation plant installed at discrete locations along the tunnel alignment that creates a longitudinal airflow within the tunnel and allows the extraction of smoke during a fire emergency. The functional requirements of the TVS are twofold:

- During normal conditions, to supply breathable air for the tunnel and station occupants and to maintain tunnel and station ambient temperatures within specified criteria.
- During an emergency (fire) event in the tunnels or stations, to maintain tenable conditions along the egress route for the specified egress period.

Figure 2 below shows TVS facilities and equipment at a typical transit station under two different modes of operation: Normal (left) and Emergency (right).
NFPA 130 requires the design of the TVS to be supported by comprehensive engineering analysis. The analysis involves dynamic, time dependent computational modeling of the aerodynamic and thermodynamic behaviour of the environment for a number of scenarios and design conditions.

The function and performance of the overall tunnel ventilation design is generally assessed by conducting one-dimensional computational analysis of the system. In cases where a one-dimensional analysis would be unsuitable, or would not yield the required accuracy, three-dimensional CFD analysis is utilised.

Although CFD will produce more accurate results than a one-dimensional analysis, the complexity, and associated time and cost implications, means that CFD is generally applicable only for assessing the ventilation system’s performance in those specific cases where the assumption of one-dimensional flow is no longer valid, such as emergency fire scenarios at stations, cross-over structures, and other structural components that may create complex air flow patterns.

Rideau Station Geometry
Rideau Station is a new Underground Station in the City of Ottawa that will provide a principal connection to the Rideau Centre and the Byward Market area. The Station will also be a significant transfer point from the bus connections on Rideau Street. Rideau station will be constructed with below grade platform and concourse levels and street-level pedestrian entrances. Three pedestrian entrances will be provided from street level which will access a split concourse - the east and west concourse levels. Figure 3 shows the street level entrances for the Rideau Station.

The east entrance will provide access from William Street to concourse level via a stair, two escalators and two elevators. The west entrance is split at street level, with a main entrance from Rideau Street which incorporates two escalators and a stair, and a connection from Rideau Centre.
with a stair and escalator. A third ‘elevator entrance’ will provide access from Rideau Centre to concourse level via two elevators.

Rideau Station will have two side platforms; the platforms are approximately 5.5 m wide and 120 m long. Each side platform will be served by two elevators, two egress stairs and two escalators leading to the concourse level. The concourse level is open to below in that the east and west sides are not connected to each other.

Figure 4 through Figure 6 show the platform and concourse layouts and a longitudinal section through the station.

**Figure 4: Platform Level, West Partial Plan**

**Figure 5: Platform Level, East Partial Plan**

**Figure 6: Concourse and Platform Longitudinal Section**

**TVS DESIGN AND OPERATION METHODOLOGY**

The TVS of the OLRT project is comprised of both passive and active components to enable the system to react to operational and emergency needs. The arrangement of the TVS system for Rideau station includes: 2 axial ventilation fans at each end of the station (4 fans total), 3 sets of jet fan banks ate the East portal, located east of the station and 4 axial fans at the adjacent station Parliament. Each of these fans or a combination can be utilised in an emergency case. In a fire emergency case the
active ventilation components, including axial ventilation fans and motorized dampers, together with the passive elements such as smoke baffles are employed, with the objective of providing a tenable egress route for the duration of the required egress period. According to NFPA 130 Section 3.3.48, a tenable environment is one in which self-rescue or survival of occupants is possible.

In the event of a train on fire at the station in which either (i) the fire has started while the train is at the station, (ii) the fire has started en route to the station, or (iii) there is a trash fire at platform, mechanical ventilation will be activated in emergency mode. In this mode all the ventilation fans operate in extract mode to maximize the air exchange at the station and remove smoke from the station area as quickly as possible. Four potential modes of operation are assumed and analysed, the following proposed modes are developed based on one dimensional study of the system using

1) “Four Fan” operation: All fans at both ends of the Rideau station working in extract mode.
2) “Six+Jet” fan operation: Four fans at Rideau Station working in extract mode. In addition, two fans at the adjacent station (Parliament) and three jet fan sets at the East Portal are also operating in extract mode.
3) Critical Fan Failure Modes:
   i. “Five+Jet” fan operation (critical fan failure mode - west): Three fans at Rideau Station working in extract mode (one fan is not operational due to a failure in the west fan plant); In addition two fans at adjacent station (Parliament) and three jet fan sets at the East Portal are also operating in extract mode.
   ii. “Four+Half+Jet” fan operation (critical fan failure mode - east): Three fans at Rideau Station working in extract mode (one fan is not operational due to a failure in the east fan plant and one West fan operates in half capacity). In addition, two fan at the adjacent station (Parliament) and three jet fan sets at the East Portal are also operating in extract mode.

Results of the analysis showed that both Case 3.i and 3.ii are the critical fan failure scenarios and thus both fan failure cases are discussed and analysed in this report. The concept of operation for case 1 is depicted in Figure 7.

**Figure 7: Four Fan Operation Concept**

**CFD MODELLING AND SIMULATING**

**Geometry Simplification**
Rideau station has complex geometry. In addition, due to the nature of the fire and smoke physics, transient simulations are needed to predict the time evolution of the tenability parameters. Therefore, the level of complexity of the model had to be carefully justified. Sufficient geometry details should be included to meet the model accuracy requirements, but the model should not be over-complicated which may cause extremely high mesh number and unnecessary long simulation time and cost.

Figure 8 shows the 3D model developed for CFD analysis of Rideau station. In this model, all the important internal components such as stairs and escalators, false roof, supporting columns, ticket stations and the stopped trains are included in the model. However, some components such as the stairs and escalators were simplified to remove the small geometry details that will not pose impacts.
to the accuracy of the fire and smoke analysis.

**Figure 8: 3D geometry model used for fire safety analysis of Rideau Station**

**1D Model and 3D CFD Model Coupling**

Critical boundary parameters for the CFD modelling included fan capacities and ramping up flow curve, tunnel-station interfaces, station entrances, concrete walls and train doors and windows. The interior concrete surfaces are modelled as solid walls with a surface roughness height. It is generally assumed that the 75% of entrance doors are open to street level so that clear air paths exist from the platform to the street. Constant pressure boundaries are assumed at all openings to the street.

It should be noted that, the airflow distribution in Rideau station is affected by the flows in adjacent tunnels and stations. To obtain realistic boundary conditions at the tunnel/station interface and ventilation shafts for the CFD model, a 1-D modeling tool “Subway Environment Simulation (SES)” program, has been utilized. The 1D tool can simulate the impacts of adjacent stations, and provide more realistic flow inputs as CFD boundary conditions. The coupling of 1D model with 3D CFD model also allows the CFD model to focus on the station to be investigated, thus significantly reducing the computational time and efforts.

**Model Representation of Fire**

There are two ways to model the fire: one is to include the detailed fire reaction kinetics; and another is to apply a volumetric heat source to simulate the growth of the fire. The majority of CFD analyses of tunnel fires adopt the second option (Elias et. al., 1996). This can be achieved by defining a fire growth curve based on a T-squared fire curve with a design growth rate and peak heat release rates (HRR), as described in NFPA 92 (NFPA, 2015). Other fire parameters used as part of fire modeling to simulate tenability criteria are summarized in Table 1.
### Table 1: Fire Properties

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train Fire Growth Rate</td>
<td>11.723W/s²</td>
</tr>
<tr>
<td>Train fire Growth Time(one Car)</td>
<td>1057s</td>
</tr>
<tr>
<td>Duration of Simulation</td>
<td>970s</td>
</tr>
<tr>
<td>Heat of Combustion (ΔH_c)</td>
<td>18MJ/kg</td>
</tr>
<tr>
<td>Air-Fuel Ratio (AF)</td>
<td>14</td>
</tr>
<tr>
<td>Sooth Yield (Y_s)</td>
<td>0.1g/g</td>
</tr>
<tr>
<td>CO Yield</td>
<td>0.05g/g</td>
</tr>
<tr>
<td>%Convective heat</td>
<td>70%</td>
</tr>
<tr>
<td>Mass Optical Density</td>
<td>0.33m²/g</td>
</tr>
<tr>
<td>Fully Developed Train FHRR</td>
<td>13.1MW</td>
</tr>
<tr>
<td>Fully Developed Train FSRR</td>
<td>0.073kg/s</td>
</tr>
<tr>
<td>Fully Developed Train FCORR</td>
<td>0.036kg/s</td>
</tr>
<tr>
<td>Train FSRR per unite heat release</td>
<td>0.0056 kg/s per MW</td>
</tr>
<tr>
<td>Train FCORR per unite heat release</td>
<td>0.0028 kg/s per MW</td>
</tr>
</tbody>
</table>

Figure 9 shows the approach of using a series of volumetric source elements to model the growing fire within a vehicle. Each of these volumes was assigned as a heat and species source, and these are in turn ramped in order to yield the desired growth rate. The total number of volumetric sources were adjusted to make sure that the release of heat within the train would create a condition representing burning of the vehicle components (Golpaygan et al. 2014).

![Location of the fire sources within the train](image)

**Figure 9: Cumulative fire size and contribution of individual source volumes**

**CFD Design Criteria, Major Design Parameters, and Project’s Specific Requirements**

A ventilation system designed to comply with NFPA 130 is required by both the Ontario Building Code (OBC) and the Project Specific Requirements. According to NFPA 130, Section 7.1.2.2, mechanical ventilation is required for systems which have a total underground length greater than 305m. Based on “Tunnel Ventilation CFD-Based Station Smoke Control Criteria Report” (hereafter referred to as CFD-DC (CFD Design Criteria)), the objective of the CFD modeling and analysis is to assess the duration for which tenability of the egress routes can be maintained by operation of the TVS. Thus the CFD analysis is used to assess the ASET. This may then be compared with the time required to evacuate persons from the station, i.e. RSET. The functional requirements are satisfied when the ASET is greater than the RSET (plus any safety margin that may be imposed by the project). All four tenability parameters are set as required in NFPA 130, which is also adopted by OBC and project specific criteria. These tenability criteria specify the maximum exposure limits to hazards that can be tolerated without causing incapacitation for persons expected to pass through a fire-affected area. Once a fire incident is initialized, the smoke can potentially spread into the intended zone of tenability. It must be demonstrated that, within the minimum time required to evacuate persons from the station, the visibility, temperature, and CO levels at the zone of tenability are within the tenability levels, and that the tunnel ventilation system has sufficient capacity to pull back this pre-ventilation spread as well as overcome any transient events.
Incident Timeline
The incident timeline is developed based on the assumption that the fire starts two minutes before the arrival of the train at the station, the requirements time of tenability for Rideau station’s concourse due to specific features of this station (Such as depth) is 480s which is more than 6mins prescribed by NFPA 130. As a result, it has been agreed that the concourse shall remain tenable for at least 6mins (480s), plus a reasonable safety factor which has been established to be minimum 1.5X the required egress time. The model is simulated for 970s (twice the tenability timeline). There are specific tenability requirements for platform as well, however this paper only deals with and describes the tenability at concourse, as it represent the most stringent condition.

DESIGN FIRE
Based on CFD-DC the design train fire for this project is a fire with a peak FHRR of 13.1 MW that grows according to a ‘medium’ t-squared growth curve as specified in NFPA 92B.

Summary of the CFD Simulation Results
As previously stated, four different scenarios have been simulated have been thoroughly analysed. This will be discussed later in the report.

The sequencing of the CFD analysis is as follows:

1. The “Four fan” operation for the base line design will be simulated, if all tenability criteria are met for the duration of required tenability timeline, the analysis will go to step 2 below, if not it will proceed to step 3.

2. Fan failure case (“Three fan” operation) for the base line design will be analyzed. If the outcome of this latest analysis proves that all tenability criteria are satisfied for the duration of required tenability, then the analysis is assumed to be completed. If not then the analysis will proceed to step 3.

3. The Critical fan failure cases “Five+Jet” and “Four+Half+Jet” fan operations for the base line design will be simulated, if all tenability criteria are met for the duration of required tenability timeline, the analysis will go to step 4 below, if not it will proceed to step 5.

4. The “Six+Jet” fan operation will be simulated and the results will be evaluated. If all tenability criteria are met for the duration of required tenability timeline, the analysis is deemed complete, if not it will proceed to step 5.

If all the steps described above fail to prove that the tenability requirements can be achieved, it is concluded that modification to the base line design is required. As a result, possible modifications in conjunction with the design team, especially architectural and mechanical, will be reviewed and the modifications deemed most efficient will be implemented. The procedure then moves back to step 1, and the analyses with the modifications incorporated are performed again. Some possible modifications to improve tenability results, if necessary, include:

- Addition of Smoke baffles and down-stands.
- Modifying (increasing) the fan capacities or operational modes.
- The above procedure will be followed in multiple iterations until the outcome of the last analysis proves that all tenability criteria are satisfied for the duration of required tenability.

“six+Jet” Fan Operation (Usual fan operation in emergency cases)
Through multiple one dimensional simulations, it was established that case with a fire at the west side of the station is the worst case scenario and as a result only the results for this case is presented in this here:
Visibility

Simulation results demonstrate that the critical tenability criterion in the “Six+Jet” fan operation scenario is the visibility criterion. Figure 10 shows the visibility criterion contour at concourse level. The criterion is reported at 2.5 m above the concourse floor.

As shown in this figure, the concourse remains tenable for the duration of simulation (T=970s). The results satisfy the tenability requirement with a safety factor of at least 2.0.

![Visibility Criteria Contours at Concourse Level](image10)

**Figure 10: Visibility Criteria Contours at Concourse Level**

Five+Jet” Fan Operation (Critical Fan Failure at Rideau West Fan Plant and fire at the Western train)

Visibility

Simulation results demonstrate that the critical tenability criterion in the “Five+Jet” fan operation scenario is the visibility criterion. Figure 11 shows the visibility criterion contour at concourse level. The criterion is reported at 2.5 m above the concourse floor.

As shown in this figure, the concourse remains completely tenable till T=780s. At this time smoke starts to go up and to the concourse levels. By the end of simulation (T=970s) few localized area of failure are observed. The results indicate that the tenability requirements are satisfied (till T=900s) with a safety factor of at least 1.8. It is important to note that even at this time step, major parts of concourse are tenable.

![Visibility Criteria Contours at Concourse Level](image11)

**Figure 11: Visibility Criteria Contours at Concourse Level**
“Four+Half+Jet” Fan Operation (Critical Fan Failure at Rideau East Fan Plant- With Western Train Fire)

Visibility
Simulation results demonstrate that the critical tenability criterion in the “Four+Half+Jet” fan operation scenario is the visibility criterion. Figure 12 shows the visibility criterion contour at concourse level. The criterion is reported at 2.5 m above the concourse floor.

As shown in this figure, the concourse remains tenable till (T=780). The results satisfy the tenability requirement and indicate that the tenability requirements are satisfied with a safety factor of at least 1.8.

Figure 12: Visibility Criteria Contours at Concourse Level

CONCLUSION
This paper provides a summary of the efforts to date to analyse the TVS performance for one of the major underground stations of the OLRT project.

The CFD analysis reveals the key characteristics of Rideau station’s ventilation system as currently designed. Based on the results of the study it is concluded that during a train fire incident at platform level exceedances in visibility criteria for the duration of simulation (970s) are observed in the “Four” fan operation scenario.

During a train fire scenario the “Six+Jet” fan operation concept (usual operational mode during an emergency) shows significant improvement over the “Four” fan operation concept; no exceedance is observed during the required time of tenability (510s) and the all tenability criteria at concourse are satisfied up to simulation time T=970s meaning a safety factor of at least S.F =2.0 while the tenability requirements at platform are also satisfied.

During a train fire scenario and a critical fan failure case at the east fan plant (“Five+Jet” fan operation) no exceedance is observed during the required time of tenability (510s) and the all tenability criteria at concourse are satisfied up to the time (T=780s) meaning a safety factor of S.F.=1.8 while the tenability requirements at platform are also satisfied .

During a train fire scenario and a critical fan failure case at the west fan plant (“Four+Half+Jet” fan operation) no exceedance is observed during the required time of tenability (510s) and all tenability criteria at concourse are satisfied up to time (T=780s) meaning a safety factor of S.F.=1.8, while the tenability requirements at platform are also satisfied. At the same time all platform tenability criteria are satisfied.
Results indicate that the operation of the ventilation fans can effectively delay the infiltration of the smoke into the concourse level and provide a tenable and safe environment at platform during the evacuation period.

It is important to note that the station tenability requirements include specific requirements for the station platform as well as the station concourse, however the results and discussion presented in this paper are focused on concourse tenability as it proved to be the most stringent requirement.

Based on the requirements set in CFD-DC the design of Rideau station’s TVS is deemed to meet the specified performance criteria.

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Innovation in Jetfan Design

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ABSTRACT

Conventional jetfans are generally recognised as being quite inefficient, with around 50% of the supplied power being wasted due to aerodynamic, mechanical and electrical inefficiencies. The primary source of aerodynamic inefficiency is the Coanda effect, which causes the high-speed jet discharged from a jetfan to adhere to the surrounding tunnel surfaces. A number of alternative jetfan designs have been developed over the past two decades to address this issue, but they all suffer from issues such as the requirement for additional space, or enhanced power consumption. A recent innovation called the MoJet® reduces the Coanda effect without the requirement for additional space, and without excessive power consumption. This paper reports on features of the MoJet design, and presents CFD calculations and full-scale aerodynamic measurements which demonstrate the superiority of the MoJet over conventional jetfans.

KEYWORDS: tunnel ventilation, jetfan, innovation

INTRODUCTION

The provision of ventilation in tunnels is often required in order to improve air quality, and to control the movement of smoke in case of fire. Longitudinal ventilation via jetfans is generally acknowledged as being a cost-effective solution for tunnels, where the length and risk profile of the tunnel allows such an installation. However, jetfans are not particularly energy efficient, with typical installations wasting over half the supplied electrical power [1].

A major reason for the low values of installation efficiency of jetfans is the Coanda effect. This causes the stream of high-velocity air issuing from a jetfan to adhere to adjacent solid surfaces including the tunnel walls and soffit. This paper will therefore focus on a number of technologies that have been developed to reduce the Coanda effect generated by jetfans.

CONVENTIONAL JETFAN VENTILATION

Conventional jetfans blow the air straight in the axial direction of the impeller and are normally aligned parallel to the tunnel axis. The theoretical maximum thrust delivered by a jetfan is given by

\[ T_{\text{max}} = \rho A_d v_d (v_d - v_\infty) \]  

where \( A_d \) is the cross section of the jetfan outlet, \( v_d \) the jet average velocity and \( v_\infty \) the velocity in the tunnel beyond the direct influence of the jetfan intake and discharge.

The effective thrust within a tunnel, \( T \), is lower than the theoretical maximum \( T_{\text{max}} \) due to the installation efficiency \( \eta_i \). The value of \( T \) is calculated as:

\[ T = \eta_i \cdot \rho A_d v_d (v_d - v_\infty) \]
The installation efficiency $\eta_i$ takes the value of unity if the jet is situated in the middle of the tunnel and is not influenced by adjacent jetfans, obstacles and tunnel surfaces. In practice, the Coanda effect reduces the value installation efficiency to around $\eta_i = 0.85$ for a jetfan beneath a tunnel soffit and to around $\eta_i = 0.73$ for a jetfan installed in a corner of a rectangular cross-section tunnel.

An interpolation of the experimental data by Kempf [2], gives the following estimate of the installation efficiency for a jetfan beneath a tunnel ceiling:

$$\eta_i = \left[ 0.0192 \left( \frac{z}{D_a} \right)^2 - 0.144 \frac{z}{D_a} + 1.27 \right]^{-1}$$

(3)

where $D_a$ is the outlet diameter of the jetfan and $z$ denotes the distance between the centre axis of the jet at the outlet and the tunnel wall.

A significant proportion of the aerodynamic thrust, typically 20% to 30%, is thereby wasted through the friction between the jet and the surrounding tunnel surfaces [1].

**PREVIOUS JETFAN IMPROVEMENTS**

A number of design innovations have been proposed to reduce the Coanda effect, including:

1. Tilting the jetfans at up to 10°, as investigated by Woods Air Movement [3]. Such tilting was demonstrated to deliver an approximately 11% enhancement in thrust at tilt angles between 6° to 7°. However, tilting the jetfans may exclude the possibility of reversible fan operation, and may cause the fan housing to encroach upon the traffic space within the tunnel.

2. Slanting the silencers at either end of a jetfan, in order to direct the flow towards the tunnel centreline ('Banana Jet®'). Marti and Brandt [4] reported that installation efficiencies of near unity can be obtained with slanted silencers mounted at about 7° from the fan axis, although their reported measurement error was ±12%. Slanted silencers may intrude upon the traffic space, or restrict the fan diameter that is possible to specify within a given equipment space.

3. Installing deflection vanes at one or both ends of a jetfan, in order to direct the discharge flow downwards. Lotsberg [5] reported from measurements in the Fodnes Tunnel in Norway that deflection vanes can be beneficial in reducing the Coanda effect, and in improving the installation efficiency from 60-70% to 90-95%. However, the paper notes that deflection vanes directly attached in front of the fan give a negative effect on fan performance (presumably through an increased pressure drop and power demand). It may reasonably be assumed that deflection vanes attached to the inlet of a fan would have a similar negative effect. If the deflection vanes are attached at some distance from the fan ends, the pressure drop and power demand are less affected, but only a proportion of the spreading jet may be captured and turned.

4. Using convergent nozzles to turn the discharge flow downwards, as reported by Tarada and Brandt [6]. The advantage of such a design is that the nozzles can be arranged not to encroach into the traffic space. However, additional power consumption may be required to overcome the pressure drop through the convergent nozzles.

All of the above-mentioned technologies therefore had a number of drawbacks that limited their usefulness in practice.
MOJET DESIGN

In order to reduce the Coanda effect while the pressure drop across the nozzles to a minimum, a new product called the MoJet has been developed [8, 9]. Figure 1 presents the MoJet design features, which incorporates the following design features:

1. The flow from the discharge nozzle is turned away from the tunnel surface by a “pressure-side angle” of between 6 to 7 degrees. This allows a significant reduction in the Coanda effect, and an enhancement in the installation efficiency.
2. In order to maintain at least the same nozzle throat area as the fan cross-sectional area, the outlet diameter of the nozzle is set to a larger diameter than the fan diameter.
3. The increased outlet diameter of the nozzle is accommodated by tilting the outlet edge of the nozzle with respect to the nozzle centreline.
4. Spun circular bellmouths are attached to the nozzles in order to reduce the entry pressure losses.

The MoJet has been successfully installed in a number of tunnels worldwide [10]. The remainder of this paper will be devoted to demonstrating a typical project application.

PROJECT APPLICATION

Introduction

A Computational Fluid Dynamics (CFD) model has been constructed within ANSYS CFX version 16.0 to assess of the performance of the proposed MoJet installation in the lower (westbound) section of a double-deck 5.4km long road tunnel. The direction of ventilation would normally be in the traffic direction, so the MoJet nozzles were installed only on the downstream side of the fans. However, the selected MoJets were reversible, with sufficient aerodynamic thrust in the reverse direction to preclude the ingestion of smoke into the non-incident tunnel bore.
**Model**

The CFD model can be seen in Figs. 2 and 3 below. The model represents a 200m long section of the lower tunnel section. Within this section two 710mm (internal diameter) MoJets have been installed adjacent each other. The MoJets are located 20m from the upstream end of the CFD model.

The CFD calculations were undertaken with approximately 5.4 million grid cells per simulation. Boundary layers were attached to all solid surfaces to resolve sharp velocity gradients. These boundary layers were calculated via 5-layer prisms with an initial layer approximately 0.1m thick, and with an expansion factor of 1.2. A typical $y+$ value for the first cell along the (rough) tunnel surfaces was 400, with a peak $y+$ value of 1700 where the jet impinges on a tunnel surface.

The velocity profile at the inlet boundary was set by means of a periodic boundary condition at the exit boundary. The calculations are therefore representative of the conditions within the tunnel (as opposed to the conditions at the inlet tunnel portal).

Additional loss coefficients have been applied to the model to simulate other resistances such as parked traffic and portal losses. The tunnel walls, floor and soffit were assumed to have a uniform sand roughness height giving an equivalent friction factor ($\lambda=4f$) of 0.01629. For the simulations reported here, the effects of swirl at the fan have been omitted.

A volumetric flow rate of 16.17 m$^3$/s has been assumed through each 710mm MoJet. The CFD model has been used to perform a number of simulations considering a range of fan locations and nozzle angles. The best solution identified is shown in Figure 4 has the fans located symmetrically about the tunnel centre line, at locations one third and two thirds across the width of the soffits.

![Isometric view of modelled 200m tunnel section, with two MoJets (on right-hand side of image)](image-url)
Figure 3  Arrangement of MoJets in the tunnel

Figure 4  CFD Model with best solution identified – 10 degrees from vertical (lower arrow indicates direction of jet)

Calculation of Installation Factor

Three simulations have been carried out. In all three cases the fans are located at 1/3 and 2/3 of the soffit width. Three different nozzle angles have been considered, one case with the jet directed vertically downwards, one case with the nozzles angled at 10 degrees towards the walls and one with the nozzles angled at 20 degrees towards the walls.
Table 1: Summary of CFD calculation results for installation factors

<table>
<thead>
<tr>
<th>Case</th>
<th>Mean Tunnel Velocity (m/s)</th>
<th>Installation Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>2.45</td>
<td>0.945</td>
</tr>
<tr>
<td>10 degrees</td>
<td>2.46</td>
<td>0.961</td>
</tr>
<tr>
<td>20 degrees</td>
<td>2.45</td>
<td>0.959</td>
</tr>
</tbody>
</table>

The results indicate than an inclination of 10 degrees towards the walls provides the best solution. However, it is entirely possible that better solutions may be obtained through other combinations of MoJet locations and jet angles.

The installation factor was calculated by comparing the total wall shear losses predicted by the CFD code with the theoretical wall shear loss for a perfect installation (installation factor of 1.0).

On the basis that:

Installation factor = Sum of useful forces on tunnel airflow / Theoretical thrust due to MoJet

The theoretical thrust due to the MoJet was calculated on the basis of Eq. (1).

Therefore the installation factor can be estimated from

$$\eta_i = 1 - \frac{\Delta T}{T_{max}}$$

where

$$\Delta T = \text{increase in skin friction drag above standard case}$$

$$= \text{Skin friction drag predicted by CFD} - \text{standard skin friction drag}$$

and

Skin friction drag in 3D CFD = Sum of predicted wall, soffit and roadway drag forces

Standard skin friction drag = $$\frac{1}{2} \rho v_T^2 \lambda \frac{L A_T}{D_h}$$

where:

$$L = \text{tunnel length (m)}$$

$$A_T = \text{cross-sectional area of tunnel (m}^2\text{)}$$

$$D_h = \text{hydraulic tunnel diameter (m)}$$

$$v_T = \text{tunnel velocity (m/s)}$$

**CFD Calculations for 10 Degree Jet Angle**

Some of the results of the 10 degree angle CFD simulation can be seen in Figures 5 to 8. The iso-surface plots (Fig. 5) and the contour plots of velocity (Fig. 7) show that the MoJet is successfully angling the jets downwards, reducing the Coanda effect at the soffit. However, this is not sufficient to completely eliminate high shear stresses at the soffit (Figure 8) and wall stresses at some areas of the soffit are somewhat higher than the rest of the tunnel and as a result frictional losses are higher than the “base case” (without any MoJets) in these regions. Nevertheless, this case shows a 13% improvement in installation efficiency for the MoJet, compared to a conventional jetfan solution as estimated through Eq. (3).
Figure 5  10m/s iso-surface (velocities within are greater than 10m/s, outside are less than 10m/s)

Figure 6  Streamlines of flow into and out of MoJets
Typical Whole-Life Costs

It is instructive to consider the impact of the higher energy efficiency of the MoJet on the whole-life cost of the ventilation system. Table 2 and Fig. 9 presents a comparison of the initial, operating and whole-life costs of the proposed tunnel ventilation installation. The 13% lower power consumption of the MoJet in this example translates into a 12% reduction in the whole-life cost of the ventilation system. The overall savings over a 20-year equipment life with the MoJet design are 33 times greater than the increased procurement cost, compared to a conventional jetfan design.
Table 2: Summary of CFD calculation results for installation factors

<table>
<thead>
<tr>
<th></th>
<th>Conventional Jetfan</th>
<th>MoJet</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan operating time</td>
<td>1,800</td>
<td>1,800</td>
<td>hours/year</td>
</tr>
<tr>
<td>Annual installed power cost</td>
<td>120</td>
<td>120</td>
<td>GBP/kW</td>
</tr>
<tr>
<td>(maximum demand tariff)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit cost energy consumption</td>
<td>0.10</td>
<td>0.10</td>
<td>GBP/kWh</td>
</tr>
<tr>
<td>Installation cost 1 per fan</td>
<td>2,000</td>
<td>2,000</td>
<td>GBP</td>
</tr>
<tr>
<td>Procurement cost 1 per fan</td>
<td>10,000</td>
<td>11,000</td>
<td>GBP</td>
</tr>
<tr>
<td>Net present value discount rate</td>
<td>3.50%</td>
<td>3.50%</td>
<td>%</td>
</tr>
<tr>
<td>Inflation</td>
<td>5.00%</td>
<td>5.00%</td>
<td>%</td>
</tr>
<tr>
<td>Write-off period</td>
<td>20</td>
<td>20</td>
<td>Years</td>
</tr>
<tr>
<td>Number of fans</td>
<td>20</td>
<td>20</td>
<td>Units</td>
</tr>
<tr>
<td>Total power requirement per fan</td>
<td>37</td>
<td>32</td>
<td>kW</td>
</tr>
<tr>
<td>Yearly maintenance cost per fan</td>
<td>500</td>
<td>500</td>
<td>GBP</td>
</tr>
<tr>
<td>Net present value (whole-life cost)</td>
<td>5,577,978</td>
<td>4,907,722</td>
<td>GBP</td>
</tr>
</tbody>
</table>

Figure 9 Present value of annual ventilation costs
FULL-SCALE TESTING

A series of full-scale tests were undertaken by Systemair GmbH to compare the installation factor of MoJets to that of conventional jetfans in a horseshoe-shaped tunnel at the Galleria Buttoli of Autostrade per l’Italia in Florence, Italy [7].

Seven sets of aerodynamic measurements were undertaken using conventional jetfans, followed by seven sets of measurements undertaken using MoJets. The positioning of the MoJets/conventional jetfans within the tunnel is indicated in Figure 11.

![MoJet installation in Galleria Buttoli of Autostrade per l'Italia in Florence, Italy](image)

![Positioning of MoJets / conventional jetfans in the Galleria Buttoli](image)
The aerodynamic measurements indicated that the MoJet improved the installation factor by approximately 11% for this particular installation, which is consistent with the CFD calculations undertaken to date. MoJet installations in corner locations (in rectangular-shaped tunnels such as cut-and-cover and immersed tube tunnels) can be arranged to deliver enhancements in installation factors of around 25%.

CONCLUSIONS

A number of alternative jetfan designs have been developed over the past two decades, in an effort to reduce the Coanda effect between the discharged jet and the surrounding tunnel surfaces. The MoJet aims to reduce the Coanda effect and hence enhance the in-tunnel thrust for a given fan airflow, within the same dimensions as a conventional jetfan. This allows an improvement in the energy efficiency of tunnel ventilation to be obtained, with a corresponding reduction in operating costs.

REFERENCES

Sensitivity Analysis of an Existing Ventilation System in a Road Tunnel

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1Fire Safety, Construction, National Research Council Canada
2Quebec Ministry of Transportation

ABSTRACT

National Research Council Canada conducted in-situ aerodynamic tests in the Louis-Hippolyte La Fontaine tunnel. The in-situ tests measured air flow parameters for the emergency ventilation system (EVS) installed in the tunnel for specific system operating conditions. These measurements provided accurate input for numerical simulations to optimize the EVS. The numerical simulations also studied the effectiveness of adopting a new impulse ventilation system and a semi-transverse ventilation system; the latter may be required for use with bi-directional traffic in a tube when the other tube is under construction.

KEYWORD: Longitudinal ventilation system, Semi-transverse ventilation system, Impulse ventilation system

INTRODUCTION

Tunnel ventilation system upgrades can be complex and require a good preparation and plan. This can include an initial study to assess the current problems based on a detailed diagnosis of the tunnel ventilation systems and to find optimum solutions to achieve the desired objectives of the tunnel ventilation system within the physical environment [1].

The study presented in this paper is to produce input for the ventilation system improvement included in the major refurbishment project for the Louis-Hippolyte La Fontaine roadway tunnel located in Montreal. The study consisted of four parts;

1) In-situ aerodynamic tests to evaluate the performance of the existing longitudinal ventilation system;
2) Evaluation of the capacity of the existing longitudinal ventilation system in controlling smoke;
3) Investigation of the effectiveness of adopting a new impulse ventilation system; and
4) Investigation of a semi-transverse ventilation system, which may be required for use with bi-directional traffic in a tube when the other tube is under construction.

Tunnel and ventilation system description

The bridge-tunnel complex is part of the Trans-Canada Highway that is considered to be one of the longest highways in the world which crosses Canada from coast to coast over a length of nearly 8 000 km. The Louis-Hippolyte La Fontaine bridge-tunnel extends over 6 km and accommodates six lanes of traffic, three in each direction. It includes a tunnel under the St. Lawrence River Ship Channel, between Montreal Island and Charron Island.

The construction of the Louis-Hippolyte La Fontaine bridge-tunnel started in 1963 and was inaugurated in 1967. The tunnel is a 1.4 km long, precast, pre-stressed concrete structure, with two
unidirectional, three lanes traffic tubes (see Figure 1). Between the two tubes, there are two service corridors.

Each traffic tube has 4 exhaust fans (VE fans) that are located in two ventilation towers at the ends of the underwater section. Figure 2 shows the ventilation systems for the tunnel.

Each service corridor is connected to 4 supply fans (VA fans) that can supply or exhaust air along the tunnel length via openings distributed along the wall between a service corridor and a traffic tube. These service corridors can also be used as evacuation routes. Doors at various locations along the length of the tunnel provide access to the service corridor. All fans can operate in exhaust or supply mode. In recent years, National Research Council Canada (NRC) and Quebec Ministry of Transportation (MTQ) conducted studies to evaluate the effectiveness of emergency ventilation strategies, which included optimization of EVS and calibration of dampers [2-4].

![Figure 1. Tunnel layout [2].](image1)

![Figure 2. Tunnel mechanical and monitoring system.](image2)

**IN-SITU AERODYNAMIC TESTS**

In-situ aerodynamic tests were conducted while a tube was closed by MTQ. The objectives of the tests were (1) to validate by measurements the actual performance of the VE and VA fans and (2) to evaluate pressure losses in the traffic tubes. Later, these results were used as input parameters for numerical simulations.

**Instruments**

The parameters measured included the stagnation pressure, the air flow velocity and temperature. The stagnation pressure was measured using a pitot tube with the center inlet connected to a micro
manometer. The velocity and temperature were measured using a hot-wire anemometer, which was connected to a data acquisition system via a velocity transducer.

The pitot tubes and anemometers were mounted on a pole with the devices located at the 0.5, 1.5, 2.5, 3.5 and 4.5 m heights above the roadway or corridor floor. The pole was traversed across the service corridors and the traffic tube to collect data at the measurement locations. The measurement pole was also used in the measurement of air flow through ceiling vents in the traffic tube and the circular outlets of the VA fans. The data was used to calculate volumetric flow rates and pressure losses. A balometer and a hand-held anemometer were also used to measure air flows through the side openings in the VA-101 and VA-103 corridors. In addition to the measurements in the tunnel, the environmental conditions were measured. This included wind direction and velocity at the portals.

**Traffic tube test results**

Air flow measurements were conducted in the west traffic tube (southbound roadway) while the tube was closed by MTQ. The measurements were made with the VE-252 and VE-254 fans located in the south tower operating at 100% in the exhaust mode. The data were used in the sensitivity analysis on the capacity of the emergency ventilation system operating as a longitudinal ventilation scheme.

In order to estimate the actual volumetric air flow rates for fans VE-252 and VE-254, measurements were made at the ceiling inlets. Air flow measurements were also conducted at 3 locations (1/4L, 1/2L, and 3/4L, L=distance between the north and south tower with the 1/4L cross section the closest location to the south tower). Air flow measurements were also made mid-way between the south tower and the south portal (1/2S).

Figure 3 shows the measurement locations and the volumetric flow rates that were calculated based on the velocity measurements. Based on the volumetric flow rates measured at 1/4L and 1/2S, the total volumetric air flow exhausted by the two fans was approximately 435 m$^3$/s. This estimate for the volumetric flow rate exhausted from the roadway is comparable to the design capacity for the VE 252 and VE 254 fans. However, the measured total outflow through the ceiling inlets was less than the total inflow (435 m$^3$/s) measured at 1/4L and 1/2S. The difference in these two measurements is mainly due to the considerable uncertainty in the accuracy of the measurements at the ceiling vents. It was difficult to access and take measurements at the ceiling opening of the traffic tube. The total flow rate of 435 m$^3$/s measured in the traffic tube at 1/4L and 1/2S was used in the numerical simulations since the value was comparable to the design capacity of the VE 252 and 254 fans.

**Loss coefficients in the traffic tube**

Using the air flow measurements in the tube, pressure losses in the traffic tube were analyzed. The analysis indicated that there are many factors affecting the changes of flow pressure along the length of the traffic tube. These include wall friction, dynamic air flow changes due to air leakage through the doors and side openings in the wall between the VA corridors and the traffic tube. In addition, there was a wind effect through the portals. The air flow measurements suggested that the wind effects increased the air flow velocity at the 3/4L measurement location.

Because of the combined effects of the factors affecting air flow in the tube, it was difficult to obtain an accurate estimate of the roughness value based on the experimental data. However, the analysis suggested that the dominant factor affecting the air flow in the traffic tube was the friction losses. Therefore, a surface roughness of 5 mm was used for the simulations as a conservative estimate, which would take into account wall effects as well as the effects of signs and other obstacles in the tube.
Figure 3. Flow rates in the traffic tube.

Figure 4. Velocity profiles at different distances from VE 252 VE 254 fans running in exhaust mode (Comparison of the simulated air velocity profiles with the test data at 1/4L)

Figure 5. Simulated air flow rates at 1/4L and 1/2S.

SIMULATION

Numerical simulations were conducted for the west traffic tube (southbound roadway). Fire Dynamics Simulator (FDS), developed by the National Institute for Standards and Technology was used. FDS [5] is a Large Eddy Simulation (LES) model, which solves a form of high-speed filtered Navier-Stokes equations, valid for low-speed buoyancy driven flows. Table 1 lists the simulations presented in this paper.
Model Geometry

The whole length of the west traffic tube was simulated in a three dimensional Cartesian domain. The section is 1390 m long in the X-axis, and the roadway is 12.8 m wide in the Y-axis and 5 m high in the Z-axis. The downward slope at the entry portal and the upward slope at the exit portal were modeled by specifying gravity vectors corresponding to the actual slope (about 4.5%) in each section of the tunnel. The tunnel concrete walls and ceiling were modeled with a surface roughness of 5 mm based on the in-situ measurement analysis.

The ends of the tunnel (north and south portals) were modeled as open boundary conditions. The VE ceiling vents and the VA vent openings were simulated as exhaust/supply vents depending on the simulation scenario by assigning volumetric flow rates. If not in use, the VA vent openings and the VE ceiling vents were simulated as closed. No metrological effects were simulated.

Fire modelling

Following an approach often used for smoke modelling studies for tunnel applications, a fire was modelled as a volumetric heat source by prescribing the required heat release rate. A gasoline pan with dimensions of 2.4 m wide, 8 m long and 1.5 m high was placed 0.5 m above the tunnel floor.

The yields of CO and soot were 0.131 and 0.360, respectively [6]. The yield of soot in particular affects estimations of visibility. The following is the equation used by FDS for the visibility estimations.

\[
\text{Visibility } S = \frac{C}{K} \\
K = K_m \rho Y_s
\]

Where \( C \) = a non-dimensional constant characteristic of the type of object being viewed through the smoke (3 for a light-reflecting sign)  
\( K_m \) = mass extinction coefficient, 8700 m²/kg³ suggested for most flaming fuels  
\( \rho \) = the local gas density (kg/m³)  
\( Y_s \) = the local mass fraction of soot (g/g)

Table 1. List of simulations.

<table>
<thead>
<tr>
<th>Ventilation Schemes</th>
<th>ID</th>
<th>Fire Size MW</th>
<th>Main Ventilation Systems</th>
<th>Additional systems</th>
<th>Fire Location Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing longitudinal ventilation scheme</td>
<td>L1_50MW</td>
<td>50</td>
<td>VE252 and VE254 in exhaust mode using measured flow rates</td>
<td>N/A</td>
<td>At ½ distance between the north tower and the centre of the tunnel</td>
</tr>
<tr>
<td></td>
<td>L2_35MW</td>
<td>35-10</td>
<td>VE252 and VE254 in exhaust mode using measured flow rates</td>
<td>N/A</td>
<td>A flow rate of 300 m³/s over the ceiling area 10 m X 5.8 m</td>
</tr>
<tr>
<td></td>
<td>L2_20MW</td>
<td>35-10</td>
<td>VE252 and VE254 in exhaust mode using measured flow rates</td>
<td>N/A</td>
<td>A flow rate of 190 m³/s over the ceiling area 8 m X 4.6 m</td>
</tr>
<tr>
<td></td>
<td>L2_15MW</td>
<td>35-10</td>
<td>VE252 and VE254 in exhaust mode using measured flow rates</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L2_10MW</td>
<td>35-10</td>
<td>VE252 and VE254 in exhaust mode using measured flow rates</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Longitudinal impulse ventilation</td>
<td>I6</td>
<td>50</td>
<td>Saccardo Fan 30 m/s At the north portal</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>I7</td>
<td>50</td>
<td>Saccardo Fan 30 m/s At the north portal</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>I8</td>
<td>50</td>
<td>Saccardo Fan 30 m/s At the north portal</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Semi-transverse ventilation scheme (for bidirectional circulation)</td>
<td>T4</td>
<td>50</td>
<td>VA202 and VA104 exhausting with 32 openings at the middle of the tunnel</td>
<td>N/A</td>
<td>At the mid length between the two towers At the mid length between the two towers</td>
</tr>
<tr>
<td></td>
<td>T4-1</td>
<td>50</td>
<td>VA202 and VA104 exhausting with 64 openings at the middle of the tunnel</td>
<td>N/A</td>
<td>The air flow rate through the openings were determined in sub-simulations</td>
</tr>
</tbody>
</table>
Grid size

The computational domain was divided into multiple meshes to reduce simulation time by running a simulation with multiple computer processors. Grid convergence tests were conducted to optimize grid set-ups that ensure reliable results and time-efficient simulations. The whole traffic tube was simulated in the grid convergence tests. The tunnel tube was divided into 6 meshes in the X-direction. A non-uniform grid set-up using a 0.25 and 0.5 m grid in the fire area showed results comparable to that from a simulation using a fine grid size of 0.25 m. These grid set-ups were adopted for the study.

Table 2 shows locations of the mesh boundaries in the X-direction and grid sizes of x (m) X y (m) X z (m) (the X, Y and Z direction, respectively) used in each simulation.

<table>
<thead>
<tr>
<th>ID</th>
<th>Mesh1</th>
<th>Mesh2</th>
<th>Mesh3</th>
<th>Mesh4</th>
<th>Mesh5</th>
<th>Mesh6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>North portal</td>
<td>200</td>
<td>330</td>
<td>550</td>
<td>1028</td>
<td>1260</td>
</tr>
<tr>
<td></td>
<td>Saccardo I6</td>
<td>Saccardo I7, I8</td>
<td>fire@452</td>
<td>VE252 254</td>
<td>@ 1113</td>
<td>South portal</td>
</tr>
<tr>
<td>L1-L2</td>
<td>2 X 1 X 1</td>
<td>1 X 1 X 1</td>
<td>0.44 X 0.5 X (0.25/0.5)</td>
<td>0.5X1X(0.5/1)</td>
<td>0.5X1X(0.5/1)</td>
<td>2 X 1 X 1</td>
</tr>
<tr>
<td>I6</td>
<td>0.5 X 0.5 X (0.25/0.5)</td>
<td>0.5 X 0.5 X (0.25/0.5)</td>
<td>0.44 X 0.5 X (0.25/0.5)</td>
<td>1 X 1 X 1</td>
<td>2 X 1 X 1</td>
<td>2 X 1 X 1</td>
</tr>
<tr>
<td>I7, I8</td>
<td>1 X 1 X 1</td>
<td>0.5 X 0.5 X (0.25/0.5)</td>
<td>0.44 X 0.5 X (0.25/0.5)</td>
<td>1 X 1 X 1</td>
<td>2 X 1 X 1</td>
<td>2 X 1 X 1</td>
</tr>
</tbody>
</table>

### Table 2 Grid set-up used in the simulations (unit in m).

#### (Longitudinal ventilation)

<table>
<thead>
<tr>
<th>ID</th>
<th>Mesh1</th>
<th>Mesh2</th>
<th>Mesh3</th>
<th>Mesh4</th>
<th>Mesh5</th>
<th>Mesh6</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>North portal</td>
<td>200</td>
<td>330</td>
<td>550</td>
<td>1028</td>
<td>1260</td>
</tr>
<tr>
<td></td>
<td>VE152 154</td>
<td>fire@700</td>
<td>VE252 254</td>
<td>VE252 254</td>
<td>South portal</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>2 X 1 X 1</td>
<td>2 X 1 X 1</td>
<td>1 X 1 X 1</td>
<td>0.5 X 0.5 X (0.25/0.5)</td>
<td>1 X 1 X 1</td>
<td>2 X 1 X 1</td>
</tr>
<tr>
<td>T4-1</td>
<td>2 X 1 X 1</td>
<td>2 X 1 X 1</td>
<td>1 X 1 X 1</td>
<td>0.5 X 0.5 X (0.25/0.5)</td>
<td>1 X 1 X 1</td>
<td>2 X 1 X 1</td>
</tr>
</tbody>
</table>

### SEMI-TRANSVERSE VENTILATION

#### (Semi-transverse ventilation)

<table>
<thead>
<tr>
<th>ID</th>
<th>Mesh1</th>
<th>Mesh2</th>
<th>Mesh3</th>
<th>Mesh4</th>
<th>Mesh5</th>
<th>Mesh6</th>
<th>Mesh7</th>
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<tbody>
<tr>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>North portal</td>
<td>200</td>
<td>330</td>
<td>590</td>
<td>800</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>VE152 154</td>
<td>fire@700</td>
<td>VE252 254</td>
<td>VE252 254</td>
<td>South portal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>2 X 1 X 1</td>
<td>2 X 1 X 1</td>
<td>1 X 1 X 1</td>
<td>0.5 X 0.5 X (0.25/0.5)</td>
<td>1 X 1 X 1</td>
<td>2 X 1 X 1</td>
<td>2 X 1 X 1</td>
</tr>
<tr>
<td>T4-1</td>
<td>2 X 1 X 1</td>
<td>2 X 1 X 1</td>
<td>1 X 1 X 1</td>
<td>0.5 X 0.5 X (0.25/0.5)</td>
<td>1 X 1 X 1</td>
<td>2 X 1 X 1</td>
<td>2 X 1 X 1</td>
</tr>
</tbody>
</table>

### SENSITIVITY ANALYSIS ON THE CAPACITY OF THE EXISTING LONGITUDINAL VENTILATION SYSTEM FOR DIFFERENT FIRE SIZES

The capacity of the existing longitudinal ventilation system using the VE-252 and VE-254 fans was investigated by simulating a fire with different heat release rates (10, 15, 20, 35 and 50 MW).

### Ventilation arrangement

The VE-252 and VE-254 fans were simulated as exhaust vents using the actual volumetric flow rates that were calculated based on the velocity measurements obtained from the in-situ tests. The in-situ measurement indicated that the total volumetric airflow produced by the two fans, VE-252 and VE-254, was approximately 435 m³/s. Based on this measurement, the VE-252 and VE-254 fans were modeled as exhaust vents with a volumetric air removal rate of 217.5 m³/s (1/2 of 435 m³/s) for each fan.

### Simulated air flow in the tunnel

To examine the air flow produced by the existing VE fans, a simulation was conducted without a fire. The simulation results were compared with the test data. Figure 4 shows the simulated airflow velocity profiles at 1/4L (L= distance between the two ventilation towers) compare well with the test data.
results. Figure 5 shows the simulated airflow rates monitored at the 1/4L and 1/2S (midway between the south portal and the south tower). The simulated air flow rates reached the steady-state after about 300 s, and the steady-state air flow estimations are very close to the test results (see Figure 3).

**Fire Modelling**

A fire was placed at ½ distance between the north tower and the center of the traffic tube (see Figure 6). This location was considered to pose the highest challenge to the existing longitudinal ventilation system. An initial simulation (Simulation L1) was carried out to assess the performance of the existing longitudinal ventilation systems (VE-252 and VE-254 running in the exhaust mode) in response to a 50 MW fire. More simulations (L2) were carried out with fire sizes less than 50 MW for the sensitivity analysis on the capacity of the existing longitudinal ventilation system. The results from this sensitivity analysis can be used in a risk assessment planned to be conducted in the future.

**Capacity of the Existing Longitudinal Ventilation System**

Figure 7 shows that temperature profiles in the tunnel when the VE-252 and VE-254 fans were used in the extraction mode with a fire of 50 MW. Using the existing longitudinal ventilation system, smoke backlayering was observed, and its length was about 150 m with a fire of 50 MW. The results also indicate that smoke was not limited to a hot upper layer but was present at lower heights in the tunnel. This agrees with the results from the previous studies by MTQ and NRC [2-4]. With the presence of the fire, the air flow induced by the VE-252 and VE-254 was different from that without the fire. As shown in Figure 8, the amount of air drawn through the south portal by the VE fans was increased and the longitudinal air flow in the tunnel was decreased with the presence of the 50 MW fire.

The ceiling temperature 10 m upstream of the fire was monitored as an indication of smoke backlayering. Figure 9 shows the simulated ceiling temperature 10 m upstream of the fire for different fire sizes. The temporal temperature changes show that the threshold fire size for the smoke backlayering to exceed 10 m was 13-20 MW. For a 10 MW fire, the existing ventilation system limited smoke backlayering to < 10 m. However, it required at least 300 s to be fully effective in controlling smoke. The smoke backlayering was limited to within 10 m of the fire for the 20 MW fire size after approximately 600 s. Figure 10 compares the temperature profiles at the 4.5 m height for different fire sizes. The results show that the length of backlayering reduces with the decrease in fire size.

Figure 7. Temperature profiles in the tunnel for the existing longitudinal ventilation system in response to a 50 MW fire.
INVESTIGATION OF THE EFFECTIVENESS OF AN IMPULSE VENTILATION SYSTEM

Simulations were conducted to investigate the effectiveness of an impulse ventilation system. Impulse ventilation, which introduces jets into a tunnel, can be used to increase longitudinal air flow. Three simulations, Simulations I6, I7, and I8, were conducted to investigate the effectiveness of using impulse ventilation in controlling smoke backlayering in the tunnel.

Ventilation arrangement

Impulse ventilation using Saccardo fans was simulated at two locations in the traffic tube: (1) at the north portal and (2) at the north ceiling vent for VE-154. At these two locations (see Figure 11), drawing external air into the tube is feasible by constructing a mechanical room at the portal or by modifying the shape of the fan elbow (e.g. VE-154) at the ventilation tower. For the simulations, a jet with a velocity of 30 m/s was injected toward the south portal at these two locations. An air flow rate
of 300 m$^3$/s or 190 m$^3$/s was injected over a rectangular area on the ceiling with an angle of 10 degree to the ceiling with the higher airflow rate used at the north portal.

*Figure 11. Locations for air injection.*

**Fire Modelling**

The same fire scenario used for the simulations for the existing longitudinal ventilation system (a 50 MW fire located at the half distance between the centre of the tunnel and the north tower) was used for the impulse ventilation simulations. This was done so that the effectiveness of the two systems, the longitudinal ventilation using the existing VE fans and the Saccardo fans, could be compared.

**Saccardo fan in response to a fire of 50 MW**

The Saccardo fans at both locations limited the smoke backlayering to <10 m for a fire of 50 MW. Figure 12 and Figure 13 show temperature and velocity profiles in the traffic tube from Simulation I8 in which, a jet was injected at the north tower with an air flow rate of 190 m$^3$/s, over a rectangular 8 m by 4.6 m area on the ceiling. The velocity profile shows that the jet lost its initial momentum within 100 m to produce an air flow velocity of 7.1 m/s. The reduction in the jet momentum was caused mainly by friction drag associated with the roughness of the tunnel surface as well as the angle of the jet.

When compared with the existing VE fans, the simulation results indicates that the Saccardo fans can be very effective from the onset in limiting smoke backlayering upstream of a fire of 50 MW. Figure 14 compares temporal changes of the ceiling temperature 10 m upstream of the fire.

In addition to limiting backlayering, the Saccardo fans also reduced the smoke temperatures downstream of the fire as the Saccardo fans injected fresh air, which diluted the smoke. However, while the area upstream of the fire was maintained smoke-free, the area downstream of the fire was full of smoke as the Saccardo fans blow the smoke to the south exit portal. The results from Simulation I8 show that using the VE fans in conjunction with the Saccardo fan could improve the conditions near the south portal as the VE fans exhaust smoke from the tunnel through the south tower. This could benefit evacuation of vehicles in the tunnel through the south portal.

*Figure 12. Temperature profiles in the tunnel for Simulation I8.*
INVESTIGATION OF A SEMI-TRANSVERSE VENTILATION SYSTEM

A semi-transverse system may be required if a tube is used with bi-directional traffic due to repairs in the other tube. In this mode of operation, the VA fan would be run in exhaust mode to extract smoke from the traffic tube through the service corridors via the upper vent openings in the wall between the VA corridors and the traffic tube. The upper side openings are located at a height of 3.9 m above the tunnel floor with dimensions of 0.5 m by 0.5 m, and at intervals of approximately 6 m.

Ventilation arrangement

Simulations were conducted to investigate the effectiveness of using the VA fans in extracting smoke from a 50 MW fire located at the middle of the tunnel. Figure 15 shows the ventilation arrangement used in the simulations. The VA-104 and VA-202 fans were simulated using an exhaust rate of 122 m$^3$/s with a varying number of upper openings in the middle of the tunnel. Inputs for the air removal rate through each upper opening were obtained using sub-simulations. In the sub-simulations, the VA-104 and VA-202 corridor and side openings were simulated with the VA fan exhausting air from the corridors. The air exhaust rate that was evaluated near the elbow of the VA fan outlet in the in-situ tests was used in the simulations.

Figure 15. Ventilation arrangements for the semi-ventilation system.
Semi-Transverse Ventilation in response to a fire of 50 MW

The results from the simulations showed that the semi-transverse ventilation system using the VA fans with the measured exhaust rate of 122 m³/s was effective in controlling smoke from a fire of 50 MW. The system successfully maintained low temperatures at a height of 1.5 m for a 50 MW fire located at the mid-length of the traffic tube.

Figure 16 shows temperature profiles from Simulation T4-1 and T4. In Simulation T4-1, 64 upper openings near the middle of the tunnel (i.e. 32 openings each in the VA-104 and the VA-202 corridor) were used to remove smoke from the traffic tube. In Simulation T4, 32 upper openings were used (i.e. 16 openings in each corridor). The temperature at the height of 1.5 m remained at ambient in both simulations. The temperature profiles indicate that the maximum ceiling temperature were higher with the 64 vent openings than with the 32 vent openings. The length of the smoke build up in the upper part of the tunnel also increased with 64 vent openings.

The visibility profiles are shown in Figure 17. Compared with the simulation with 32 vent openings, the visibility in the vicinity of the fire was significantly improved in the simulation with 64 vent openings. The length of the section with visibility less than 10 m was reduced by 75%.

Figure 16. Temperature profiles from Simulation T4-1 and T4.

Figure 17. Visibility profile from Simulation T4-1 and T4.
CONCLUSIONS

In order to get accurate input parameters for numerical simulations needed for design of the EVS, NRC conducted in-situ aerodynamic tests in the Louis-Hippolyte La Fontaine tunnel. The in-situ measurements indicated that the measured capacities were comparable to the design capacities of the fans. Based on the test data, pressure losses in the tunnel were evaluated and used in the simulations.

Numerical simulations were conducted to optimize the Emergency Ventilation System (EVS) for the tunnel. With the existing longitudinal EVS, simulations estimated the length of smoke backlayering for various fire sizes. The existing longitudinal ventilation system using the VE 252 and VE 254 required at least 300 s to be fully effective (see Figure 14) for a small fire (10 MW). It was able to limit backlayering to less than 10 m for fire sizes of 10, 13 and 20 MW. For the larger fire sizes (35 and 50 MW), there was more extensive smoke backlayering. For the 50 MW fire size, the smoke backlayering length was about 150 m and that, upstream of the fire, smoke was present at lower heights.

Initial simulations were conducted for an impulse ventilation system. The numerical simulations were conducted using typical jet parameters that were suggested for Saccardo type nozzles (i.e. a velocity of around 30 m/s [7]). The estimated air flow velocities in the tube were relatively high. It is likely that a system that produced lower velocities would be able to limit smoke backlayering. If it is decided to use impulse ventilation for the EVS in the tunnel, the system parameters including the jet velocity, imposed angle (between the jet and the ceiling of the tunnel) and the fan size would need to be optimized.

The simulation results from this study showed that using the VA fans for a semi-transverse ventilation system, during upgrade/construction, could be effective. However, the simulation results indicate that visibility can be poor in the vicinity of the fire. To fully evaluate the effectiveness of the system, a criterion for the acceptable length of the zone with low visibility would need to be established.

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Water Mist and Major Fire Spread in a Tunnel: A Theoretical Model

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ABSTRACT

A model of the effect of water mist 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 water mist 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 water mist. The increase in the critical heat release rate which may be produced by the presence of the water mist 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 C1, which is an acronym of Fire Spread in Tunnels, Model C, Version 1. It has been developed from an earlier model, FIRE-SPRINT A3 and considers a case where, in the absence of a fire fighting system, there is the potential for a major fire.

KEYWORDS: Tunnel ; Fire ; Mist ; Water ; Model ; Non-linear

INTRODUCTION

Major fire spread in tunnels has already been modelled in a series of papers by this author; see chapters 10 and 16 of reference[1] 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 [2] and major fire spread in a tunnel; see, for example, [3] and chapters 10 and 16 of reference[1]. The flashover and major fire spread phenomena are strongly suggestive of a non-linear ‘bifurcation point’ and lend themselves to such modelling. For tunnel fires, the critical heat release rate (HRR) for fire to spread from the initial fire to the target object has been calculated. 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 [4] 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 [5] 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 [6]; 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 independent organizations.

A crucial question which arises is: if a water-mist 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 water mist? The presence of water mist may be assumed to create extra heat losses in the system. In relation to the FIRE-SPRINT models created: if water mist were to be incorporated into FIRE-SPRINT A3, to create another model, what values for the critical HRR would be found? This is the question addressed in this paper. 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.

WATER MIST SYSTEMS

The droplets produced by water mist systems are much smaller than those for a conventional sprinkler system and a large part of their cooling action is thought to be via the evaporation of these droplets. Most of the experimental tests on these systems have been conducted by the companies which manufacture and sell them. As such, the results released have been very selective and it is to be assumed that very few, if any, negative results would be placed in the public domain.

Tests carried out by commercial companies sometimes claim that a fire has been ‘suppressed’ when this has not actually been the case [7]; taking ‘suppression’ to mean a non-trivial reduction in heat release rate which is permanent and not resurgent. Fire ‘control’ may be taken to imply that the heat release rate has, at least, been held steady and not increased to any non-trivial degree. Very few experimental tests on water-mist systems have been carried out by independent organizations and there need to be many more. One such set of tests was that carried out by the Technical Research Institute of Sweden (SP), see reference [8]. This large scale test was not actually carried out in a tunnel, but considered a HGV fire on the ‘ro-ro deck’ (ie roll on, roll off deck) of a ship. It compared a conventional water spray system with a high-pressure water mist system and found that “the high-pressure water mist system provided fire control at a discharge rate density of 5.8 mm/min, but not to the level that was achieved with the water spray system at 5 mm/min. Tests at 3.75 mm/min and 4.6 mm/min, respectively, provided no fire control and had to be terminated” and “the test results indicate that a high-pressure water-mist system would require higher flow rates as compared to a traditional water spray system in order to provide fire control”. This contradicts the idea that water mist systems use less water than traditional sprinkler systems.

A test has been carried out by Efectis Nederland to consider the suitability of water mist in relation to a BLEVE (‘Boiling liquid expanding vapour explosion’) risk, see [9] and [10]. The test was intended to simulate the effect of a fire on a LPG (Liquefied petroleum gas) tank. In the test the LPG tank was water filled and the ventilation velocity was 4m/s. It was found that for a ‘solid’ fire (ie consisting of pallets) with an estimated potential (ie un-controlled) heat release rate of about 200 MW a serious risk of a BLEVE due to a possible rupture of the tank existed even with water mist in operation. In this test the activation time of the mist was approximately 7 minutes after ignition. It may, possibly, have been the case that if the activation time had been significantly earlier then a serious BLEVE risk may not have existed. It certainly shows, though, that an extremely early activation time is essential and if a relatively large fire is allowed to come into existence then a serious BLEVE risk is possible, even with water mist. Further, after activation, the water mist system must be capable of effectively controlling or suppressing the fire and not allowing resurgence or merely slowing growth. Water mist seems to be less effective against solid fuel fires than are traditional sprinkler systems [7]. The Burnley Tunnel fire (Melbourne, Australia, 2007), see [11] and [12], clearly shows the need for very fast action to effectively suppress a fire in a tunnel; and in the Burnley Tunnel a traditional sprinkler deluge system was used. In that fire there was “an immediate fire of considerable intensity
(approximately 10MW)" [11] and the fire continued to grow rapidly until the sprinkler system was activated at about one and a half minutes after ignition. It is likely that a water mist system would not have been able to effectively cope with this fire. Even with fairly early activation of the first nozzle of a water mist system (at about 2 minutes after ignition), in at least one reported test a fire continued to grow to over 60MW [7].

The vital need for effective suppressing or controlling action to be taken extremely soon after ignition, given a fire in a tunnel, also emerges from the results of a theoretical study concerning a HGV (heavy goods vehicle) in a tunnel similar in size to the Channel Tunnel [13]. Given the uncertainty and lack of efficacious response which may well exist in the case of a real-world serious fire in a tunnel then activation within a very short time may well not occur. It is necessary to allow for the unanticipated and not assume that, necessarily, things will always go according to plan. Flexibility is paramount.

Also, it needs to be mentioned that in the solid fuel tests of reference [9] a “lethal” carbon monoxide risk existed and poor visibility for hundreds of metres downstream of the fire for a long time. In addition, humidity is very important in considering risk; in a very moist atmosphere pain due to heat transfer and skin burns occur at a much lower temperature than in a dry atmosphere [9]. Very fine droplets are created by water mist systems and a large part of their action may be assumed to be via the evaporation of these droplets. The relatively low momentum of these droplets, compared with traditional water spray systems, means that less, perhaps much less, water would be expected to reach the fuel bed than is the case with a conventional system with larger droplets. If there is a longitudinal ventilation in existence then a key question becomes ‘how much of the water mist would be swept away by the ventilation?’ That is, how much of the mist would be retained in the fire zone and be able to take part in cooling, and not be swept away downstream? This question has been addressed by Rein, Carvel and Torero [14]; see also the paper by Crosfield et al, which reaches similar conclusions [15]. In the theoretical study by Rein et al they found that for a water mist spray “individual droplets may be carried hundreds of metres downstream of the nozzle location before hitting the road deck under ventilation conditions that are commonplace in tunnels”. Their findings indicate that for droplets of the order of 90-120 µm, which, they say, are “typical” diameters for current commercial water mist systems, droplets were swept about 50m downstream of the nozzle. That work assumed a tunnel of height about 6m and a longitudinal ventilation velocity of about 2m/s. For a 4 m/s ventilation velocity such droplets were swept about 100m downstream. Smaller droplets would be projected much further and larger droplets a shorter distance downstream. This is a theoretical study and independent experimental work is needed. By independent is meant: such experiments should be conducted by reputable independent organizations, without the involvement of commercial organizations, other than to supply equipment. Also, there should be more than one such experimental investigation to try to get an idea of the probabilistic spread; given that ‘identical’ experiments may well produce significantly different results; see [16] ; also see [17]. Further, such experiments should be at full-scale, not reduced scale. Although full-scale tests are essential, it may be noted that Li and Ingason [18] have carried out small-scale tests which indicate that high longitudinal ventilation velocities inhibit the effectiveness of automatic sprinkler systems for which the nozzles are thermally activated. It is suggested that they are suitable for tunnels with high ventilation velocities only when special strategies are adopted. This emphasises the importance of fixed fire-fighting systems being operated only as part of an integrated system of control.

A MODEL OF MAJOR FIRE SPREAD WITH WATER MIST

The effect of water mist has been incorporated into the non-linear model FIRE-SPRINT A3, which is an acronym for Fire Spread in Tunnels, Model A, Version 3. The model without mist 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 [4]; here a very brief description only is given.
BASIC STRUCTURE OF FIRE SPRINT A3

This model 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 [4].

PUTTING WATER MIST INTO FIRE-SPRINT A3

A model, which is being identified with the acronym FIRE-SPRINT C1, has been created by putting water mist into FIRE-SPRINT A3. Key assumptions in creating the new model 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 $D_{\text{m1}}$ (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 NDSW (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 NDNLS (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.
7. Further details of the assumptions made are given in [19].

ILLUSTRATIVE SIMULATIONS

Initial simulations with a longitudinal forced ventilation velocity of 2m/s are described next. Variation in forced ventilation velocity is considered further on in this section. 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 stationary train [20]. The train is taken to be stationary and forced longitudinal.
Figure 1: Lateral view of the tunnel
(The CV consists of sections S1, S2, S3; see in conjunction with Figure 2. The lower shaded region indicates the region below the floor.)

(© Alan N. Beard, 2001)

Figure 2: Cross-section of the tunnel, through the target object
(© Alan N. Beard, 1998)
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 is 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 water mist, for this initial case, a discharge rate density of 4 mm/min has been assumed. Also, for this case, NDNLs has been assumed to have the value 0.31 and NDSW to have the value 0.14; see [19]. Full details of the other input values are as given in Appendix A. Solutions for the case of \( v = 2 \text{m/s} \) have been found and the profile of equilibrium states in the T/Mfun plane and the eigenvalue trace are given in [19]. (Mfun is the unenhanced fuel mass loss rate, see [4]).

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 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 \( S = L_0 - L_1 \). The critical value of the heat release rate, \( Q_{fc} \), at which the loss of stability occurs is found to be about 49.5 MW. 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 [4], ie FIRE-SPRINT A3 without water mist. That is, given the assumptions made for this initial case, the water mist appears to have increased the critical rate of heat release by approximately 11 MW.

It is known, however, from simulations using FIRE-SPRINT A3 [4], 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 water mist is calculated to increase the critical rate of heat release by about 5MW and not 11MW. This is because the value for \( Q_{fc} \) becomes 36.7 using FIRE-SPRINT C1, compared with 32.2 using FIRE-SPRINT A3. (The results for the ‘reduced CV length’ are for \( L_0 = 10.325 \text{m} \) and \( L_1 = 3.875 \text{m} \); separation remains the same at 6.45m). See [19] for more on this.

Simulations have also been conducted with variation in forced ventilation velocity. In addition to \( v = 2 \text{m/s} \), 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 4mm/min. It is to be expected that the values of NDNLs and NDSW will vary with forced ventilation velocity. This means that it has been necessary to estimate the values of NDNLs and NDSW at these velocities. This is considered in Appendix B, where the following two equations have been derived:

\[
N_{\text{DNLS}} = 1 - \exp(-0.186 \text{ \textit{V}}) \quad \{1\}
\]

\[
N_{\text{DSW}} = N_{\text{DNLS}} (1 - \exp(-0.3 \text{ \textit{V}})) \quad \{2\}
\]

Where: \( N_{\text{DNLS}}, N_{\text{DSW}} \) are as defined above; ie fractions between 0 and 1, inclusive.

\( \text{\textit{V}} = \) Velocity of the longitudinal forced ventilation velocity in m/s

The above equations are intended to provide approximate estimates of NDNLs and NDSW 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.
Table 1: Values assumed for the parameters NDNLS and NDSW for different forced ventilation velocities, using the equations derived in Appendix B.

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>NDNLS</th>
<th>NDSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.31</td>
<td>0.14</td>
</tr>
<tr>
<td>3</td>
<td>0.43</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>0.53</td>
<td>0.37</td>
</tr>
<tr>
<td>5</td>
<td>0.61</td>
<td>0.47</td>
</tr>
<tr>
<td>6</td>
<td>0.67</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Using 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 C1 with those using FIRE-SPRINT A3, ie without water mist. The increase in critical HRR is given at each velocity. It is seen that for the case of a forced ventilation velocity of 6m/s that the system does not go unstable for FIRE-SPRINT C1, 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 1 also shows that for velocities 2 to 5m/s that the increase in critical HRR ranges from 8.9 to 11.7 with an average of 10.2 MW.

Table 2: Values calculated for the critical HRR for fire spread using FIRE-SPRINT C1 (ie with mist) and using FIRE-SPRINT A3 (ie without mist).

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Using FIRE-SPRINT A3 (MW)</th>
<th>Using FIRE-SPRINT C1 (MW)</th>
<th>Increase in critical HRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>38.6</td>
<td>49.5</td>
<td>10.9</td>
</tr>
<tr>
<td>3</td>
<td>71.8</td>
<td>80.7</td>
<td>8.9</td>
</tr>
<tr>
<td>4</td>
<td>104.5</td>
<td>113.6</td>
<td>9.1</td>
</tr>
<tr>
<td>5</td>
<td>139.0</td>
<td>150.7</td>
<td>11.7</td>
</tr>
<tr>
<td>6</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 C1 (ie with water mist) and using FIRE-SPRINT A3 (ie without water mist); 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 C1 (MW)</th>
<th>Increase in critical HRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>32.2</td>
<td>36.7</td>
<td>4.5</td>
</tr>
<tr>
<td>3</td>
<td>54.5</td>
<td>64.2</td>
<td>9.7</td>
</tr>
<tr>
<td>4</td>
<td>87.3</td>
<td>94.1</td>
<td>6.8</td>
</tr>
<tr>
<td>5</td>
<td>119.1</td>
<td>125.6</td>
<td>6.5</td>
</tr>
<tr>
<td>6</td>
<td>152.1</td>
<td>158.3</td>
<td>6.2</td>
</tr>
</tbody>
</table>

It may be seen from Table 3 that at a value for velocity of 6m/s that the system does go unstable and fire spread is predicted. The increase in critical HRR ranges from 4.5 to 9.7MW with an average of 6.7MW.

FLAME DEFLECTION AND THE CRITICAL HRR FOR FIRE SPREAD

It needs to be noted that in these simulations the degree of flame deflection has been assumed to remain the same as the velocity of forced ventilation is increased. In reality it would be expected that the amount of flame deflection would increase with increase in ventilation velocity. The experimental work of references [21] & [22] indicates that a significant flame deflection would be expected and the probabilistic modelling, using Bayesian methods, of reference [23] 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 [5], which assumes flame impingement, show that the calculated values for Qfc in that case are much less than for spontaneous ignition. Also, flame deflection without actual impingement would be expected to reduce the Qfc; all else the same. It is very likely, therefore, that the values of Qfc reported in this paper are 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 Qfc.

As these considerations would apply to the cases both with and without mist operating, ie to both FIRE-SPRINT A3 and FIRE-SPRINT C1, then the increases in Qfc found with mist (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 Qfc 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.
CONCLUSION

A theoretical model for the critical HRR, Qfc, necessary for fire to spread from an initial fire to a target object in the presence of water mist has been created. It assumes a tunnel similar in size to the Channel Tunnel and a separation 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 object. It employs 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 water mist discharge rate density of 4mm/min (ie 4 litres/min/m²). It has been assumed that the fire has the potential for the HRR to continue to rise significantly beyond the activation of a water mist system. (Such fires have been reported in the literature; see [7])

It has been found that the expected increase in Qfc, due to the presence of the water mist, is very approximately in the range 4-12 MW. That is, the water mist has increased the expected value of critical HRR for fire to spread by about 4-12MW, by comparison with a tunnel with no mist operating. This assumes the values for input parameters as given. There would be uncertainty in these values, especially in the values of NDNLS and NDSW. In a separate study using FIRE-SPRINT C1 [19] which considered different values for these parameters it was concluded that, in a real world case, the increase in Qfc because of the presence of water mist could be as low as about 1MW or as high as 16MW. In practice it would be prudent to assume a value closer to the lower end of this range rather than the higher end. Caution should be the watchword.

While great accuracy is not being claimed, it is expected that these numbers would be very broadly indicative of the increase in critical HRR expected with water mist. It is evident that it is essential that water mist systems be activated extremely early after ignition, to try to stop the fire reaching a high enough HRR for spread to be possible in the presence of the mist. It would be wise to assume that this latter principle would apply to large-drop sprinkler systems as well. Experimentalists are urged to test these results in full-scale tests. Also, experimentalists are urged to carry out tests in order to provide estimates for the parameters NDNLS and NDSW. All such tests should be carried out by reputable independent organizations and not involve commercial companies other than to supply equipment. In summary: it is hoped that the theoretical results found in this work will provide a broad indication of the heat release rate necessary for fire to spread in the presence of water mist. Experimental tests are needed both to try to provide more information in order to estimate input parameters and to test computed values of critical heat release rate.

With regard to fire protection in a real-world tunnel, it should certainly not be assumed that water mist is necessarily preferable to a more conventional, large-droplet, system. Because a system is ‘more novel’ it is not necessarily better. The historical record of tunnel fires certainly indicates that more conventional systems may well be more effective in many, perhaps all, cases. Whichever system is used, it is essential that it be employed as part of an integrated system of control.

APPENDIX A : INPUT DATA

FIRE-SPRINT C1 is derived from FIRE-SPRINT A3 and the values used for parameters which are common to both are as given in reference [4]; other than for flame temperature, Tf, for which see below. Assumed values of parameters which have been introduced as part of creating FIRE-SPRINT C1 are as given in [19] unless given below or otherwise stated in the text.

Tf = 1100 (°K) ; assumed to be lower than the flame temperature without mist (ie lower than 1300 °K as used in reference [4]).
NDNLS = 0.31 ; NDSW = 0.14 ; Dm1 = 4.0 mm/min

APPENDIX B : EQUATIONS FOR NDNLS AND NDSW

Estimates need to be arrived at for the values of NDNLS and NDSW 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 \( N_{\text{DNLS}} \) will be derived and then an equation for \( N_{\text{DSW}} \), at a given \( N_{\text{DNLS}} \). To derive an approximate equation for the dependency on \( V \) of \( N_{\text{DNLS}} \), ie the fraction of water discharged into the CV which does not hit lower surfaces, the following assumptions have been made:

1. \( N_{\text{DNLS}} \) is a number between 0 and 1.0, inclusive.
2. For \( V = 2\text{m/s} \) then \( N_{\text{DNLS}} = 0.31 \). This has been estimated in [19] using available information as given there.
3. As \( V \) tends to infinity then \( N_{\text{DNLS}} \) tends to 1.0
4. A suitable form for an equation is: \( N_{\text{DNLS}} = 1 - \exp(-b \cdot V) \); \( b \) = a constant

The assumptions above may be combined to give:

\[
N_{\text{DNLS}} = 1 - \exp(-0.186 \cdot V) \quad \{\text{B1}\}
\]

This equation has the property that at \( V = 0 \) then \( N_{\text{DNLS}} = 0 \). This would not be expected to be very realistic for a water mist system. Therefore, 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 \( N_{\text{DSW}} \), ie the fraction of water discharged into the CV which is transported downstream, the following assumptions have been made:

1. At \( V = 2\text{m/s} \) then \( N_{\text{DNLS}} = 0.31 \) and \( N_{\text{DSW}} = 0.14 \). This has been estimated in reference [19] using available information as given there. In that paper, to estimate an initial value for \( N_{\text{DSW}} \) the results of experimental tests were used. The tests chosen were full-scale experiments which would have been expected to produce large fires (of the order of tens of megaWatts) if mist had not been deployed.
2. As \( V \) tends to infinity then \( N_{\text{DSW}} \) tends to \( N_{\text{DNLS}} \).
3. A suitable form for an equation is: \( N_{\text{DSW}} = N_{\text{DNLS}} (1 - \exp(-a \cdot V)) \); \( a \) = a constant

The assumptions above may be combined to give:

\[
N_{\text{DSW}} = N_{\text{DNLS}} (1 - \exp(-0.3 \cdot V)) \quad \{\text{B2}\}
\]

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


Influence of Fire Suppression on Combustion Products in Tunnel Fires

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ABSTRACT

A series of model scale tunnel fire tests with and without fire suppression were carried out to investigate effects on production of key combustion products including CO and soot. The key parameters accounted for in the tests include fuel type, ventilation velocity and activation time. The results show that fire suppression indeed has influence on production of combustion products especially for cellulose fuels. In case that the fire is not effectively suppressed, e.g. when the water density is too low or activation is too late, the CO concentration and visibility could be worse than in the free-burn test. From the point of view of production of combustion products, only fire suppression systems with sufficient capability and early activation are recommended to be used in tunnels.

KEYWORD: tunnel fire, fire suppression, ventilation, activation, CO yield, soot yield, visibility

INTRODUCTION

Nowadays use of water-based fire suppression systems in tunnels has attracted much attention and the regulations and standards are also changing with regard to its use [1]. Despite this, there are still numerous issues needed to be clarified before quantitative guidelines can be made.

The Swedish Transport Administration (STA) plans to construct a new highway connection through the western part of Stockholm called the Stockholm bypass, due for completion in 2025. A new type of water based fire suppression system will be installed in the tunnel. In earlier studies within the frame of the EU co-funded project (TEN-T)1, a concern was raised that if the system activates late, an increase of toxic substances and smoke could be produced. The impact of this effect could be mitigated by activating the system early. Further research was needed to investigate the implication of this observation in future testing [2]. The work presented here is directly related to the research question raised.

There have been many full scale fire suppression tests carried out in tunnels [3-11]. These tests have been mainly concerned about the design fires in tunnels with focus on specific fire suppression systems. Model scale tests have also been performed to systematically investigate the design fires with different fire suppression systems [12]. Tests with automatic suppression systems in tunnels have also been carried out in model scale [13].

At present it is clear that by equipping a tunnel with a deluge water-based fire suppression system of enough capacity, e.g. greater than 10 mm/min for a water spray system, the design fire can be reduced to a lower level [14]. It is, however, not clear how the combustion products are released in such cases. As the fire is suppressed due to the intervention of the water sprays, strong interaction between the

1 In 2012 the Swedish Transport Administration and the Stockholm bypass project was granted co-funding for various tunnel safety studies from the Europena Union (EU) through the Trans-European Transport Network (TEN-T). The research was performed during the period 2012-2014.
combustion and water sprays exist. This results in changes in the production of combustion products, which in turn changes the environment in the tunnel. Therefore this issue is very important for analysis of evacuation in a tunnel fire after activation of a suppression system. A scenario similar to the use of water-based fire suppressions is the fire-fighting operation in a tunnel fire. Note that fire fighters use fire hoses to suppress and extinguish the fire. The agent used can be water, foam, or mixture of water and foam, but for attacking solid fuel fires water is mostly used. In such cases, the same adverse effect as that using a fixed water-based fire suppression system exists. Clearly, this issue has to be clearly addressed from the point of view of both tunnel safety designs and fire-fighting operations.

The main objective of the work is therefore to investigate effects of a deluge water-based fire suppression system on combustion products in tunnel fires. The focuses are on CO concentration, CO yield, soot yield and visibility.

EXPERIMENTS

Tests were carried out inside a 1:4 model scale tunnel, according to the Froude scaling [1]. The tests were carried out both with and without water-based fire suppression system to investigate the effect of fire suppression on production of key combustion products. The key parameters accounted for in the tests include fuel type, ventilation velocity and activation time. Before the tunnel tests, a series of pre-tests were also carried out while the results are not presented here.

The model tunnel is 15 m long, 2.8 m wide and 1.4 m high, see Figure 1. The water spray system with T-Rex nozzles was designed to cover a region of 7.5 m, corresponding to 30 m in full scale. The designed water flow rate is 5 mm/min (full scale 10 mm/min). The longitudinal ventilation velocity in the tunnel was set to be 1.5 m/s, or 3 m/s. The Heavy Goods Vehicle (HGV) mock-up was simulated using two different types of fuels, i.e. wood pallets and Polyethylene (PE) cribs. The fuels were placed in a 1 m diameter steel pan with approximately 80 mm high rims. In some tests the front, the back side and top of the fire load were covered by steel plates.

Measurements are shown in Figure 1. All ceiling thermocouples were placed 100 mm below the ceiling, except at Pile A. One plate thermometer was attached to the ceiling right above the fire source. At Pile A, the bi-directional tubes were placed along the centreline of the tunnel while the gas analysis and thermocouples were placed horizontally 50 mm from the gas analysis. Two laser/photocells were installed at Pile A. The distance between the emitter and receiver is 0.4 m.
Measurements at pile A are used to estimate the flow rate, heat release rate (HRR), CO production and soot production. In analysis, superpositions of individual horizontal cross sections are applied for all the parameters. More details can be found in the report [15].

RESULTS AND DISCUSSION

The parameters focused on are the yield and production rate of the key combustion products, i.e. CO and soot. The yield of one combustion product, \( Y \) (kg/kg), is defined as the amount of the combustion product produced by consuming 1 kg of fuel. Theory of estimations of these parameters can be found in the report [15].

Wood pallet fires in tunnel tests

Heat release rates in wood pallet fires

Figure 2 shows comparisons of heat release rates in the free burn tests and fire suppression tests for a velocity of 1.5 m/s and 3 m/s, respectively. The heat release rate at the activation time was 550 kW in test 5 and 750 kW in test 7, as shown in Figure 2. The heat release rate at the activation time was 100 kW in test 17 and 850 kW in test 19, as shown in Figure 2. Clearly, for a given velocity, the heat release rates approximately follow the same curve, indicating good repeatability. It can also be seen that for both velocities, the heat release rate decreased immediately after the fire suppression system was activated. In other words, the wood crib fire was effectively suppressed at both velocities. It appears that the fire exposed to higher ventilation is easier to extinguish. The reason could be that the flame is highly inclined under 3 m/s, which facilitates the water to reach the fuel surfaces.

CO production in wood pallet fires

CO concentration at mid tunnel height

Figure 3 shows comparisons of CO concentration at mid tunnel height (measured at G2 in Figure 1) in the free burn tests and fire suppression tests for a velocity of 1.5 m/s and 3 m/s, respectively. The location is 10.6 m downstream of the fire, corresponding to 42.4 m at full scale. To be on the safe side, the CO concentration at mid tunnel height (0.7 m in model scale and 2.8 m in full scale above tunnel floor) could be used to represent the situation at the human level.

The CO concentration at mid tunnel height in the free burn test obtained the highest value for both 1.5 m/s and 3 m/s. The CO concentration curve in the free-burn test approximately follows the heat release rate curve. During the decay period, the CO concentration in a fire suppression test with late activation is higher than that in the free-burn test, especially in the tests with 3 m/s. Note that there could be two reasons for the increase in the CO concentration in a fire suppression test. One reason is
the possible increase in CO production rate due to strong interaction of the combustion gas with the water droplets. This effect will be shown in the following section. Another possible reason is that the water droplets cool down the gas and also entrain the upper-layer gas into the lower layer. Both the cooling and the entrainment effects results in de-stratification of the smoke layer. However, the free burn tests still represent the worst scenario from the point of view of CO concentration in this test series, as the early 10 min (20 min at full scale) could be regarded as the key period for evacuation.

Further, comparing the two suppression tests shows that early activation reduces the CO concentration significantly.

![Figure 3 Comparison of CO concentration in free burn and suppression tests (Wood pallet).](image)

**CO production rate**

Figure 4 shows comparisons of CO production rates in the free burn tests and fire suppression tests for a velocity of 1.5 m/s and 3 m/s, respectively. Clearly, it shows in Figure 4 that the maximum CO production rates in the fire suppression test 7 is even higher than that in the free-burn test, although they are approximately at the same level. However, given that the heat release rate in the fire suppression test is much lower than that in the free-burn test, the CO yield in test 7 should be much higher than in the free-burn test. After around 9 min, the CO production rate in the fire suppression test 7 is much greater than that in free-burn test 1. Similar trend can be found for 3 m/s. After around 8 min, the CO production rate in the fire suppression test 19 is much higher than that in free-burn test 14. In contrast, the CO production rates in the fire suppression tests 5 and 17 with earlier activation are always lower than those in the corresponding free-burn tests. This implies the importance of the activation time.

**CO yield**

Figure 5 show comparisons of CO yields in the free burn tests and fire suppression tests with wood pallets for a velocity of 1.5 m/s and 3 m/s, respectively. For small heat release rates in the growth period and in the decay period, the uncertainties in estimation of the heat release rates could be high, given that the CO yield is calculated based on the fuel mass burning rate. Further, the influence of ignition source on the results at early stages decreases with the increasing heat release rate. Therefore data for heat release rates lower than around 30 kW (1 MW at full scale) are mostly ignored in the following figures.

It can be seen in Figure 5 that in the free burn fire tests with wood pallets, the maximum CO yield is approximately 0.032 kg/kg for a velocity of 1.5 m/s and 0.025 kg/kg for 3 m/s. In these tests, the CO yield is higher at early stage and much lower after 2 min. Some influence of the ignition source can be expected. After activation the CO yield in the suppression tests starts to increase. It can also be observed that generally the CO yield increases with the decreasing heat release rate, and after the heat release rate is lower than around 100 kW to 200 kW (3 MW to 6 MW at full scale) significant
increase in CO yield can be found, see Figure 5.

\begin{figure}[h]
\centering
\begin{subfigure}{0.49\textwidth}
\centering
\includegraphics[width=\textwidth]{fig4a}
\caption{1.5 m/s}
\end{subfigure}
\begin{subfigure}{0.49\textwidth}
\centering
\includegraphics[width=\textwidth]{fig4b}
\caption{3 m/s}
\end{subfigure}
\caption{Comparison of CO production rates in free burn and suppression tests (Wood pallet).}
\end{figure}

\begin{figure}[h]
\centering
\begin{subfigure}{0.49\textwidth}
\centering
\includegraphics[width=\textwidth]{fig5a}
\caption{1.5 m/s}
\end{subfigure}
\begin{subfigure}{0.49\textwidth}
\centering
\includegraphics[width=\textwidth]{fig5b}
\caption{3 m/s}
\end{subfigure}
\caption{Comparison of CO yield in the free burn test and fire suppression tests (Wood pallet fires).}
\end{figure}

The CO yield in test 5 increases rapidly after suppression and reaches 0.1 at around 8 min, however, at this moment the heat release rate is around 30 kW close to extinguishment and therefore the results are not presented further after 8 min due to the large uncertainties as mentioned previously. The CO yield in test 7 increases to around 0.033 kg/kg at around 11 min and then ramps up to 0.08 kg/kg. The CO yield in test 17 increases linearly after 3 min and reaches 0.10 kg/kg at around 7 min. In test 19, the CO yield increases continuously to 0.09 kg/kg at around 10 min. It can also be found that the maximum CO yield with suppression could be 3 to 4 times that in the free-burn tests. The increase of CO yields indicate strong interaction between the water droplets, the produced water vapours and the combustion gases, which results in incomplete combustion and CO production.

An interesting finding is that the CO yield behaves very differently compared to the CO concentration at the mid-tunnel height. Note that the maximum CO concentration in the free burn test is still the highest, as shown in Figure 3. Although the CO yield after activation of fire suppression is much higher, the heat release rate at this moment has been effectively suppressed in these tests, i.e. test 1 and test 14, and therefore the CO concentration at mid-tunnel height does not show a significant increase effect as the CO yield does.

Note that in all these fire suppression tests, the maximum heat release rates are all lower than 40 % of the maximum heat release rate in the free-burn test, that is, the fire sizes have been reduced to less
than 40% of that in the free-burn test. It can be expected that if the fire is not effectively suppressed after activation, the CO concentration could be much higher than that shown in Figure 3.

**Soot production in wood pallet fires**

Note that after activation the soot production cannot be accurately estimated, instead only upper limits can. The reason is that after activation a large amount of water droplets exist in the flow and behave as a light barrier and thus significantly affect the measurement of obscuration. These water droplets are produced both by nozzles and by condensation of water vapour. In case the deposition of the soot is negligible, the calculated soot production or soot yield could be used as the upper limits as the attenuation accounts for effects of both soot and water vapour. The contribution from the water droplets is difficult to estimate, and therefore the data is proposed to be regarded as the upper limit for soot until better methods or analysis can be carried out.

**Soot production rate**

Figure 6 shows comparisons of soot production rates in the free burn tests and fire suppression tests for a velocity of 1.5 m/s and 3 m/s, respectively. For 3 m/s, the maximum soot production rate in the free burn test 14 is much higher than in the fire suppression tests. For 1.5 m/s, the maximum soot production rates in the free burn test 1 and the fire suppression test 5 approximately lie at the same level, and the value in test 7 is much lower. The results also show that after suppression the production rate in test 5 is much higher than the other two tests at 1.5 m/s. One reason could be a large amount of water droplets is produced after activation of fire suppression system. Another reason could be that large measurement error in test 5 is introduced as the laser measurement is very sensitive to deflection caused by, e.g., heat.

**Soot yield**

Figure 7 shows comparisons of soot yields in the free burn tests and fire suppression tests for a velocity of 1.5 m/s and 3 m/s, respectively. The soot in the free burn test tends to increase with time. The soot yield in the free burn test and in suppression tests before activation is mainly in a range of 0.002 - 0.02 kg/s. Note that the data from test 5 before activation as shown in Figure 7 are slightly higher than the others, which indicates possible large measurement error as mentioned earlier.

There is also a trend that after activation the soot yield increases. In test 5 the soot yield increases significantly with time after activation, while in test 7 only slight increase in soot yield could be observed. In test 17 the soot yield also increases significantly with time after activation while in test 19, the soot yield increases to 0.075 kg/s at around 8 min and keeps at this level till the end. Note that the maximum soot yield can be found to be as high as 0.22 kg/s. It can also be observed that generally the soot yield increases with the decreasing heat release rate,
and after the heat release rate is lower than around 200 kW significant increase in soot yield can be found.

Although during some period of a test with fire suppression the soot yield can be significantly higher than that in a free-burn test, the total production of soot particles in the free-burn test is still the highest as shown above.

However, as indicated earlier, it should be kept in mind that after activation, the soot measurement does not only measure soot but also water droplets. Therefore the data can only be considered as upper limit for the soot yield.

![Graph](a) 1.5 m/s  ![Graph](b) 3m/s

**Figure 7** Comparison of soot yields in free burn and suppression tests (Wood pallet). Note that after activation the data are not really soot yields.

![Graph](a) 1.5 m/s  ![Graph](b) 3m/s

**Figure 8** Comparison of visibility in free burn and suppression tests (Wood pallet).

**Visibility at mid tunnel height in wood pallet fires**

On contrary to the estimation of soot production, the visibility measurements are reliable as it indeed accounts for effects of both soot and water vapours as it is in reality. Figure 8 show comparisons of visibilities at mid tunnel height in the free burn tests and fire suppression tests for a velocity of 1.5 m/s and 3 m/s, respectively. Note that the visibility in the free burn test is generally the smallest compared to fire suppression tests. The main reason is that the heat release rate decreased immediately after activation of the fire suppression system. According to the scaling theory presented in Section 2.1, the visibilities are the same in all scales.
PE crib fires in tunnel tests

**Heat release rates in PE crib fires**

Figure 9 shows comparisons of heat release rates in the free burn tests and fire suppression tests for a velocity of 1.5 m/s and 3 m/s, respectively. In all the tests the fires without coverage are suppressed immediately after activation of the fire suppression system, even the fire size at activation is close to the maximum size in a free-burn test. Note that the heat release rate curve in test 26 slightly deviates from the others. This should be due to the influence of ignition source. The same trend can be found for test 8.

![Figure 9](image1.png)

**CO production in PE crib fires**

**CO concentration at mid tunnel height**

Figure 10 show comparisons of CO concentrations at mid tunnel height in the free burn test and fire suppression tests for velocity of 1.5 m/s and 3 m/s, respectively. Clearly, the results show that after activation, the CO concentration at mid-tunnel height decreases immediately, following the same trend as shown in the heat release rate curves. In test 8, the CO concentration in the growth period also slightly deviates from the others, as the corresponding heat release rate curve does.

![Figure 10](image2.png)

**CO yield**

Figure 11 show comparisons of CO yields in the free burn test and fire suppression tests for velocity
of 1.5 m/s and 3 m/s, respectively. It is shown that the CO yield is mainly in a range of 0.01 kg/kg to 0.08 kg/kg for 1.5 m/s, and 0.01 kg/kg to 0.06 kg/kg for 3 m/s. This indicates that the CO yield decreases with ventilation velocity.

After activation of fire suppression, the CO yield is approximately at the same level as in the free-burn test. In tests with suppression, the CO yield increases slightly in the decay period, i.e. when the heat release rate is lower than 100 kW – 200 kW.

![Comparison of CO yield in the free burn test and fire suppression tests (PE crib fires).](image)

In summary, the influence of fire suppression on CO yield is insignificant although in some tests the CO yield after suppression increases slightly.

Comparing the results of the PE crib fires and the wood pallet fires show that they behave very differently with regard to production of CO. In the PE crib fires with fire suppression, the CO concentration is generally lower than that in the free-burn test and the CO yield increases slightly after fire suppression. In contrast, in the wood crib tests with late activation, the CO concentration in the decay period is slightly higher than that in the free-burn test. The difference in the CO yield of the wood pallet fires is, however, much larger, and the CO yield after activation rises continually to around 0.10 kg/kg, 3.5 to 4.5 times that in a free-burn wood pallet test. This indicates stronger interaction between the water droplets, the produced water vapours and the combustion gases for wood pallet fires, which results in incomplete combustion. There could be two reasons for this. One reason could be that the cellulose materials, e.g. wood, absorb water into the material, which to some extent behaves as a water sink. During fire suppression, the unburnt fuels can be pre-wetted while part of the fuels could be extinguished and then absorbs water. During the fire, a large amount of water vapours could be produced from these extra water sources and interact strongly with the combustion gases. Another reason could be that for a same maximum heat release rate, a wood pallet corresponds to a larger exposed fuel surface area that indicates more fuel surfaces could be pre-wetted.

**Soot production in PE crib fires**

**Soot production rate**

Figure 12 shows comparisons of soot production rate in the free burn test and fire suppression tests for velocity of 1.5 m/s and 3 m/s, respectively. Note that soot production rate after suppression does not mean real soot production rate but approximately represents its upper limit as both soot and water droplets affects the soot measurement. Despite this, in all the tests the maximum soot production rate in the free-burn test is the highest. In test 8, the soot production rate at the early stage is higher than that in the free-burn test. However, this correlates well with the heat release rate curve in test 8 which shows the fire develops more rapidly in the growth period.
Figure 12  Comparison of soot production rate in free burn and suppression tests (PE crib).

Soot yield
Figure 13 show comparisons of soot yields in the free burn test and fire suppression tests for velocity of 1.5 m/s and 3 m/s, respectively. It can be seen that the soot yield in the free burn test tends to increase with time.

The soot yield in the free-burn test 3 with 1.5 m/s increases to around 0.04 kg/kg at approximately 0.6 min (partly due to contribution from the ignition source) and decays immediately to 0.002 kg/kg. It rises up again to approximately 0.06 kg/kg after 4.5 min. Similar trend can be found in test 12 with 3 m/s.

It is shown that when after activation the heat release rate decreases to a certain level, e.g. 150 kW – 200 kW, the soot yield increases significantly with time. Fortunately this period is very short and also corresponds to small heat release rates. Therefore the contribution to the smoke production rate is limited even if the soot yield is so high.

Figure 13  Comparison of soot yield in free burn and fire suppression tests (PE crib).

Again, it should be kept in mind that after activation, the soot measurement does not only measure soot but also water droplets. Therefore the data can only be considered as upper limit for the soot yield.

Visibility at mid tunnel height in PE crib fires
Figure 14 shows comparisons of visibilities at mid tunnel height in the free burn test and fire suppression tests for velocity of 1.5 m/s and 3 m/s, respectively. The minimum visibility in the free-burn test is the lowest. The deviation in visibility between the free burn test 3 and test 8 in Figure 14
at the early stage correlate well with the deviations in the heat release rate curves. Therefore during the whole period, it can be concluded that the free-burn test is the worst case.

![Graph showing comparison of visibility in free burn and suppression tests.](image)

**Figure 14** Comparison of visibility in free burn and suppression tests (PE crib).

**CONCLUSION**

The CO yields in the free burn tests tend to decrease slightly with the ventilation velocity and the time. In tests with fire suppression, the CO yields generally increase with the decreasing heat release rates. In tests with later activation after the heat release rate decreases to around 100 kW to 200 kW (3 MW to 6 MW at full scale), significant increase (3.5 to 4.5 times increase) in CO yield could be observed, especially for wood pallet fires. Note that without activation of the water spray system the fires could develop up to 1800 kW (57 MW) to 3200 kW (100 MW). In other words, production of CO mainly occurs when the fire is close to the extinguishment. However in most tests with suppression, the contribution of the high CO yield to the CO production rate is limited as the corresponding heat release rates are at a low level. Given that the maximum CO concentration at mid tunnel height (10.6 m downstream, corresponding to 42 m at full scale) in the free burn test is still the highest for all the fuels and velocities tested, the free burn tests could still represent the worst scenarios. Further, early activation reduces the CO concentration significantly.

The soot yields in the free burn test tend to decrease with the ventilation velocity and increase with time. When the heat release rate decreases to a certain value, e.g. 150 kW – 200 kW after activation, the soot yields increase significantly with time. Fortunately this period is very short and also corresponds to small heat release rates. Therefore the contribution to the smoke production rate is limited even if the soot yield is high. In all the tests the maximum soot production rate in the free-burn test is the highest.

The visibility in the free burn tests for all the fuels is generally the lowest compared to fire suppression tests due to that the heat release rate decreased immediately after activation of the fire suppression system.

In summary, test results of CO concentration at the early stage indicate that in most cases, the free burn test corresponds to the worst scenario despite that in the decay period of a fire with late activation the CO concentration could be higher. Further, test results of visibility show that that the free burn test corresponds to the minimum value.

It is observed that wood pallet fires behave differently compared to the PE crib fires. In the wood crib tests with late activation, the CO concentration in the decay period is slightly higher than that in the free-burn test. The difference in the CO yield between free burn and suppression tests is, however, much larger.
Polyurethane (PUR) crib fires were also tested and similar trends as the PE crib fires can be found in the report [15].

Based on the test data and the above analysis, it can be concluded for the fires tested that low-pressure fire suppression does not cause significant adverse effect in case that the fire can be effectively suppressed after activation, that is, the fire size has been reduced to less than at least 40% of that in the free-burn test. To achieve this goal an early activation is required. In case that the fire is not effectively suppressed the CO concentration and visibility could be much worse than in the free-burn test.

Therefore, from the point of view of production of combustion products, only fire suppression systems with sufficient capability and early activation are recommended to be used in tunnels.

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ABSTRACT

One of the most dangerous fire events that can happen in road tunnels is a fuel tanker fire, when flammable or combustible liquid fuel spills on the tunnel roadbed and catch fire. The fire develops extremely fast, with its size directly dependent on the size of the liquid pool on the roadbed surface. The tunnel roadbed is never flat and is usually sloped both longitudinally and transversely (cross slope). While there have been some attempts to evaluate the fuel pool size on a flat or longitudinally sloped surface, there is no methodology of evaluation of fuel pool size, fire zone length and fire heat release rate on a sloped roadbed surface. While there is some controversy as to the exact heat release ratio for a given fuel type and fuel depth, very little experimentation has been performed or documented on fuel flow across an unbounded sloped surface. This paper presents results of the scaled tests that measure the size, shape and depth of water and fuel on a sloped road surface. A 1.2 m x 1.2 m (4 ft x 4 ft) section of concrete surface representing a concrete road was built, and flow tests were performed on the sloped surface with water and gasoline at different flow rates, at different slope and roughness of the surface. The test data was used to determine the liquid pool area based on the flow rate. This data shows that the geometrical shape of the pool remains proportionate for the different parameters tested. Since this is an unbounded experiment the test results can be directly applied to a fuel spill on a sloped surface (roadway) by adjusting the fuel flow rate. This flow pattern and flow dynamics were then used to calibrate a CFD model that emulated the flow pattern of the liquid fuel across an inclined concrete road surface. Using the calibrated CFD model and standard drainage calculations the drainage system can be designed to limit the size of the pool of liquid fuel.

KEYWORD: Tunnel Fire Size, ISTSS, Fuel Pool Development in Tunnel and Drainage as a Means to Mitigate Tunnel Fire Size

INTRODUCTION

There was the Tunnel Fire in California at Interstate 5 and Hwy 2 on July 13, 2013, when flammable liquid fuel estimated at 28,390–32,933 L (7500-8700 US gal) of gasoline spilled and burned for 2 hours. This event reminded us of the highest risk of such fires and the need to study the liquid fuel spill fire dynamics.

Two problems can be identified from a liquid fuel spillage causing fire in the tunnels:

- Fire pool development, fire size and fire dynamics which were studied by Ingason [7] and Mealy et al [5].
- Tunnel drainage as a mitigation means to reduce fire size by capturing fuel spill is addressed in more detail in this paper.

There has been previous research conducted to understand the spill and burning dynamics of these types of scenarios [1, 2, 3, 7]. It is well known that the size of liquid fuel pool fire is proportional to the pool area. Ingason demonstrated that the pool and fire size is mainly controlled by the flow rate of fuel from a damaged tanker, the flow characteristics, the slope and roughness of the road surface and the design of the drainage system [7]. The heat release ratio and thus the size of the liquid fuel fire also depends on the depth of fuel layer, but this phenomenon is out of the scope of this paper. NFPA
502 [1] recognizes that drainage system can be very effective in capturing spilled fuel and can aid in reduction of the fire size. There is known experimental data and the empirical Manning equation also known as the Gauckler–Manning formula [4] developed in Europe back to 1890, which allow for the evaluation of the drainage once it is channelized (gets to the side of the road) and is being conveyed as gutter flow. There are also some known studies on liquid fuel flow when dropped on a flat plate [5] and small scale experiments [7] but very little experimentation has been performed or documented on fuel flow across an unbounded sloped surface. For this reason this paper concentrates on the development of the area of the flow and its development based on the slope of the road and flow rate prior to becoming channelized.

In the case of a flammable liquid cargo incident in the tunnel that involves a fuel spill on the roadway that catches fire, it is important to capture spilled fuel within the fire zone in order to prevent fire propagation. The fuel leakage flow depends on the diameter of the hole and the fluid pressure at the hole (fuel flow rate) of the damaged tank. Effect of leakage fuel flow diameter and drainage rate on the fire size of fuel tankers was published in PIARC documents [3]. If a fire suppression system is used to protect the tunnel, the water discharged from sprinklers and hose valves also has to be collected and conveyed through the drainage system without flooding the roadway; a clear path of access for emergency vehicles has to be maintained at all times. The drainage conveyance and collection system are designed based on requirements from Section 7.12.2 and 7.12.5 of NFPA-502 (2014 edition) [1] and Urban Drainage Design Manual (HEC-22). Standard hydraulic equations which can be found in HEC-22 are utilized to perform the drainage calculations [2].

**SCALE TEST DESCRIPTION**

The scaled test module was designed to emulate a concrete road. A 1.2 m (4 ft) by 1.2 m (4 ft) section of concrete pavement mounted on an adjustable table was constructed (see Figure 1). The table size was selected due to constructability constraint and required to be a sufficient size to evaluate the fully developed flow. A table was constructed that could hold the concrete pavement, and it was made so that it was adjustable for different road slopes from flat to 10%. A level and leveling blocks were used to set the slope of the table. The surface was originally finished with a broom finish to emulate a rough, worn road surface. After the rough surface tests were completed a smooth (traweled finish) concrete surface was added, and the tests were repeated.

The table was built with sufficient stiffness (plywood and wood braces) to maintain a flat surface without sagging. 5.04 cm (2 inches) of concrete was poured on top of the surface and a broom finish was applied. A 2.54 cm (1 inch) by 2.54 cm (1 inch) grid was placed above the surface so that the flow pattern could be accurately measured. Nails and string were used to form the grid for repeatability and accuracy of measurements. Slots were cut in all 4 legs with washers and bolts so that each leg could be raised independently, and a level was used to ensure proper slope. The slope height for the length of the level was calculated, and blocks of wood were cut at the precise height; each time the table was releveled the blocks were used for accuracy and repeatability.

The liquid fuel flow has to be calibrated and repeatable. A bucket attached to a guillotine at a fixed height was used for every experiment. A 1.26 cm (½ inch) diameter hose was connected to two ball valves in series for repeatable flow tests. The first ball valve was used as a shut off valve and the second one was used as a flow regulating valve. The regulating valve, a calibrated rod and a stopwatch were used to calibrate and set the flow rate. The flow discharge valve system was held in place by a brace that could be rotated 180 deg. By rotating the brace to the back the flow could be emptied into a bucket, while using the calibrated rod (tick marks every 1.26 cm (½ inch)) and the stopwatch, the regulating valve was adjusted until the correct flow was achieved. Once the flow rate was calibrated the brace could be rotated back to the test table to run the tests.

Initial tests were performed with water and the results recorded. The tests were repeated with unleaded gasoline that contained 10% ethanol. All data was recorded, plotted (See Figure 5 through 11) and used for calibration of a CFD model.
Once the table slope and the flow rate were set, the fluid was released at 2.5 cm (1 in) above the surface to simulate the potential failure of a small diameter fuel line or damage to a delivery hose flange on the bottom of a fuel tanker. This does not represent a complete destruction of a delivery hose that would give a hole diameter of 100 mm (3.9 in). Each test was repeated a minimum of 3 times and the data recorded (see Table 1 and Table 2).

**EXPERIMENTAL RESULTS**

Scale tests of fuel flow across an unbounded sloped surface were performed to measure size, shape and depth of water and fuel. The resultant wetted area can be seen in Figures 2 and 3. Figure 2 shows results of tests at 5% road slope with water flowing at 0.0631 L/s (1 gpm) on rough and smooth surfaces. It appears that the wetted surface area for the smooth surface is wider than for the rough surface. While the increase in width is not significant the smoother surface is better defined and slightly more conservative which is why the following figures and graphs are based on the smooth surface data instead of the rough surface data. From Figure 2 one can see that the back flow of 12.7 cm (5 inches) is similar for both rough and smooth surfaces. However, 12.7 cm (5 in) down from the discharge point the plume development is wider for the smooth surface than for the rough surface (55.9 cm (22 in) vs 43.2 cm (17 in) respectfully). Note that the hydraulic jump and the backflow of the fluid when it impacts the sloped surface, as well as the development of the flow pattern, are very similar to the results obtained by Ingason [7].

Figure 3 shows gasoline test results at 5% and 7% slopes. The results show that a flatter slope produces a wider wetted area, which results in a larger pool area. The pattern of the gasoline pool is similar to the water pool, however, the difference in wetted area width is slightly less.

The experimental results presented in this paper are consistent with the experimental results found by Ingason [7]. Specifically, Ingason [7] provides an equation showing that the flow width correlates to the flow rate and that the plume area is correlated to the slope. The experimental results, summarized in Table 1 and Table 2, support the statement that the flow width correlates to the flow rate while Figure 14 shows the plume area correlating to the road slope. Ingason [7] goes on to state that the test width is nearly independent of the roadway slope. Figure 4 and Figure 6 (water) agree with the Ingason [7] statement showing only minor changes in the flow width between 3% and 5% of road slopes. In contrast, Figure 8 (gasoline) shows more distinctive flow widths within the range of road slopes than Figure 4 and Figure 6 and indicates that the slope does correlate to a change in width. Equations (1) quantify the relationship between the width of the flow and the distance away from the point of the
spill, but do not attempt to correlate the empirical coefficients based on changing the slope and flow rate. An equation for flow rate versus the flow width is presented by Ingason [7]. Although such an equation is not presented in this paper, Figure 10 shows an extrapolated curve for a projected flow rate of 12 L/s (190 gpm). The extrapolation has been achieved by manipulating Manning’s formula [4] under the assumption that the velocity and final flow depth for a given surface slope, and all other parameters except for the flow rate are identical.

Test data shown in Figures 4 and 6 was used to develop the empirical equations (1) that produce a smooth curve fit through the data points. Integration of the developed equations (1) results in the area curves shown in Figures 5 and 7.

The summarized gasoline test results used for developing relations between flow and the wetted area (width) as a function of slope are presented in Figures 8 and 9. The empirical constants for the equations (1) to be used with gasoline were developed based on the test data shown in Figure 8. Integration of the developed equations (1) results in the area curves shown in Figure 9.
The general equations describing the width of the plume $Y$ along the length of the roadbed surface at a distance $X$ from the spill for different roadbed slope and roughness surfaces were developed based on the tests results for water and gasoline (Equations 1).

$$ \text{Width } y = C \ast (1 - e^{(-k \cdot X)}) $$

$$ \text{Area } A = C \ast (x + (1/k) \ast e^{(-k \cdot x)} - 1/k) \quad (1) $$

Empirical coefficients $C$ and $K$ were developed from the tests results. Coefficient $C$ for water varies from 33.7 to 37.2, while coefficient $K$ varies from 0.073 to 0.093 for 7% slope and 3% slope respectfully. For gasoline coefficient $C$ varies from 40 to 42, while $K$ varies from 0.046 to 0.1 for 3% slope and 7% slope.

Figures below show that the steeper grade the less the wetted area is and that the wetted area increases further away from the spillage source. 90% of the maximum pool width is achieved shortly downstream from the spill point (approximately at the same distance as the back flow distance). The data points and the smooth fit of the curves show that the asymptotic line for the 0.06 L/s (1 gpm) and 0.012 L/s (2 gpm) was reached within the experiment physical boundaries of 0.7 m (2 ft) (effective test area).
Figure 4: Water plume width with 0.12 L/s (2 gpm) at 3%, 5% and 7% slope

Figure 5: Wet Water Area with 0.12 L/s (2 gpm) at 3%, 5% and 7% slope

Figure 6: Water Width 0.06 L/s (1 gpm) at 3%, 5% and 7% slope

Figure 7: Water Area 0.06 L/s (1 gpm) at 3%, 5% and 7% slope

Figure 8: Gasoline Plume width vs flow length 0.12 L/s (2 gpm) at 3%, 5% and 7% slope

Figure 9: Gasoline Plume area vs flow length 0.12 L/s (2 gpm) at 3%, 5% and 7% slope
CFD Analysis for Free Flow

The tests results were used for CFD model calibration. The CFD model was calibrated based on the conditions of the experiment and used for a full size problem. The full size problem represents the liquid fuel spill design flow rate of 12.0 L/s (190 gpm) which corresponds to 5.6 kg/s (12.3 lb/s) and represents a 50 mm (1.9 in) equivalent diameter of leakage hole in a tanker spill on a road [6]. Road slope with 4% and 2% cross slope were simulated to estimate the shape and size of the fuel plume on the actual roadbed of a tunnel. Blue dots on Figure 10 represent discreet points obtained from the CFD output while the red curve shows the approximation equations (1) with C=4.7 and K = 0.15. Figure 11 shows the area of the plume spread along the tunnel with smooth concrete roadbed surface area.

![Plume Width vs. Area (12 L/s(190 gpm)Gasoline, Smooth Concrete)](image)

Figure 10: CFD Gasoline Plume width vs flow length 12 L/s (190 gpm) at 3%, 5% and 7%
Volume of fluid (VOF) method was applied in the CFD analysis to model the gravity current on the surface. VOF is an Eulerian fixed-grid method which models surface tension and wall adhesion as an additional source term in the momentum equation. Standard wall function was used for road surface. The mesh size was approximate 0.8 mm, which is ten times less than the resultant surface roughness.

The smooth surface experimental tests correspond to 9 mm (0.03 ft) roughness of the surface in the CFD model. The design fuel flow rate of 12 L/s (190 gpm) was then applied to the design tunnel road slope to obtain the area of the fuel spill. The empirical coefficients in equations (1) were extrapolated. The value of $k$ is based on slope and fluid viscosity and is not as easy to solve for or extrapolate for the experimental values.
The result of a plume area of 121 m² (1,300 ft²) is utilized to determine the maximum fire Heat
Release Rate (HRR), the tunnel drainage design and a fixed fire suppression system (minimum
required suppression density which was calculated to be 0.0217 L/s-m² (0.32 gpm/sf) to control the
fire size).

It is well known that the size of liquid fuel pool fire is proportional to the pool area. It also depends on
the depth of fuel layer, but this phenomenon is out of the scope of this paper. The following is a
sample figure which shows the design fire size as a function of roadbed longitudinal slope and
roadbed cross slope. These figure were developed for a sample 2-lane tunnel (10 m or 30 ft wide) with
a 30 m (100 ft) long fire suppression zone and gasoline fuel spill. The example demonstrates that the
design fire size heavily depends on the roadbed cross slope and longitudinal slope. For a 4% road
slope and 1% cross slope the fuel flows down the road and out of the zone prior to reaching the side of
the road. Note that the results can be considered conservative as the depth of fuel layer was not taken
into account in the sample calculations and its impact on the fire size requires additional studies.

![Figure 13: Sample Gasoline Fire HRR from pool fire as a function of Longitudinal Road Slope at
Constant Tunnel Cross Slope of 2%](image-url)
Figure 14: Sample Gasoline Fire HRR from pool fire as a function of tunnel cross slope at Constant Longitudinal Road Slope of 4%

The example shows that tunnel slope and drainage design has a significant impact on the design fire size. The cross slope of the tunnel from 1% to 4% can reduce the liquid pool design fire size 3 times, which has a significant impact of tunnel fire life safety systems design. This is based on the premises of effective drainage system.

Tests and CFD analysis results allow for evaluation of liquid pool size and flow pattern, which provides essential information for the tunnel drainage design.

ROAD TUNNEL DRAINAGE TO CONTROL POOL FIRE

Drain inlets shall be coordinated with the sprinkler zones if fixed firefighting system is provided for road tunnel. The road tunnel drainage design is based on the approach that each drain inlet shall capture 100% of spill fuel flow to prevent fuel and fire propagation along the tunnel to the next zone. In addition each drain inlet shall capture 50% of fuel and firefighting flow and prevent tunnel from flooding.

Drainage Inlet Capacity Calculation:

The roadway slope and flow patterns obtained from model tests are used to determine the amount of water and fuel flowing into each drainage inlet. For each drainage inlet, two types of flows are considered: the mix of suppression system water flow and fuel spill along the curb ($Q_1$), and sprinkler system water directly flowing towards the curb opening ($Q_2$). Equation (2) shows the relationship of the different contributing flow areas to the total flow. Figure 15 shows the schematic drainage diagram for a tunnel with 4% longitudinal slope and 2.2% cross slope and provides a schematically representation of equation (2). The water directly flowing towards the drainage inlet has two components: the water that flows towards the trench with a depressed curb opening ($Q_{2'}$) and the water that flows towards the grate with a non-depressed curb opening ($Q_{2''}$).
\[ Q_{1i} = \alpha A_1 + Q_{fs} + Q_{hv} \] 
\[ Q_2 = Q_2' + Q_2'' = \alpha A_2 \] 
\[ Q_{1Tc} = \text{minimum of } (Q_{1c} + Q_2'), Q_{curb}, Q_{trench} \] 
\[ Q_{1b} = (Q_{1i} + Q_2') - Q_{1Tc} \] 
\[ Q_{TB} = Q_{1b} - Q_{grate} \] 
\[ Q_{TI} = Q_{1i} + Q_2 \]

where:

- \( Q_{1i} \): Total incoming water and fuel spill flow along the curb, m\(^3\)/s (ft\(^3\)/s) (see Figure 15)
- \( Q_2 \): Total incoming water directly flowing towards the drainage inlet, m\(^3\)/s (ft\(^3\)/s)
- \( Q_2' \): Total incoming water directly flowing towards the trench, m\(^3\)/s (ft\(^3\)/s) (see Figure 15)
- \( Q_2'' \): Total incoming water directly flowing towards the grate, m\(^3\)/s (ft\(^3\)/s) (see Figure 15)
- \( A_1 \): Area affected by sprinklers, fuel and hose valve, m\(^2\) (ft\(^2\)) (see Figure 15)
- \( A_2 \): Area affected by sprinklers only, m\(^2\) (ft\(^2\))
- \( \alpha \): Sprinkler discharge rate, for example 0.000217 m/s (0.000713 ft/s) based on density of 0.217 L/s-m\(^2\) (0.32 gpm/ft\(^2\))
- \( Q_{fs} \): Flow rate of fuel spill, m\(^3\)/s (ft\(^3\)/s)
- \( Q_{hv} \): Flow rate of hose valve, m\(^3\)/s (ft\(^3\)/s)
- \( Q_{1c} \): Captured portion of \( Q_{1i} \) at trench, m\(^3\)/s (ft\(^3\)/s)
- \( Q_{1Tc} \): Total captured portion of \( Q_{1i} \) and \( Q_2' \) at trench, m\(^3\)/s (ft\(^3\)/s)
- \( Q_{1b} \): Bypassed portion of \( Q_{1i} \) and \( Q_2' \) at trench, m\(^3\)/s (ft\(^3\)/s)
- \( Q_{curb} \): Total drainage capacity of depressed curb opening, m\(^3\)/s (ft\(^3\)/s)
- \( Q_{grate} \): Total drainage capacity of grate, m\(^3\)/s (ft\(^3\)/s)
- \( Q_{TI} \): Total incoming flow rate towards curb opening: sum of \( Q_{1i} \) and \( Q_2 \), m\(^3\)/s (ft\(^3\)/s)
- \( Q_{TB} \): Total bypassed portion of \( Q_{1b} \) at grate, m\(^3\)/s (ft\(^3\)/s) (see Figure 15)

Manning’s equation for uniform open channel flow [4] can be used to evaluate the spread of gutter flow along the curb (\( Q_{1i} \)), which will be unique for each gutter configuration. The equation can also be used to size the drain conveyance.

CONCLUSIONS

Roadbed slope – longitudinal, and especially cross slope, are important factors for evaluation of flammable liquid fuel fire size, length of the fire zone and the tunnel drainage system design. Our scaled fuel flow experiment with different slopes and roughness of the flow surface, as well as different flow rates for water and liquid fuel was performed to calibrate the CFD model. The size and the shape of a fuel spill on a roadbed obtained from this analysis was used to calculate the design fire size, to determine the fire suppression zone length, and to set the required water flow rate for the fixed
fire suppression system. Sample calculations demonstrated that the design fire size can be reduced 3 times with an increase of the tunnel cross slope from 1% to 4% (see Figure 14) and with an adequate drainage system design. The roadway slope and flow patterns obtained from the model tests were used to determine the amount of water and fuel flowing into each drainage inlet.

The surface roughness of concrete does not play a major part in the plume area for the tested flow rates and slopes.

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Studies on Fire Spread in Road Tunnels

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ABSTRACT

Fire incidents are among the most relevant for people in a tunnel. Therefore, it is important to be sufficiently prepared for such events. A large scale fire test is to be used to help evaluate the initial burning duration and the time it takes for the fire to spread to other vehicles in the tunnel, and in particular how long it takes for a truck carrying wooden pallets to catch fire, taking into consideration the extremely high temperatures. The goal, therefore, is to determine the time it takes for a fire to spread to other vehicles in the tunnel.

In the large scale fire test, an accident in a tunnel with one-way traffic is simulated between a truck loaded with approximately 3.7 t of wooden Europol pallets and a passenger car. Directly behind each of the vehicles involved in the accident there is another car which stops at a distance of 1.0 m. Approximately 300 litres of burning diesel are discharged from the truck's fuel tank, which is simulated by using approximately 400 litres of isopropanol. A 10 m² burning pool forms underneath the truck. Other objectives of the large scale fire test are the validation of the CFD models and the evaluation of the progression of the thermal release ratios estimated for the simulation. The thermal release ratios generated in the test are determined and evaluated using various models.

KEYWORDS: tunnel, fire, security, critical infrastructure, large scale test, simulation, protection

INTRODUCTION

Massive spalling can occur in "normal" concretes as a result of a fire load so that the stability is at risk under certain circumstances. Because tunnels are very special infrastructures, the evaluation of the consequences of fire events is of importance not only from an engineering but also from an economic point of view. Such a fire event is, for example, a tanker loaded with petrol that catches fire in a tunnel and whose burning load escapes and spreads through the tunnel according to its topology (so-called pool fires) and may ignite further vehicles in the tunnel. These scenarios have been evaluated within the scope of a BASf research project, during which a full-scale tunnel fire test is performed [1].

If the petrol escapes at high speeds (> 200 kg/m²) the duration of the fire of the initial burning pool from an accident tanker is relatively short at 5-8 minutes. A large scale fire test is to determine. Amongst other things, the time the fire needs to spread to other vehicles in the tunnel, in particular to a truck loaded with wooden pallets and a car is determined. The large scale fire test also served to validate the CFD models used to simulate tunnel fires and their assumed heat release rate (HRR) curves.

And finally, the test should clarify whether very small burning pools (approx. 10 m²) that only burn for a short time, which can result from the diesel that escapes from a truck tank, would be enough for the fire to spread to the load of the same truck or to other vehicles nearby.
TEST SCENARIO
The test simulated an accident in a one-way traffic tunnel between a truck (DAF, gross vehicle weight 11 t) loaded with approx. 3.7 t of wooden Europool pallets and a car. Two further cars stop directly behind the vehicles involved in the accident at a distance of 1.0 m. The leakage of approx. 300 litres of burning diesel from the truck's tank is modelled by approx. 400 litres of isopropanol. The pool was realised by 10 fire troughs of 1 m² each, in which the isopropanol was equally distributed. The filling level was approx. 40 mm. With an average combustion rate of 5.0-5.5 mm/min (see [2]) one can assume a pool fire duration of 7-8 minutes.

Figure 1  Test tunnel with vehicles

The fire test was performed in the test tunnel of MFPA Leipzig GmbH. The tunnel has a rectangular cross-section with a width of 6 m and height of 5 m as well as a length of 35 m (see Fig. 1 and Fig. 2). The ends of the tunnel were closed with smoke aprons up to a height of 2.5 m above the ground for the fire test. The test tunnel also has three chimneys, each of which is along the linear axis at the quarter points of the structure. They discharge the fumes to the atmosphere up to 2 m above the roof of the tunnel and have a free cross-section of 2 m x 2 m.

The truck that was loaded with 170 Europool pallets had an unloaded weight of 5100 kg and a total weight with pallets of 8800 kg. At the end of the test the truck's mass was 4422 kg. This means that along with the pallets, 678 kg of combustible material from the truck was also burnt. In addition, 3 mid-range cars were brought in position, a VW Golf (weight before/after test 1060/860 kg), a Ford Mondeo (weight before/after test 1303/1074 kg) and a further Ford Mondeo (weight before/after test 1236/1004 kg). The total weight loss for the cars was thus 661 kg. Assuming an average calorific value of approx. 37 MJ/kg for the burning parts of the cars and truck, and assuming a combustion efficiency of 1.0, the resulting fire load is

\[ E = 400 \cdot 0.785 \text{kg/m}^2 \cdot 31 \text{MJ/kg} + 3700 \cdot 17.3 \text{MJ/kg} + 678 \text{kg} \cdot 37 \text{MJ/kg} + 661 \text{kg} \cdot 37 \text{MJ/kg} \approx 123 \text{GJ} \] (1)
TEST PERFORMANCE

The heat release rates over time were estimated in preparation for the test. A "natural" fire development acc. to [3] (natural fire model) was hereby assumed for the cars and truck. The plateau phase was taken into account by a heat release rate of 5.5 MW. The assumed fire load is approx. 7.5 GJ and roughly corresponds to 200 kg of flammable equipment. A maximum heat release rate in the full fire phase of 35 MW was assumed for the truck loaded with wooden pallets and a fire load, incl. cargo, of 85 GJ was assumed. The fire load of the isopropanol is calculated acc. to

\[ E_{\text{theor}} = \Delta H_u \cdot V_{Iso} \cdot \rho_{Iso} \]  

the energy available for the fire and is 9.7 GJ for the fire tests performed with the values \( \Delta H_u = 31 \text{MJ/kg} \), \( V_{Iso} = 400/ \) and \( \rho_{Iso} = 785 \text{kg/m}^3 \). The heat release rate in the full fire phase, assuming the average combustion rate determined in [2] of 5.5 mm/min, is 27 MW.

In order to determine the key fire parameters such as heat release rate, gas and component temperatures and heat flux density, more than 200 measuring points were installed in the tunnel. Sheathed thermocouples of the type K (Ni-Cr / Ni-Al) acc. to EN 60584 (DIN IEC 584) were used to measure the gas temperatures in the ceiling areas of the tunnel and in the chimneys. The differential pressures at the ends of the test tunnel and in the chimneys could be determined with differential pressure sensors. The differential pressure probes were connected to pressure sensors.
Three gas measuring instruments were used to measure the oxygen, carbon monoxide and carbon dioxide proportions in the fumes.

**Table 1  Test observations**

<table>
<thead>
<tr>
<th>Minute of test</th>
<th>Observation</th>
<th>Photo documentation</th>
</tr>
</thead>
</table>
| 0.             | START OF TEST  
Ignition of fire troughs                                                  |                     |
<p>| 1.             | All troughs burning. The flames reach the wooden pallets and shortly afterwards the tunnel ceiling for the first time. |                     |
| 2.             | The wooden pallets and the two cars at the side of the truck catch fire. A very large amount of smoke is produced. |                     |
| 3.             | The car behind the truck has not yet caught fire.                            |                     |</p>
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.+5.</td>
<td>Flames come out of chimney B. Two cars and the truck are burning almost completely. The pallets are completely engulfed in flames. A lot of smoke comes out of all the chimneys.</td>
</tr>
<tr>
<td>6.</td>
<td>All of the cars and the truck are burning. The pallets are completely engulfed in flames. The full fire phase begins. The hydraulic cylinders of the loading flap are destroyed.</td>
</tr>
<tr>
<td>12.</td>
<td>All of the vehicles, incl the load, continue to burn fully.</td>
</tr>
<tr>
<td>25.</td>
<td>The intensity of the fire continues to decrease. The cars are still burning, but not as intensely.</td>
</tr>
<tr>
<td>30.</td>
<td>The cars alongside the truck and the truck's cab are almost burnt out.</td>
</tr>
</tbody>
</table>
The wooden pallets have collapsed completely and continue to burn less intensely. The car behind the truck has also burnt out almost completely.

TEST EVALUATION

Fig. 3 (left) shows the mean temperature curve for all 20 measuring points arranged approx. 10 cm below the ceiling as well as the minimum and maximum temperature curves over time. The full fire phase that can be observed during the test is very clear from the temperature curves.

![Temperature Curves](image)

Figure 3  Left: Mean, minimum and maximum gas temperature curves over time 10 cm below the tunnel ceiling; Right: Mean gas temperature curves over time in chimneys A, B and C

The heat release rate (HRR) was determined on the basis of the results of the aforementioned sections. Four fundamentally different methods were used:

- the temperature proportionality method,
- the enthalpy method,
- the oxygen consumption method,
- as well as a so-called "natural" fire development acc. to [3] (natural fire model).

The temperature proportionality method that was already used in [2] is based on the considerations of Hildebrandt and Wilk [5]. A direct proportionality between the curve for the gas temperatures in the test tunnel and the heat release rates was taken as a basis so that the development of the heat release rate can be determined with the aid of the measured temperature curve. This approach has been partly expanded. Whereas a part of the energy released in the first minutes of the test heats up the overall mass in the tunnel (the non-combustible parts of the vehicles had an overall weight of approx. 7500 kg) and the materials used to build the tunnel, these heated up masses release their heat again at the end of the test and thus increased the gas temperature. With a "natural" fire development acc. to [3] it is assumed that the full fire phase ends when approx. 70% of the combustible mass (thus approximate-
ly 70% of the fire load) has been burnt. If these findings are transferred to the temperature proportionality method and it is postulated that, to be on the safe side, only 60% of the total fire load has to be burnt at the end of the full fire phase, and at the same time it can be guaranteed that 40% of the fire load is converted in the decay phase (principle of the conservation of energy), the result is the so-called modified temperature proportionality method.

The enthalpy method determines the heat release rate with the aid of the enthalpy flows measured in the inlet and outlet openings of the test tunnel and thus via the heat content (enthalpy) of the gas at certain times. This method has already been used in the tunnel fire tests for the EUREKA project [6] and is described in more detail by JANSSENS [7].

The oxygen consumption method, that can be used to determine the heat release rate, is based on the oxygen consumption as a result of the fire and is determined with the aid of the measured gases O₂, CO₂ and CO. Various methods that take gas shares into account either fully or in part are described in DIN 18230 2 [8]. Since no useful data for the composition of the fumes chimney B can be obtained from the measurement, this method was carried out twice and separate from each other, assuming that

- the composition of the fumes in chimney B corresponds to the relevant mean of the fume shares of chimney A and C, and
- the composition of the fumes in chimney B corresponds to the minimum value (min) of the fume shares of chimney A and C.

Since there is only a relatively minor difference between the heat release rate curves over time that were determined, the mean curve is also shown.

With a so-called "natural" fire development the heat release rate is determined and superimposed on the basis of the combustion periods and fire intensities observed for each share during the fire test. Fig. 4 (left) shows the computed heat release rate curve in accordance with the aforementioned methods.

Once the heat release rate had been determined by various methods, the total released energy was then determined, i.e. the fire load, as a control.

This was done using the relationship

\[ E = \int \dot{Q}(t) \, dt \]  \hspace{1cm} (3)

The result of the integration of the different fire curves is also shown in Figure 4 (left). The theoretical value of the total released energy is \( E = 123 \) GJ.

Since the principle of energy balance is used to determine the curves in both the original and on the modified temperature proportionality method, as well as for the "natural" fire development, the deviation is a priori zero. It can be seen that the fire load was overestimated by approx. 20% with the oxygen consumption and enthalpy methods, resulting from the accumulation within the tunnel structure. At the same time, there is a good correlation between the results so that it can be concluded that the assumptions made on account of measured variables that cannot be evaluated are reasonable. The oxygen consumption method thus shows a maximum upper limit that probably differs by more than 10%.

An upper (oxygen consumption method) and a lower limit (temperature proportionality method) for the fire development can be estimated for the heat release rate. The lower limit hereby assumes a simplification of the fire development. The total released energy up to the end of the full fire phase thus tends to be underestimated. The upper limit, on the other hand, does not comply with the principle of energy conservation, i.e. the method used of oxygen consumption calorimetry and/or enthalpy flows overestimates the heat release rate.
The heat release rate in the full fire phase, which last from approx. the 5th minute of the test to approx. the 20th minute of the test, can be estimated to be approx. 75-80 MW from the curves shown in Fig. 4 (left). A plateau forms, as is also assumed with a "natural" fire development acc. to [3]. The HRR displays an exponential drop in the decay phase. The fire development phase can be approximated by a linear curve.

The distribution of the heat release rate between the isopropanol, the truck loaded with wooden pallets and the cars can be roughly estimated from the calculations of the heat release rate curve and the observations made during the test. These shares are shown separately in Fig. 4 (right).

**Figure 4:** Left: Computed heat release rate acc. to the oxygen consumption method (blue), enthalpy method (black) as mean of the grey curves, original temperature proportionality method (dark red), modified temperature proportionality method (red) and the "natural" fire development (green); Right: Possible heat release rate curves for the isopropanol, the truck loaded with wooden pallets and the cars

**Figure 5** FDS model of the full-scale tunnel fire test
SIMULATION

The test data is now taken to validate the CFD program (FDS) in use. To this end, all available geometric and meteorological data as well as the estimates for the HRR curves (see Figure 3 (right)) are taken into account. Figure 5 shows the FDS model. ¼ of the tunnel has been modelled as completely transparent for a better visualisation only.

The computed temperature-time curves for the temperatures in the ceiling area and in the chimneys as a result of the simulation are shown in Figure 6. A comparison with Figure 3 shows a relatively good consistency of the results. It can therefore be concluded that the validated CFD models are able to predict the consequences of tunnel fire incidents well. The validated CFD models are used, amongst other things, to determine the influence of the tunnel geometry and topology on the temperature-time curve.

CONCLUSION

By means of a large scale tunnel fire test it could be shown that even spatially restricted pool fires (10 m² in the test) result in very high temperatures with steep rises in temperatures and that the fire can spread to other vehicles within a matter of minutes (approx. 2 minutes in the test). It was possible to determine the energy release rate over time with a good degree of approximation and a good correlation between the methods on the basis of the various approaches.

The test results were used to validate a CFD model so that the results could be transferred to other tunnel geometries and topologies with the validated CFD models.
REFERENCES


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Thermal Runaway Propagation Model for Vehicle Fires

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ABSTRACT

This paper proposes a thermal runaway propagation model to simulate the heat transfer and thermal decompositions of components and assembly incorporating the inherent chemical kinetics of the individual components provided by adiabatic calorimetry. Modelling the thermal decomposition and thermal runaway is an important tool in understanding thermal behaviour of the system under various operating conditions. One of the main objectives of the electric drive vehicles (EV) development is to provide longer battery runtime for the electronic devices and extend driving range for the EVs, which can be achieved by packing galvanic cells to enhance the energy content. The batteries for EV contain a higher amount of energy and operate in harsher environment comparing to other types batteries. They are exposed to large temperature variations, shock, vibration, as well as high levels of charge and discharge. Due to the increasing demand of the EVs, it is essential to understand the potential risk associated with this energy storage device, especially under abusive environment. Thermal runaway has been reported to be the common failure of batteries. Batteries undergo thermal runaway generate a high amount of heat, produce the smoke that may consist of toxic gases, and have the potential to cause fire and explosion. The evaluation of battery behaviour under abusive environment is normally carried out in purpose built adiabatic calorimetry. The tests include short-circuit, nail penetrating, thermal stability, crush and overcharge. However those tests are conducted using an individual cell. The performing full scale abuse tests remained to be dangerous, time-consuming and capital-intensive. This study is aimed at bridging some the gap between the individual cell tests and full scale tests. In this paper, the adiabatic calorimetry method was explored to establish the thermal decomposition kinetic parameters pre-exponential factor $A$, the activation energy $E_a$ and the activation energy and $\Delta H$, the reaction heat of thermal decomposition. The parameters and thermal decomposition rate $k = A \exp \left( -\frac{E_a}{RT} \right)$ are used for modelling the thermal decomposition to thermal runaway of the vehicle fires.

KEYWORD: thermal decomposition, thermal runaway, thermal decomposition kinetic model, vehicle fires

INTRODUCTION

As a part of the initiatives of reducing carbon emission and air pollution of transport sector, a range of vehicles with diverse powering systems are under development and start to emerge into the market. Example of such new types vehicles include the electric vehicles (EV), hybrid vehicles and hydrogen fuel cell vehicles. It is expected that those emerging vehicles will co-exist with the traditional internal combustion engine (ICE) powered vehicles in the short and medium term, and change the vehicle population patterns on the roads and in the underground parking facilities and tunnels. For the purpose of Quantitative Risk Assessment (QRE) of emerging vehicles on the underground parking and tunnels, it is important to develop numerical tools to predict the hazardous consequence of the vehicles. The objective of this paper is to explore using thermal lumped method to provide quantitative assessment of the fire scenarios from vehicles.
**Full-scale Vehicle Fire Tests**

Full scale fire test is very important to obtain the first hand information on the hazard level of vehicle fires. A series of full scale vehicle fire tests was carried out by Lecocq, et al (2014) [1] to establish the fire consequences of an electric vehicle and an internal combustion engine vehicle ignited by an external gas burner fired onto the front passage seat. The heat release rate and the effective heat of combustion from the fires were determined to assess the thermal impact of the fires. The comparison of the heat release rate from the fires showed that the overall heat release curves for EV and ICE cars have the similar pattern, the fires could be divided into three stages, namely the establishing, fully developed or sustained burning and then the decay stage. After a period of delaying time following the ignition, both EV and ICE fires established at an exponential rate to their peak heat release rate, then the heat release rates had a few fluctuations during the sustained burning stage, and finally both EV and ICE fires decayed at a similar rate and duration. The main difference between the EV and ICE car fires were the fluctuating peaks during the sustained burning stage of the fires. Some of the peaks were thought as the contribution by the powering systems, such as the battery package of the EV.

The fire and explosion hazards of the battery used in the EV has been well recognized. Thermal runaway has been reported to be the common failure of batteries. Apart from the external heating, overcharging, overdischarging, cell rupture due to crush or penetration damage could also lead to the battery thermal management failure and result battery induced fires. The consequence of battery induced EV fire scenarios could be different from the consequence of fire scenarios caused by external fire source as tested in [1]. For the quantitative risk assessment of EV fires in a tunnel or an underground parking, it is necessary to be able to assess the consequences of fire scenarios caused by various possible mechanisms. Full scale experimental tests of vehicle fires could provide the most valuable information on the fire load such as the heat release rate curves and the maximum heat release rate, however due to the cost it is not practical and sometime not possible to carry out full scale tests in many variations in testing conditions.

**EV and ICE Vehicles**

The EV and ICE vehicles differ in energy systems, but both types of vehicles share the same overall design technology to meet the requirements of comfort interior and comparable aerodynamic performance. Both vehicles are furnished to the same standards and specifications. Because the combustible furnish material contributed a large portion of the combustion heat in vehicle fires, the fire performance of the furnishing material would be similar for EV and ICE vehicles. Therefore, the qualitative assessment is focused on the battery hazards. One of the main objectives of the electric drive vehicles development is to provide longer battery runtime for the electronic devices and extend driving range for the EVs, which can be achieved by packing galvanic cells to enhance the energy content. The batteries for EDV contain a higher amount of energy and operate in harsher environment comparing to other types batteries. They are exposed to large temperature variations, shock, vibration, as well as high levels of charge and discharge. Due to the increasing demand of the EVs, it is essential to understand the potential risk associated with this energy storage device, especially under abusive environment. Thermal runaway has been reported to be the common failure of batteries. Batteries undergo thermal runaway generate a high amount of heat, produce the smoke that may consist of toxic gases, and have the potential to cause fire and explosion. The evaluation of battery behaviour under abusive environment is normally carried out in purpose built devices, such as the Adiabatic Calorimetry. The tests include short-circuit, nail penetrating, thermal stability, crush and overcharge. However those tests are conducted using an individual cell. The performing full scale abuse tests remained to be dangerous, time-consuming and capital-intensive.

This study is aimed at bridging some the gap between the individual cell tests and full scale tests. The study is aimed at development of kinetic modelling for the prediction of the thermal behavior of EV battery during thermal runaways utilizing the kinetic data from the thermal reactions and the results form battery cell thermal abuse tests. The paper firstly discussed the experimental methods used for determining the heat release rate and the adiabatic calorimetry for testing the chemical kinetics of material thermal runaway behavior. The objective is to develop a heat transfer model combining with the thermal runaway kinetic model to simulate temperature development of the combustible material.
and the sequence of thermal runaway events inside the vehicle following an ignition.

**THE EXPERIMENTAL TECHNIQUES**

**Estimation of rate of heat release by means of oxygen consumption measurements**
The commonly used method to establish the heat release history from a fire in tunnel is by measurement of the oxygen consumption during the fire using online gas analysis on the effluents [2-4]. The principle is based on the observation that although the heat released per unit mass of material consumed varied greatly, the amount of heat released per unit of oxygen consumed was fairly constant, the heat release rate per unit volume of oxygen consumed is approximately the same for a range of materials used to construct buildings and furnishings. Based on the observation, the oxygen consumption calorimetry technique was proposed to estimate the heat release rate of commonly materials found in fires by capturing all of the products of combustion in an exhaust hood and measuring the flow rate of oxygen in that exhaust flow to determine the oxygen depletion by the fire. The principle of oxygen consumption calorimetry was implemented in the cone calorimetry [5-9] and large scale fires tests to calculate the heat release rate [1], specially the maximum heat release rate. The accuracy of the method is discussed via considering the thermodynamic dates of the materials [5]. The accuracy also depends on the oxygen concentration measurement of the effluents.

Although the oxygen consumption method is very effective in determine the fire heat release rate from a fully established and fully developed sustained fire, however the method completely ignored the chemical reactions, it is less effective in the ignition stage of the fire, while the materials are dominated by the fuel thermal-decomposition and the oxygen consumption is low at this process. The thermal decomposition is normally studied in small sample using thermogravimetric methodology.

**Thermogravimetic Experiment and Adiabatic Calorimetry**
At the ignition stage of the fire, the solid combustible materials undertake thermal decomposition processes govern by the temperature of the solid bed. The thermal decomposition is controlled by either internal or external heat transfer, or, by the inherent chemical kinetics of the solid’s thermal decomposition. During the thermal decomposition, the volatile matter is released as gases (e.g, CO, CO2, H2 and hydrocarbons). One way of measuring the rate of decomposition is to continuously monitor the solid mass using the thermogravimetric experimental tests, whilst the temperature of the solid sample is elevated at a constant rate. The reaction rate of thermal decomposition can be evaluated by the Arrhenius law which is described as Eq1.

\[ k = A \exp \left( \frac{-E_a}{RT} \right) \]  
where \( k \) is the thermal decomposition rate, \( A \) is pre-exponential factor for the reactions, \( E_a \) is activation energy, \( R \) is the gas constant and \( T \) is the temperature of the solid material.

The kinetic parameters the activation energy and pre-exponential factors for the reactions can be deduced from the equation derived by Townsend and Tou [10] for an adiabatic process.

\[ \ln k = \ln A - \frac{E_a}{RT} \]  
Adiabatic Calorimetry is one of the experimental methods to assess the thermal decomposition behavior of batteries using the thermogravimetric principle. With increasing interest in lithium-ion batteries for auto-motive applications, there is need to a better understand the abuse tolerance of theses batteries and the consequence of these batteries during vehicle fires. The critical parameters for thermal hazardous behavior are obtained including the exothermic onset temperature \( T_o \), heat of decomposition \( \Delta H \), maximum temperature \( T_{max} \), maximum pressure rise \( P_{max} \), self-heating rate \( \frac{dT}{dt} \) and pressure rise rate \( \frac{dP}{dt} \).
Comparing the oxygen consumption rate method and the thermogravimetric methodology, the oxygen consumption measurements provide the overall thermal impact from the whole assembly, however it couldn’t really provide quantitative information on the contribution and thermal hazard behavior of the individual components. Thermogravimetric methodology can be used to provide the inherent chemical kinetics of the thermal properties of individual components, however, it is only practical for testing using small sample.

A heat transfer model is proposed in this paper to simulate the temperature elevation and thermal decomposition of the combustible material following an ignition. The vehicle is divided into modules or key components according to functions and layout. Modelling the thermal decomposition and thermal runaway is an important tool in understanding thermal behavior of the system under various operating conditions. The numerical model is intended to simulate the heat transfer and thermal decompositions of components and assembly incorporating the inherent chemical kinetics of the individual components provided by adiabatic calorimetry.

HEAT TRANSFER MODEL

In order to set up a numerical model for the evaluation of the heat transfer and temperature within the vehicle, the vehicle is idealized and represented by a few key components called modules according to the functions and layout of the components. In general, the vehicle combustible furnishing is one of the main contributors to the heat release during a vehicle fire, therefore the whole combustible furnishing is considered as a single module in the heat transfer calculation. The vehicle powering system is also considered as an essential module, which is the battery pack for EV, battery pack plus liquid fuel tank for hybrid, and liquid fueling system for ICE. An example of an idealized vehicle is illustrated in Figure 1. For simplification, it is assumed that the temperature and the chemical decomposition reaction is uniform within the module as illustrated in Figure 2. Therefore, each module is considered as a temperature node in the thermal network for heat transfer calculation as illustrated in Figure 3. The thermal decomposition rate of the mass in the module is controlled by the chemical kinetics model of thermal decomposition (Eq 3). The thermal resistance between the temperature nodes are derived from the heat transfer through conduction, convection and radiation as expressed in Eq4. The temperature of the node is determined by the energy balance of the external incident heating and the heat generated by the thermal decomposition reactions and the energy gain through the temperature raise as described in (Eq4-7).

The assumptions made to simplify the energy balance are summarized as the following:

a) Within the module, the solid fuel bed is sufficiently porous and isotropic as well as homogenous with constant physical properties.

b) The temperature gradient within the solid could be neglected and temperature within the module is uniform.

c) Heat transfer through the solid body is by conduction.

d) Heat transfer at the surface to the surroundings is by convection and radiation.

e) The solids are reactive so that adequate fuel and oxygen are available throughout the whole self-heating process.

f) At the ignition stage, the energy gained is used to raise the temperature of the solid and accelerate the thermal decompositions. Once the thermal run away is established, the volatile material released through decompositions would enter the gases and burn in the flames.
Figure 1: The illustration of the vehicle modular layout.

Figure 2: The illustration of the thermal network of the modules.

Figure 3: The illustration of thermal resistant network for heat transfer calculation. $T$ is temperature, $R$ is the thermal resistance, subscribe 1,2,3 and 4 is representing modules and $\infty$ is the vehicle surroundings.
Decomposition kinetics where the change in density of starting material is represented by set of reaction:

$$\frac{\partial \rho_s}{\partial t} = -A_s \rho_s \exp\left(-\frac{E_s}{RT_s}\right)$$  \hspace{1cm} (3)

where $\rho_s$ is the density of the solid, $A_s$ is the pre-exponential factor for solid, $E_s$ is the activation energy, $T_s$ is the temperature of the solid and $t$ is time.

Heat transfer at the surface of the module:

$$\dot{Q}_{in} = -\lambda_s \frac{\partial T_s}{\partial y}\bigg|_{\text{surface}} = h_c (T_s - T_\infty) + \sigma \varepsilon (T_s^4 - T_\infty^4)$$  \hspace{1cm} (4)

Where $\dot{Q}_{in}$ is the external incident heat flux (kW/m²), $h_c$ is the convective heat transfer coefficient, $\sigma$ is the Stefan-Boltzmann constant and $\varepsilon$ is the surface emissivity.

The reaction heat generation during the thermal decompositions $\dot{Q}_s$:

$$\dot{Q}_s = -\Delta H \frac{\partial \rho_s}{\partial t} = \Delta H A_s \rho_s \exp\left(-\frac{E_s}{RT_s}\right)$$

Where $\Delta H$ is the heat of reaction.

The temperature of the solid materials is determined by the energy balance of the external incident heating and the heat generated by the thermal decomposition reactions and the energy gain through the temperature raise.

$$m_s = \rho_s V$$  \hspace{1cm} (5)

$$m_s c_p \frac{\partial T_s}{\partial t} = \dot{Q}_s S_A$$  \hspace{1cm} (6)

$$m_s c_p \frac{\partial T_s}{\partial t} = \dot{Q}_{in} S_A + \dot{Q}_s V$$  \hspace{1cm} (7)

Where $m_s$ is the total mass of the solid, $V$ is the volume of the solid, and $S_A$ is the surface area of the solid and $c_p$ is the heat capacity of the solid.

KINETIC MODEL FOR THERMAL DECOMPOSITION AND THERMAL RUNAWAY

In spite of the fact that the thermal decomposition involves many chemical reactions, the overall rate at which the solid particles lose mass can be described as if one single decomposition reaction was occurring [11]. For most of solid material, a single reaction scheme and first order kinetics with a fixed heat reaction is used in the thermal decomposition kinetic model for thermal hazard analysis. The kinetic parameters pre-exponential factor $A$, the activation energy $E_a$ and the activation energy and $\Delta H$ the heat of reaction of some selected materials are listed in Table 1. The curves of thermal decomposition rate $k = \dot{Q}_{in} S_A$ against the temperature of the solid material are showed in Figure 4. The temperature conditions for thermal runaway are clearly demonstrated in Figure 4 where the thermal decomposition rate $k$ started to increase exponentially. The exponential rate of thermal decomposition at thermal runaway conditions explained the trend of heat release rate’s exponential increasing from nearly zero value during thermal decomposition stage to the peak heat release rate of sustained burning. The kinetic model could be used to model the thermal decomposition process and the thermal runaway temperature and combustible material release rate at the thermal runaway and sustained burning.
Table 1  Kinetic parameters for thermal decomposition obtained the thermogravimetric method.

<table>
<thead>
<tr>
<th>Material</th>
<th>A (sec(^{-1}))</th>
<th>(E_a) (kJ/mol)</th>
<th>(\Delta H) Heat of reaction (kJ/kg)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood 1</td>
<td>6x10^7-7.5x10^8</td>
<td>125</td>
<td>125-210</td>
<td>[12]</td>
</tr>
<tr>
<td>Wood 2</td>
<td>4x10^8-2x10^9</td>
<td>152-179</td>
<td>840-2300</td>
<td>[12]</td>
</tr>
<tr>
<td>Battery Anode</td>
<td>0.035</td>
<td>3300</td>
<td>50</td>
<td>[13]</td>
</tr>
<tr>
<td>Battery Cathode 1</td>
<td>1.75x10^9</td>
<td>115</td>
<td>180</td>
<td>[13]</td>
</tr>
<tr>
<td>Battery Cathode 2</td>
<td>1.077x10^12</td>
<td>159</td>
<td>220</td>
<td>[13]</td>
</tr>
<tr>
<td>Battery Electroly</td>
<td>3x10^15</td>
<td>170</td>
<td>140</td>
<td>[13]</td>
</tr>
<tr>
<td>Leather 1</td>
<td>1.35x10^6</td>
<td>81.5</td>
<td></td>
<td>[14]</td>
</tr>
<tr>
<td>Leather 2</td>
<td>6.5x10^10</td>
<td>148</td>
<td></td>
<td>[14]</td>
</tr>
</tbody>
</table>

\[ k = A \exp \left( -\frac{E_a}{RT} \right) \]

Figure 4  Thermal decomposition rate \( k = A \exp \left( -\frac{E_a}{RT} \right) \) against the temperature of the solid material.
CONCLUSIONS

In this paper, the adiabatic calorimetry method was explored to establish the thermal decomposition kinetic parameters pre-exponential factor $A$, the activation energy $E_a$ and the activation energy and $\Delta H$. The reaction heat of thermal decomposition. The parameters and thermal decomposition rate $k = A\exp\left(-\frac{E_a}{RT}\right)$ are used to develop an initial numerical model for modelling the thermal decomposition to thermal runaway of the vehicle fires. The proposed method has potential to be used to examine the thermal runaway propagation with in the vehicles and to provide QRA information for various fire scenarios.

References

Modelling Tunnel Fires Considering the Structure, Fluid Flow and The Soot

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ABSTRACT

The time dependent thermal behaviour is analyzed with FLUENT for the fluid as well as the solid region (concrete component) in case of a 100 MW \(n\)-heptane fire. To study the effect of parameters in mathematical-physical models several sensitivity studies were carried out to investigate the effect on the fluid flow as well as on the component. The influence of soot was additionally considered. FDS simulations as well as empirical calculations considering underlying assumptions are additionally used to examine the plausibility of results from the FLUENT simulations. This is an appropriate method if no experimental results are available. Recommendations are given for choosing parameters in mathematical-physical models e.g. radiation models. The results of the CFD investigations show that considering the influence of soot provides maximum temperatures which were 200 K lower than without soot.

KEYWORD: heat transfer, conduction, radiation, computational fluid dynamics, temperature dependent properties, model checking, analytical and empirical calculations, ANSYS FLUENT, FDS

INTRODUCTION

The protection of individuals as well as the protection of the structure is the major objective for tunnel infrastructures. The German Ministry of Transport and Digital Infrastructure (BMVI) predicts a significant increase for the German transport of goods by 38 percent until 2030. The expected traffic loads in particular the increasing freight transport involving the transport of dangerous goods as well as higher fire loads in vehicles and changes in fire loads increases the risk of incidents. Safety measures are required. The effectiveness of these safety measures has to be proved. This is increasingly done by the use of CFD methods which are part of the performance based design within fire safety engineering. The aim is to provide results which are reliable as well as traceable by regulatory and engineers. This requires the development and recommendation of appropriate mathematical-physical models.

In this paper a CFD model is introduced to consider both the fluid flow and the temperature time characteristic within the structure, at the same time, for a 100 MW tunnel fire. The aim of the work is to consider both the material specific burning behaviour which is dependent from temperature and ventilation as well as the component behaviour which is dependent from material specific properties which are especially of thermo-hygro concern. Due to under practical conditions the combustion process is incomplete the influence of soot was additionally investigated. Because coupling of fluid and solid region is a very complex system different techniques were used to check this model. This includes the use of different CFD models, sensitivity analysis, analytical and empirical calculations. All verification procedures and numerical methods are still subject of research and development. Preliminary work which was carried out in last years is described below. Numerical investigations of the thermal coupling of fluids and solids by means of FEM were performed in [1], [2] and [3]. Numerical investigations of coupled heat transfer processes with CFD in case of fire on the example of a test model were carried out in [4]. Numerical results of the temperature gradient throughout the thickness of concrete in tunnel segments were presented in [5].
TUNNEL FIRE SCENARIO

The tunnel fire is caused by a tank truck with a heat release of 100 MW from n-heptane liquid pool fire \( A = 2.3 \text{ m} \cdot 16 \text{ m} \). The fire was numerically analysed with computational fluid dynamics (CFD). The CFD model considers both the fluid flow and the temperature time characteristic within the structure, at the same time. Because the focus is on coupling fluid and solid region a tunnel section of 40 m and a tunnel cross section of 45.6 m² is considered. The main dimensions are 9.04 m width, 5.85 m height. Dimensions of the cross section were chosen from [6] page 76. The wall thickness of the quartz containing concrete component is 0.4 m. The fire was located in the middle of the tunnel on the left lane. The n-heptane was released spontaneously for 60 minutes. On the one hand the heat released during the n-heptane fire is dissipated by the flow and on the other hand transported towards the concrete component. The temperature-dependent heat transfer mechanisms involve the behaviour of the fluid inside the tunnel as well as the behaviour inside the concrete structure. Transient fire simulations are performed with the CFD program ANSYS FLUENT and FDS.

MODEL DESCRIPTION

ANSYS Fluent

The numerical simulation of turbulent fluid flows as well as the heat and mass transfer and chemical reactions are based on the solution of conservation equations for mass, momentum, concentration and energy. All transport equations can be described by a general (generic) transport equation. The differential form of the general transport equation is:

\[
\frac{\partial}{\partial t} (\rho \phi) + \frac{\partial}{\partial x_i} (\rho u_i \phi) = \frac{\partial}{\partial x_i} \left( \Gamma \frac{\partial \phi}{\partial x_i} \right) + S_\phi
\]  
(1)

Combustion model

The fire represented by a n-heptane \( C_7H_{16} \) combustion is modelled using the eddy dissipation model. This turbulence-chemistry interaction model is based on the work of Magnussen and Hjertager [7]. The model is based on the hypothesis that chemical reaction is fast in relation to the transport process of the flow. The net-production rate \( R \) due to reaction \( r \) is:

\[
R_{k,r} = MIN \left( R_{k,r(React)} , R_{k,r(Prod)} \right)
\]  
(2)

\[
R_{k,r(React)} = v'_{k,r} M_k A \rho k \xi \left( \frac{Y_R}{v'_{k,r} M_R} \right) \quad \text{and} \quad R_{k,r(Prod)} = v'_{k,r} M_k A B \rho \xi \left( \frac{\sum_{i=1}^N Y_{P,i}}{\sum_{j=1}^N v'_{j,r} M_j} \right)
\]  
(3)

where \( Y_p \) the mass fraction of species products, \( Y_R \) the mass fraction of reactants, A empirical constant with 4.0 and B empirical constant with 0.5 suggested by Magnussen. The reaction rate in eq. 1 and eq. 2 depends from the ratio \( \xi / k \). This concept complies with the Eddy Break Up model (EBU), which was introduced by Spalding. Magnussen and Hjertager adapted the EBU and generalized it for non-premixed and partially premixed combustion - Eddy dissipation model (EDM). Combustion takes place if turbulence is present \( k / \xi > 0 \), an ignition source is not required. The EDM is appropriate for non-premixed flames.

The chemical reaction is represented by a global one step reaction mechanism for \( C_7H_{16} \) and \( O_2 \) combustion. When reactants mix at the molecular level, they instantaneously form products. The stoichiometric molecular formula with its educts and products is shown below:

\[
C_7H_{16} + 11 O_2 \rightarrow 7 CO_2 + 8 H_2O
\]  
(4)
The fire was modeled with a mass-flow-inlet with a pyrolysis flow rate of 2.24 kg/s [8] for \( n \)-heptane \( (\Delta H_c = 44.6 \text{ MJ/kg}) \) which represents a heat release of 100 MW. This is an assumption; because pyrolysis rate is influenced by several parameters e.g. fuel thickness, heat transfer in sloped tunnel geometry etc.. These influences are further discussed in the ‘Results and Discussion’ part of this paper. The heat of combustion in the Eddy Dissipation model is calculated from enthalpy of formation

\[
\Delta H_c = \frac{\Delta \tilde{h}}{M} \quad \text{with} \quad \Delta \tilde{h} = \left( \sum_{i=1}^{N} v_i \Delta h_i^r \right)_{\text{reactants}} - \left( \sum_{i=1}^{N} v_i \Delta h_i^p \right)_{\text{products}}
\]

where \( \Delta h_i^r \) ([kJ/mol] enthalpy of formation and \( \Delta H_c \) [kJ/g] heat of combustion. The investigated fire is fuel controlled \( (r = 15.169 \text{ kg}_{\text{air}}/\text{kg}_{\text{fuel}}, \phi < 1) \) which was evaluated according to [16] with

\[
r = 137.8 \left( a + \frac{b}{4} - \frac{c}{2} \right) / \left( 12a + b + 16c \right) \quad \text{and} \quad \phi = \frac{\dot{m}_f}{\dot{m}_a}.
\]

Soot model

The calculated temperatures and the radiation heat transfer are substantially influenced by the absorption coefficient of the combustion products. The combustion products are H2O, CO2, CO, N2 as well as soot. For soot prognosis the one-step-soot model developed by Khan and Greeves was applied. The calculation of the time depended rate of soot production is based on an empirical approach. The model could only apply to turbulent flows. It is assumed that soot behaves like a fluid, which means that the particle will be transported with the fluid without an inertial force. The transport equation for soot mass fraction is solved by

\[
\frac{\partial}{\partial t} (\rho Y_{\text{soot}}) + \nabla \cdot (\rho \mathbf{v} Y_{\text{soot}}) = \nabla \left( \frac{H_i}{\sigma_{\text{soot}}} \nabla Y_{\text{soot}} \right) + R_{\text{soot}}
\]

where \( Y_{\text{soot}} \) is the soot mass fraction (kgSoot/kgMixture), \( \sigma_{\text{soot}} \) the turbulent prandtl number for soot transport, \( R_{\text{soot}} \) the net production rate of soot  (kg/(m³s) and \( \rho \) the density of the mixture (kgMixture/m³). The net production rate \( R_{\text{soot}} \) is the difference between the time dependent rate of soot production due to methane combustion (soot formation) and due to production of carbon (soot combustion)

\[
R_{\text{soot}} = R_{\text{soot,form}} - R_{\text{soot,comb}}
\]

The rate of soot production due to combustion is calculated via \( R_{\text{soot,form}} = C_s \rho_{\text{fuel}} \phi e^{-E/RT} \), where \( C_s \) soot formation constant (kg/(N m s)), \( \rho_{\text{fuel}} \) the partial pressure of the fuel (Pa), \( \phi \) equivalence ration, \( r \) equivalence exponent and the \( E/ R \) activation energy (K). The rate of soot combustion is calculated from

\[
R_{\text{soot,comb}} = \min[R_1, R_2], \quad R_1 = A \rho Y_{\text{soot}} \varepsilon \, / \, k \quad \text{and} \quad R_2 = A \rho \left( \frac{Y_{\text{oxy}}}{Y_{\text{soot}}} \right) \left( \frac{Y_{\text{soot}} V_{\text{soot}}}{V_{\text{soot}} + V_{\text{fuel}} V_{\text{fuel}}} \right) \varepsilon \, / \, k
\]

where \( A \) the constant of Magnussen model, \( Y_{\text{oxy}} \) (kgO2/kgMixture), \( Y_{\text{fuel}} \) (kgfuel/kgMixture) the mass fractions of the oxidizer and the fuel; \( V_{\text{soot}} = 2.52 \) (kgO2/kgSoot), \( V_{\text{fuel}} = 3.63 \) (kgO2/kgfuel) the stoichiometric coefficients for soot and fuel. The following values were used for the one-step soot model \( A = 4, \quad C_s = 3, \quad \phi_{\text{min}} = 1.67, \quad \phi_{\text{max}} = 3, \quad r = 3, \quad E/ R = 20000 \). Soot-radiation interaction was chosen to consider the effect of soot on the absorption coefficient \( \kappa \).
Radiation model and analytical calculations

The radiative heat transfer between the surfaces of the tunnel considering absorbing and emitting smoke gases and soot is modelled by using the discrete ordinates model [9], [10], [11]. This discrete ordinates approximation model solves the radiative transfer equation (RTE). The radiation behaviour was assumed to be grey. Absorption coefficients for CO₂, H₂O were taken into account with the weighted sum grey gas model (WSGGM). The total absorption coefficient $\kappa$ is the sum of $\kappa_{\text{WSGGM}}$ and $\kappa_{\text{soot}}$. Solving the RTE requires angular discretization for $N_\theta(\theta)$, $N_\phi(\phi)$. For choosing the radiation discretization parameters $N_\theta$, $N_\phi$, preliminary analytical and numerical investigations were carried out and described below.

The figure 1 shows the boundary conditions for the analysed quadratic two-dimensional domain and the electrical circuit model for analytical calculations. The resulting analytical net heat fluxes were

$$\frac{Q_2}{A_2} = 601394.32 \, \text{W/m}^2 \text{ (left side) and}$$

$$\frac{Q_4}{A_4} = -601394.32 \, \text{W/m}^2 \text{ (right side)}$$

respectively.

![Figure 1](image-url)

**Figure 1** a) model for analytical and numerical investigations b) electrical circuit model for analytical calculations

For numerical investigations the number of quadrilateral elements as well as the number of angular discretisation’s for $N_\theta$, $N_\phi$ were varied. The parameters for $N_\theta$ and $N_\phi$ were 2, 4, 8, 16 and the parameters for the number elements are shown in table 1.

<table>
<thead>
<tr>
<th>$n$</th>
<th>49</th>
<th>100</th>
<th>196</th>
<th>400</th>
<th>784</th>
<th>1600</th>
<th>3249</th>
<th>6400</th>
</tr>
</thead>
<tbody>
<tr>
<td>per side</td>
<td>7</td>
<td>10</td>
<td>14</td>
<td>20</td>
<td>28</td>
<td>40</td>
<td>57</td>
<td>80</td>
</tr>
</tbody>
</table>

The results of this investigation are shown in figure 2. The figure 2 depicts the deviations in percent between the numerical and analytical determined net heat flux (left side of the model) for varied $N_\theta$ (theta) and $N_\phi$ (phi) discretisation on y-axis and the number of elements on x-axis. The smallest deviation from the exact analytical value with -0.28 % was achieved by $N_\theta = 4$, $N_\phi = 4$ and $n = 49$ elements. Increasing the number of elements while using same angular discretization leads to higher deviations. These deviations could be reduced while increasing the number of angular discretization’s $N_\theta = 16$, $N_\phi = 16$. Using $N_\theta = 8$, $N_\phi = 8$ or $N_\theta = 16$, $N_\phi = 16$ for angular discretization leads to nearly consistent results.
The results show a connection between the number of elements and the required number of angular discretization. To find a compromise between the computational effort and known deviations a angular discretization of $N_\theta = 6$ and $N_\phi = 6$ was used within this investigation.

![Figure 2](image_url)  

*Figure 2* Deviations in percent between the numerical and analytical determined net heat flux (left side of the model) for varied $N_\theta$ (theta) and $N_\phi$ (phi) discretisation on y-axis and the number of elements n on x-axis

### Material Properties

The physical properties of the materials are changing with increasing temperatures due to a fire. Thus, temperature-dependent material properties for the fluid components ($C_7H_{16}, H_2O, CO_2, N_2, O_2$) as well as for the concrete component were taken into account (see table 2, table 3, figure 3 a, b).

<table>
<thead>
<tr>
<th>Table 2</th>
<th>temperature-dependent material properties for the fluid components $C_7H_{16}, H_2O, CO_2, N_2, O_2$ [11]</th>
</tr>
</thead>
<tbody>
<tr>
<td>material properties</td>
<td>method / characteristic values</td>
</tr>
<tr>
<td>specific heat capacities</td>
<td>polynomial functions</td>
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<tr>
<td>conductivity</td>
<td>kinetic theory</td>
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<tr>
<td>thermal conductivity</td>
<td>kinetic theory</td>
</tr>
<tr>
<td>dynamic viscosity</td>
<td>Sutherland</td>
</tr>
<tr>
<td>density</td>
<td>ideal incompressible gas</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>temperature-dependent material properties for the mixture of the fluid components [11]</th>
</tr>
</thead>
<tbody>
<tr>
<td>material properties</td>
<td>method / characteristic values</td>
</tr>
<tr>
<td>specific heat capacity</td>
<td>ideal mixture</td>
</tr>
<tr>
<td>thermal conduction</td>
<td>dynamic viscosity</td>
</tr>
<tr>
<td>density</td>
<td>ideal incompressible gas</td>
</tr>
<tr>
<td>absorption</td>
<td>weighted sum gray gas model for</td>
</tr>
<tr>
<td>mass diffusion</td>
<td>constant diffusion coefficient of $2.88 \cdot 10^{-5} \text{ m}^2/\text{s}$</td>
</tr>
</tbody>
</table>

The temperature-dependent material properties specific heat capacity $c_p(T)$, thermal conductivity $\lambda(T)$, density $\rho(T)$ of the concrete component were also modeled (see figure 3 b). The concrete is quartz containing and its moisture content is 1.5 % of the concrete mass. The temperature-dependent material properties were taken from [12].
Figure 3  

temperature-dependent material properties  
a) specific heat capacity $c_p(T)$ for fluid components $H_2O$, $CO_2$, $N_2$, $O_2$,  
b) specific heat capacity $c_p(T)$, thermal conductivity $\lambda(T)$, density $\rho(T)$ of the concrete component[12]

**Fluid and solid domain**

The geometry of the tunnel was decomposed into a fluid and a solid domain, figure 4. An interface was used to connect the fluid and the solid region. The three-dimensional unsteady heat conduction for the 0.4 m thick concrete solid region was modeled by using the Fourier heat transfer equation. Thus, the temperature distribution in concrete structure can be predicted. Both portal openings of the tunnel, which are connected to the environment, were modelled as pressure-outlet. A mass-flow-inlet boundary was used as inlet for $n$-heptane.

**Analytical calculations, time step size, grid size for solid and fluid**

Preliminary analytical and numerical investigations were carried out for the concrete component (two-dimensional, thickness 0.4 m) to prepare the three-dimensional coupled model as well as for choosing the required grid size and time step size. Additionally sensitivity checks were done for the fluid region. Next figure 5 shows the results of analytical calculations based on solving Duhamel theorem [15], [14]. Temperature time curves were evaluated for different component depths for constant thermal diffusivity $a = 0.8 \times 10^{-6} \text{ m}^2/\text{s}$, figure 5 a). The figure 5 b) shows the analytical and numerical values for a component depth of 0.01 m. Figure 5 b) shows consistent results.
Figure 6 shows the numerical calculated temperature time curves a) for component depth of 0.01 m and b) component depth of 0.02 m and different time step size $\Delta t = 15$ s, 60 s, 150 s, 300 s at constant grid size $\Delta x = 0.01$ m.

Figure 5 a) temperature time curves at different depths for const. thermal diffusivity $a = 0.8 \cdot 10^{-6}$ m²/s
b) analytical and numerical values for component depth of 0.01m, const. thermal diffusivity $a = 0.8 \cdot 10^{-6}$ m²/s, numerical time step size $\Delta t = 15$ s, grid size $\Delta x = 0.01$ m

The figure 6 shows best results for time step size of $\Delta t = 15$ s. A time step size of $\Delta t = 60$ s and $\Delta t = 15$ s lead to nearly identical results. For long times of fire exposure (50 min) time step size $\Delta t$ is not of major influence. For short times and small component depths the time step size $\Delta t$ plays an important role. For rough estimation the time step size $\Delta t = \frac{1}{2} \Delta x^2 / a$ could be used, where $\Delta x$ grid size in m, a thermal diffusivity in m²/s. Best estimation is achieved via $\Delta t = \frac{1}{4} \Delta x^2 / a$. The figure 7 a) discusses numerical predicted temperature time curves for constant thermal diffusivity $a$ as well for temperature dependent material properties.
The figure 7 b) shows the results of a grid size study ($\Delta x = 0.005 \text{ m}, 0.01 \text{ m}, 0.02 \text{ m}$) for constant thermal diffusivity compared to analytical value. Best results were reached by $\Delta x = 0.005 \text{ m}$. The figure 7 b) shows the grid size study for constant as well as temperature dependent material properties.

Figure 7  

a) numerical predicted temperature time curves for component depth of 0.02 m and const. thermal diffusivity $a = 0.8 \times 10^{-6} \text{ m}^2/\text{s}$ and $a = 0.4 \times 10^{-6} \text{ m}^2/\text{s}$ as well as temperature-dependent material properties for time step size $\Delta t = 60 \text{ s}$ and grid size $\Delta x = 0.01 \text{ m}$ 

b) analytical predicted temperature and numerical predicted temperatures for a component depth of 0.01 m and const. thermal diffusivity $a = 0.8 \times 10^{-6} \text{ m}^2/\text{s}$ with time step size $\Delta t = 15 \text{ s}$ and for different grid sizes $\Delta x = 0.005 \text{ m}, 0.01 \text{ m}, 0.02 \text{ m}$; temperature-dependent material properties (see figure 3 b)

The figure 8 shows the results for mass flow into and out of the tunnel (fluid region see figure 4) for different grid sizes $\Delta x = 0.02 \text{ m}, 0.03 \text{ m}, 0.04 \text{ m}$.

Figure 8  

mass flow in and out of the tunnel (fluid region) for different grid sizes $\Delta x = 0.02 \text{ m}, 0.03 \text{ m}, 0.04 \text{ m}$ a) left portal in b) right portal in; number of cells $N_x \cdot N_z$
The x-axis in figure 8 shows the reciprocal value of the number of cells which was calculated via \( N_x \cdot N_z \) for the portal. The sensitivity study in figure 8 shows the influence of grid size and indicates a prognosis. This method could be useful if the exact value is not known. By drawing straight lines and extrapolation to zero of the horizontal axis the result can be estimated (Richardson-extrapolation). Empirical calculations for values of mass flow into the tunnel were carried out with \( \dot{m}_a = 0.5 \cdot A \cdot h^{3/2} \) where \( A \) is the portal area and \( h \) the height of the opening [16]. The empirical calculations gives \( \dot{m}_a = 55.1 \text{ kg/s} \) and provides a good prognosis, but lead to slight over estimation compared to numerical values.

**RESULTS AND DISCUSSION**

**Coupled model ANSYS Fluent**

The first transient calculations of the turbulent flow were carried out with the standard two equation \( k-\varepsilon \) turbulence model. The following model constants of the turbulence model, which were established by Launder and Spalding, were used:
\[
C_{1\varepsilon} = 1.44, \quad C_{2\varepsilon} = 1.92, \quad C_{\mu} = 0.09, \quad \sigma_k = 1.0, \quad \sigma_{\varepsilon} = 1.3.
\]
The \( k-\varepsilon \) model was considered for first calculations and the \( sst-k\omega \) model was used due to several advantages for later calculations. Because the main aim of the work was to couple fluid and solid region, an ideal combustion of \( n \)-heptane was considered first. The influence of soot will be discussed in the following section. The figure 9 shows the calculated temperatures for the fluid and solid region. Temperatures were evaluated in the middle section of the tunnel (see figure 4). The figure 9 a) shows both fluid and solid temperatures and figure 9 b) shows concrete temperatures as a function of depth and time.

![Graph showing calculated temperatures](image_url)

**Figure 9**

a) Numerical results of the calculated fluid and component temperatures as a function of time  
b) Numerical results of the calculated component temperatures of the concrete component as a function of depth and time, temperature curves at \( t = 5, 15 \) and \( 60 \) min

The effects due to a fire are influenced by fire load, ventilation and the tunnel structure. The results of the coupled transient analysis show that temperatures of 150 °C in the surface layer were reached after only a few minutes. According to ZTV-ING it has to be ensured that the temperature of load bearing reinforcement does not exceed 300 °C. The 300 °C criterion for load bearing reinforcement is used to avoid high strains and plastic deformations due to fire exposure. Within 60 min of fire exposure the temperature in depth of 6 cm is below 300 °C. The results of the temperatures show that the requirement concerning the temperature is fulfilled within 60 min of fire exposure.
Temperature field ANSYS Fluent and FDS and the influence of soot

To check the plausibility of numerical predicted results for the temperature field also calculations with FDS were performed, see figure 10, figure 11. An ideal combustion of \( n \)-heptan as well as a quasi-steady state was considered for both Fluent and FDS (figure 10, figure 11). The figure 10 a) shows the calculated temperature field with Fluent at the cross section in the middle of the tunnel (fire region) and figure 10 b) shows results with FDS respectively.

Both Fluent and FDS predict nearly the same maximum temperatures, which were around 1500 °C, as well as nearly the same temperature field for the cross section. Furthermore the calculated temperatures for the \( n \)-heptane combustion are in the range of literature values. For an ideal \( n \)-heptane combustion values were given for the adiabatic flame temperature at lower oxygen limit with 1418 °C and for the flame temperature at maximum flame speed with 1941°C, according to [14]. Because this is an ideal combustion a more practical condition was considered. The soot in Fluent was considered via one-step-soot model as described in previous section and soot in FDS was considered via soot yield. The results of soot calculations with Fluent and FDS are shown in figure 12.
Considering the influence of soot provides maximum temperatures which were approximately 200 K lower than without soot. The figure 12 shows that maximum temperatures, which were predicted, were around 1350 °C when soot was considered. Both Fluent and FDS results confirm that and show significantly the influence of soot on the temperature filed. As a consequence the thermal exposure of the concrete component will be significantly lower when considering the soot. The influence of soot on the temperature time behavior inside the concrete component has to be further investigated and is part of future work. Despite this, the results from these simulations will be studied, as far as feasible, into the context of real fires which come from [16] and into the context of numerical studies which come from [1].

Influence of fuel thickness and heat transfer on pyrolysis rate

The pyrolysis flow rate in this investigation was assumed to be 2.24 kg/s for n-heptane which was released from a mass-flow-inlet (accidental open of a tank). The values for pyrolysis flow rate for pool fires, $\dot{m}'' = \dot{m}''(1 - e^{k_D})$, were from [8]. Under practical conditions estimating the pyrolysis flow rate for liquids in a tunnel fire is more complex and depends on several parameters. The pyrolysis flow rate of a liquids fuel in a tunnel is influenced by e.g.

- the fuel type and geometry
- the fire-induced environment
- the ventilation conditions
- the heat transfer from the above and the solid under (interaction)
- the outflow in drainage channel and the sloped surface
- the combustion rate (sinking rate) and
- the fuel thickness (fuel depth).

Especially the experimental results from [16] ‘Table 4.5 Summary of pool fire tests in tunnels and laboratories’ show that fuel thickness of liquid fuels has an significant influence on pyrolysis flow rate and thus on the heat release rate. The values of the heat release rate were reduced when lowering the fuel depth. Thus values of the heat release rates can be much lower than what is obtained in deep fuel experiments. According to [16] the heat release rate per fuel surface area of large fuel depth could be reduced by 70-80% if the fuel is only few millimeters deep e.g. fuel on asphalt road surface. The thickness of fuels flowing out on a sloped surface in a tunnel could be also much lower. The fuel thickness is an important parameter which needs to be considered. Modelling tunnel fires considering these influences should be part of further investigations.

REFERENCES

Electric Vehicle Fires

Francesco Colella\textsuperscript{1}, Hubert Biteau\textsuperscript{1}, Nicolas Ponchaut\textsuperscript{1}, Kevin Marr\textsuperscript{1}, Vijay Somandepalli\textsuperscript{1}, Quinn Horn\textsuperscript{1}, Richard Thomas Long\textsuperscript{1}

\textsuperscript{1}Exponent, USA

ABSTRACT

This paper presents and discusses the flammability characteristics of Li-ion battery packs in the context of electric vehicle (EV) fires. The paper is structured in two sections. The first section of the paper discusses the typical flammability characteristics of battery vent gases in comparison to more common hazardous gases. In addition, small scale cone calorimetry results from single Li-ion cells are presented and analysed in terms of energy content and peak heat release rate (HRR). The second section of the paper focuses on results from full-scale fire tests involving full size battery packs and an electric vehicle mock-up. The paper discusses the full-scale electric vehicle fire test data in comparison to traditional vehicle fire test data also in the context of electrical vehicle fire suppression.

KEYWORD: Electric vehicles fires, Li-ion batteries, suppression

INTRODUCTION

Recent improvements in battery technology allowed the development and growth of the electric vehicle fleet. With the introduction of a new fleet of vehicles in tunnels, understanding the safety aspects associated with electric vehicles is of paramount importance as (1) electric vehicle car fires, using new generation Li-ion batteries, are not well characterized, and (2) the methods available to control and suppress these fires are not widely understood.

The most typical catastrophic failure mechanism that can lead to battery fires in vehicles is a thermal runaway event. In large, multi-cell packs such as those commonly used in electric vehicles, the heat generated by one failed cell can heat up neighboring cells and lead to a thermal cascade throughout the battery pack very quickly. Thermal runaway events result in the venting of flammable gases, and these gases can generate a fire or an overpressure event if ignited in a confined area. An effective suppression of electric vehicle fires requires the suppressant agent to come in contact with the battery packs in order to maximize the cooling of the batteries and slow-down or stop the cascading event. This process indirectly avoids further venting of flammable gases and potential reignitions. The characterization of electric vehicle fires requires a multi-step process that includes a combination of small, intermediate and full scale testing. This paper summarizes the most recent findings in the field of Li-ion battery fire safety including (1) characterization of vented gases, (2) flammability characteristics of Li-ion battery, (3) challenges associated with EV fire suppression.

SINGLE CELL FAILURE AND VENTED GASES

Thermal runaway occurs when the temperature of a cell increases in an uncontrolled manner, leading to its failure. This temperature increase generates gases, which vent when the pressure inside the cell rises above a design value. For Li-ion cells, these gases are hot and combustible, which can become a hazard if a pack was not designed to control the causes and consequences of thermal runaway.

All thermal runaway events are a result of a rise in cell temperature. This temperature rise can have multiple causes, including, but not limited to:

- The exposure of cells to a high temperature environment generated by a malfunction in
battery thermal management systems or if exposed to a fire.

- A defect inside the cell can result in an internal short circuit, which causes the cell to heat up at the location of the defect.
- A surge in the charging or discharging current. When cells are charged or discharged, heat is generated. The higher the current, the higher the heat generation.
- An improper electrical connection at the tab of a battery. This causes an increased electrical resistance which generates heat at the electrical contacts.
- Mechanical damage to the cell or battery which can also lead to internal shorts and result in heat generation.

During a thermal runaway event, the cell produces gases that build up within the cell. Some cell designs (e.g. cylindrical 18650 cells) include a specially designed vent that opens, and releases the gases. In some cases, this vent can become obstructed or may not open correctly, which may result in a violent rupture of the cell enclosure. Other cell form factors, such as pouch cells, do not include a specific vent and the gases will release at weak points in the external pouch, typically near the tabs of the cell or along the pouch seams in unconstrained cells. The first step towards understanding electric vehicle fire requires the characterization of the gases vented during a thermal runaway event.

Exponent developed a test method where thermal failure of a cell was initiated in an enclosed chamber filled with an inert gas (argon). After the cell vented, the resulting gases were collected in a sample canister and analyzed for composition analysis using gas chromatography-mass spectroscopy (GC-MS). Although the cells tested were vented into an inert environment, partial combustion could still take place due to the decomposition of the positive electrode active material, which releases oxygen during decomposition. For other cell chemistries that do not produce oxygen during thermal runaway, partial combustion is not expected in the inert chamber environment.

The results presented in this paper are relative to small format Li-ion pouch cells (7.7 Wh nominal, 2.1 Ah, 3.7 V) even though both the testing and analytical methods presented could be similarly applied to large format cells. The cells consisted of a negative electrode with graphite active material and a positive electrode with LiCoO₂ active material. Note that cell chemistry, cell geometry, as well as the way the thermal runaway process is initiated influence the quantitative behavior of the failure.

Table 1 summarizes the amount of gas vented during a thermal runaway event, for pouch cells at three different states of charge (a more detailed description can be found in [1]). For comparison, the volume reported is referenced to standard pressure and temperature (27 °C, standard atmospheric pressure). It should be noted that for large battery packs, the amount of gas that is released can be substantial.

<table>
<thead>
<tr>
<th>State of Charge</th>
<th>Vented Gas Volume</th>
<th>Volume per Wh</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>0.8 L / 0.2 Gal</td>
<td>0.10 L/Wh</td>
</tr>
<tr>
<td>100%</td>
<td>2.5 L / 0.7 Gal</td>
<td>0.33 L/Wh</td>
</tr>
<tr>
<td>150%</td>
<td>6.0 L / 1.6 Gal</td>
<td>0.78 L/Wh</td>
</tr>
</tbody>
</table>

Table 1 shows that the higher the state of charge, the larger the amount of gases released. This relationship is not linear and a cell that is charged at 100% will generate more than twice the amount of gas than a cell at a 50% SOC.

Table 2 summarizes the gas composition for different SOCs. With the exception of carbon dioxide, all the substances reported in Table 2 are flammable. In addition, carbon monoxide and some of the hydrocarbons are not only flammable, but also can pose significant health hazards.
Table 2  Vented gas composition for a 7.7 Wh pouch cell [3]

<table>
<thead>
<tr>
<th>Gas</th>
<th>50% SOC (%vol)</th>
<th>100% SOC (%vol)</th>
<th>150% SOC (%vol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>32.3</td>
<td>30.0</td>
<td>20.9</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>3.61</td>
<td>22.9</td>
<td>24.5</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>31.0</td>
<td>27.7</td>
<td>29.7</td>
</tr>
<tr>
<td>Methane</td>
<td>5.78</td>
<td>6.39</td>
<td>8.21</td>
</tr>
<tr>
<td>Ethylene</td>
<td>5.57</td>
<td>2.19</td>
<td>10.8</td>
</tr>
<tr>
<td>Ethane</td>
<td>2.75</td>
<td>1.16</td>
<td>1.32</td>
</tr>
<tr>
<td>Propylene</td>
<td>8.16</td>
<td>4.52</td>
<td>0.013</td>
</tr>
<tr>
<td>Propane</td>
<td>0.68</td>
<td>0.26</td>
<td>2.54</td>
</tr>
<tr>
<td>Isobutane</td>
<td>0.41</td>
<td>0.20</td>
<td>0.13</td>
</tr>
<tr>
<td>n-Butane</td>
<td>0.67</td>
<td>0.56</td>
<td>0.39</td>
</tr>
<tr>
<td>Butenes</td>
<td>2.55</td>
<td>1.58</td>
<td>0.60</td>
</tr>
<tr>
<td>Isopentane</td>
<td>0.45</td>
<td>0.07</td>
<td>0.036</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>1.94</td>
<td>0.73</td>
<td>0.30</td>
</tr>
<tr>
<td>Hexanes +</td>
<td>4.94</td>
<td>2.32</td>
<td>8.21</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.14</td>
<td>0.11</td>
<td>0.33</td>
</tr>
<tr>
<td>Toluene</td>
<td>0.061</td>
<td>0.018</td>
<td>0.052</td>
</tr>
<tr>
<td>Ethyl-benzene</td>
<td>0.009</td>
<td>0.002</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Note that Table 2 summarizes the species volume fraction of the vent gases. The absolute volume of each species depends on the total volume of gas vented, which increases as the SOC increases. Therefore, the total volume of hydrogen released from a 150% SOC cell is significantly more than from a 50% SOC cell despite having similar hydrogen volume fractions.

The combustion characteristics of the vented gases is summarized Table 3 and compared with those of common gases. The combustion properties of the vented gases are similar to typical hydrocarbons despite the large presence of carbon dioxide. Another point to note is that the gases vented from Li-ion cell failures have a broader combustion range than typical hydrocarbons increasing the potential for ignition. More information on the testing methodology to evaluate the explosibility characteristics of battery vented gas are available in [1,2].

Table 3  Combustion characteristics of vented gases released during a thermal failure of 7.7 Wh cells, and of common gases [4]

<table>
<thead>
<tr>
<th>Gas</th>
<th>LFL</th>
<th>UFL</th>
<th>(P_{\text{max}}) (barg)</th>
<th>(K_g) (m-bar/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-Ion Vent Gas (100% SOC)</td>
<td>6%</td>
<td>~38%</td>
<td>7.1</td>
<td>65</td>
</tr>
<tr>
<td>Li-Ion Vent Gas (150% SOC)</td>
<td>6%</td>
<td>40%</td>
<td>7.7</td>
<td>90</td>
</tr>
<tr>
<td>Methane</td>
<td>5%</td>
<td>15%</td>
<td>6.7</td>
<td>46</td>
</tr>
<tr>
<td>Propane</td>
<td>2%</td>
<td>10%</td>
<td>7.2</td>
<td>76</td>
</tr>
<tr>
<td>Ethane</td>
<td>3%</td>
<td>12%</td>
<td>8.0</td>
<td>171</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>4%</td>
<td>75%</td>
<td>6.5</td>
<td>250</td>
</tr>
</tbody>
</table>

CELL COMBUSTION

The next step towards a complete characterization of the risk associated with electrical vehicle fires requires the understanding of the battery combustion behavior. Cells consist of organic materials such as the separator, the packaging and the electrolyte—all of which are flammable. Often, the combustion event does not only involve the combustion of the vented gases, and the cell itself also burns and releases energy.
To quantify the amount of energy that can be released by a cell involved in a fire, cells were tested in a cone calorimeter. Cone calorimeters are typically used to estimate the heat released during the combustion of fabrics or other typical organic materials using oxygen consumption calorimetry. In a cone calorimeter, a sample usually reaches ignition and burns after being subjected to an external heating. The energy released during combustion and the volume of combustion products are determined by collecting and analyzing the oxygen, carbon dioxide and carbon monoxide contents of the exhaust gases. The standard method by which the cone calorimeter results are processed had to be modified to account for the actual complex composition of a Li-ion cell. A detailed description of the challenges associated with performing calorimetry of Li-ion cells is discussed in [5]. During the test, both the vented gases and the cell itself will ignite and burn.

Although the cone calorimeter can be used to determine several parameters (e.g critical heat flux for ignition, ignition time, etc.), one of the most important parameters measured is the heat release rate (HRR). The HRR is the amount of energy produced by the combustion process per unit of time (expressed typically in kW). It is the single most important parameter for determining the fire hazards associated with a given material or product and for designing fire protection systems. Figure 1 shows the evolution of the heat release rate as a function of time for a 7.7 Wh Li-ion cell at 50% SOC. At the peak of the combustion event, the fire releases 18 kW of power. Once again, the heat release rate is very dependent on the state of charge of the cell. A cell that is completely discharged (0% SOC) has a peak heat release rate of only approximately 2 kW. The heat release rate for a fully charged cell was not obtained because the combustion products from the cell could not be completely contained by the calorimeter.

The net heat of combustion of a cell could be estimated using the total energy released during the combustion of the cell. A comparison with common materials reveals that the heat of combustion for a 50% SOC Li-ion cell falls between that of PMMA and Acetone (see Table 4).

<table>
<thead>
<tr>
<th>Material</th>
<th>Net Heat of Combustion (kJ/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas Fir</td>
<td>19.6</td>
</tr>
<tr>
<td>PMMA (clear plastic)</td>
<td>25</td>
</tr>
<tr>
<td>50% SOC Li-ion cell</td>
<td>28.1</td>
</tr>
<tr>
<td>Acetone</td>
<td>30.8</td>
</tr>
<tr>
<td>Gasoline</td>
<td>44.1</td>
</tr>
</tbody>
</table>
Interestingly, the 50% SOC Li-ion cell is able to store 0.6 kJ/g of electrical energy well below the amount of energy released during a fire. The amount of electrical energy per unit mass stored in the cell can be calculated by using the cell capacity (i.e. 7.7 Wh), the cell mass (i.e. 23 g) and the SOC (i.e. 50%).

**ELECTRIC VEHICLE FIRE SUPPRESSION**

The understanding of single Li-ion cell failures (i.e. small scale failures) such as thermal runaway is the first step to correctly address hazards (thermal, chemical and electrical) associated with electric drive vehicle (EDV) fires (i.e. large scale failures). A failing Li-ion cell is susceptible to cause a cascading event where thermal runaway propagates through the battery packs. In addition, the cell chemistry, the battery energy density and the state of charge of the battery appears as critical contributors to the intensity of Li-ion cells combustion reaction. The characterization of such propagation ultimately requires full scale testing.

A few studies have investigated the fire behavior of EDVs and compared it with that of conventional Internal Combustion Engine (ICE) vehicles. Watanabe et al. estimated the HRR produced by an EDV and a comparable ICE vehicle based on their respective mass loss rates [8]. The authors found that the peak HRR for the EDV was about 3 times greater than that of the ICE vehicle. The total energy released from the EDV fire was about 1.5 times greater than that of ICE vehicle. Lecocq et al. conducted fire tests on an EDV and the same model of vehicle but equipped with an internal combustion engine [9]. A gas burner located on the front driver’s seat was used as the ignition source. Both vehicles showed similar fire development and no projectile were observed for the EDV. The peak HRR was 4.2 MW and 4.8 MW, respectively, for the EDV and the ICE vehicle. Hydrogen Fluoride (HF) was produced in large quantities from the burning of both vehicles. Based on the test observation, a distinct area of HF emission was attributed specifically to the combustion of the EDV battery.

Full scale HRR and fire suppression testing of EDV in an effort to develop best practices for emergency response to incidents involving EDV battery hazards [10]. A battery pack tested was designed for an Extended-Range Electric Vehicle (EREV) with a nominal energy of 16 kWh and enclosed in a fiberglass case). The pack spanned nearly the length of the vehicle from the rear axle to the front axle and was rigidly mounted underneath the floor pan.

The HRR from the 16 kWh battery pack with fully charged Li-ion cells was measured using the same methodology as for single Li-ion cells but implemented in a large-scale calorimeter. Li-ion cells were induced into thermal runaway using four propane burners located underneath the battery pack. The propane burners were set to develop a HRR of 400 kW (100 kW each) for the first 20 minutes of the test and be after shut off. The resulting HRR is presented in Figure 2. The peak HRR was approximately 700 kW at 17 minutes and 30 seconds after the start of the test. The actual peak HRR from the battery pack is obtained by subtracting the 400 kW developed by the four propane burners and was estimated to be about 300 kW. This estimation indicates that the thermal runaway propagation through Li-ion cells was not instantaneous but occurred in stages. A first HRR peak of about 550 kW 3 to 4 minutes after the burners were turned on was attributed to the battery cover mainly composed of plastic materials. The average HRR from the battery pack alone was estimated to be approximately 128 kW and the total energy released 720 MJ (200 kWh). HF was not detected during the HRR testing. All visible flames ceased about 1 hour and 34 minutes after the start of the test. 3 hours after complete extinction, a maximum temperature of approximately 150°C was still measured on the exterior shell of the battery pack. The HRR testing provided valuable information with regards to the fire intensity and the combustion gases generated during the burning. It allowed the development of a suppression strategy.

The large-scale calorimeter test was followed by multiple full scale suppression tests where the battery pack was installed in a vehicle mock-up (see Figure 3). Two battery packs were used during the tests.
• a 4.4 kWh hybrid vehicle battery pack enclosed in a metal case and rigidly mounted in the lower portion of the rear cargo area behind the rear seats.
• a 16 kWh electric vehicle battery pack similar to the one used for the large-scale calorimeter tests.

A total of six full scale suppression tests were performed. The vehicle interior components (e.g. upholstered car seats, dashboard and carpeting) were installed in the mock-up vehicle for two suppression tests only (see Figure 3). The remaining four tests were performed with the battery pack in place but without the car interior components. The four propane burners were located underneath the battery pack in the same configuration as for the HRR testing.

The battery pack in the mockup vehicle was ignited by the four propane burners simulating a car crash with an ICE vehicle with rupture of its gasoline tank and ignition of the fuel. The propane burners were allowed to run until visible signs of battery involvement occurred. These include (1) arcing, visible flames or projectiles emanating from the battery, (2) battery internal temperature above 80°C, (3) decrease in the cell voltage, and (4) venting of electrolyte.

Suppression activities were conducted with an incident commander, an assistant as well as two active firefighters, one on the nozzle and one on the hose. The 1.75-inch diameter hose line was connected to a private hydrant and discharged approximately 125 gpm of water at 75 psi. Table 5 summarizes the six full scale suppression tests performed with the mock-up vehicle.
A complete description of the full size suppression tests and the corresponding observations is beyond the scope of this paper. The present paper provides test specific details for test #6 only, involving the 16 kWh battery pack installed in the mock-up vehicle along with the interior component. The authors encourage the interested readers to refer to [10] for a complete description of the tests.

During test #6, the passenger compartment was fully involved within 7 minutes. Active suppression with water started 22 minutes after the start of test. The firefighters focused on applying water to the battery pack from several angles (Rear, front, side, through wheels). Water was applied multiple times due to several re-ignitions for a total duration of approximately 14 minutes. Despite the efforts of the firefighters to tackle the fire, cooling of the shielded battery pack was insufficient to prevent propagation of thermal runaway events leading to Li-ion cells re-ignition. Firefighters adapted their strategy to continuously apply water to the battery pack for a prolonged period of time. Temperatures on the exterior shell of the battery pack reached back near ambient conditions approximately 3 hours after the beginning of the test. Table 6 summarizes the water flow results for the six suppression tests.

The test results show that the water requirements necessary for a complete suppression of electric vehicle fires are significantly larger than what is typically employed for standard ICE vehicle fire suppression. It should be noted that the drastic reduction of water used for the suppression of the fire during test #6 can be explained by a more effective water delivery strategy adopted by the firefighters. In particular, they operated with the intent of cooling down the battery packs to avoid re-ignitions rather than to suppress the flaming combustion.

### Table 5
**Summary of the six full scale suppression tests**

<table>
<thead>
<tr>
<th>Test #</th>
<th>Battery pack size</th>
<th>Test setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4 kWh</td>
<td>Battery only</td>
</tr>
<tr>
<td>2</td>
<td>4 kWh</td>
<td>Battery only</td>
</tr>
<tr>
<td>3</td>
<td>4 kWh</td>
<td>Battery and interior components</td>
</tr>
<tr>
<td>4</td>
<td>16 kWh</td>
<td>Battery only</td>
</tr>
<tr>
<td>5</td>
<td>16 kWh</td>
<td>Battery only</td>
</tr>
<tr>
<td>6</td>
<td>16 kWh</td>
<td>Battery and interior components</td>
</tr>
</tbody>
</table>

### Table 6
**Summary of the water flow calculations for all suppression tests**

<table>
<thead>
<tr>
<th>Test #</th>
<th>Suppression operation time [min]</th>
<th>Total Water flow [gal]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.88</td>
<td>275</td>
</tr>
<tr>
<td>2</td>
<td>36.6</td>
<td>442</td>
</tr>
<tr>
<td>3</td>
<td>49.67</td>
<td>1060</td>
</tr>
<tr>
<td>4</td>
<td>26.52</td>
<td>1754</td>
</tr>
<tr>
<td>5</td>
<td>37.6</td>
<td>2639</td>
</tr>
<tr>
<td>6</td>
<td>13.88</td>
<td>1165</td>
</tr>
</tbody>
</table>

## EDV FIRES IN TUNNELS

Small and large scale testing of battery packs highlighted several potential issues associated with electrical vehicle fires in tunnels. By using the data contained in Table 1, it can be estimated that thermal runaway of large scale battery packs for electric vehicles applications can generate several cubic meters of pure flammable gases and, if properly mixed with air, they can generate several tens of cubic meters of a flammable mixture. The time scale associated with such release largely depends on the nature of the heat insult and the evolution of the fire emergency: if the EDV is the first vehicle that ignited, a relatively slow thermal cascade is expected and the corresponding venting of flammable gases is expected to be slow. On the contrary, if an EDV is exposed to high external heat fluxes from a nearby large vehicle (*e.g.* a fire involving a HGV), the venting of combustible cases can occur on shorter time scales. The resulting flammable cloud can combust as flash fire or generate an overpressure event depending on the ventilation conditions as well as the presence of confined or
congested areas (i.e. due to the presence of wreckage) in the tunnel. The potential for overpressure events become higher for fire loads involving large battery pack cargos the amount of vented gas could be substantial.

In some EDV vehicle designs, the contact between suppression agents (i.e. water) and the battery pack is impeded by the vehicle floor pan preventing efficient cooling of the Li-ion cells and favoring the propagation of thermal runaway events and flames re-ignitions. This might result in more challenging suppression activities. Longer active suppression and larger volumes of water than for traditional ICE vehicle fire are necessary to tackle EDV fires (see Table 6). In addition to suppressing the flames, the battery pack also needs to be cooled to prevent thermal runaways, repeated venting of flammable gases, and re-ignition.

Another aspect of fires involving electrical vehicles in tunnels is the emissions of hydrogen-fluoride (HF) and hydrochloric acid (HCl). Some large scale tests [9] reported the generation of these compounds during the combustion process and during the suppression activities. However, the data currently available are too scattered to draw general conclusions on the potential exposure of tunnel users during the evacuation phases.

CONCLUSIONS

This paper presents results of recent research on the characterization of electric vehicle fires. As discussed in this paper, the characterization of electrical vehicle fires requires complex combination of small scale and large scale testing. This paper presents novel data regarding the vent gas composition, energy release, and flammability of battery and battery packs. A review of the large scale fire involving electric vehicle is presented and discussed in terms of peak heat release rate, and most importantly in the context of fire suppression.

REFERENCES

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Risk Analysis in Road Tunnels – Most Important Risk Indicators

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ABSTRACT

Methodologies on fire risk analysis in road tunnels consider numerous factors affecting risks (risk indicators) and express the results by risk measures. But only few comprehensive studies on effects of risk indicators on risk measures are available. For this reason, this study quantifies the effects and highlights the most important risk indicators with the aim to support further developments in risk analysis. Therefore, a system model of a road tunnel was developed to determine the risk measures. The system model can be divided into three parts: the fire part connected to the fire model Fire Dynamics Simulator (FDS); the evacuation part connected to the evacuation model FDS+Evac; and the frequency part connected to a model to calculate the frequency of fires. This study shows that the parts of the system model (and their most important risk indicators) affect the risk measures in the following order: first, fire part (maximum heat release rate); second, evacuation part (maximum pre-evacuation time); and, third, frequency part (specific frequency of fire). The plausibility of these results is discussed with view to experiences from experimental studies and past fire incidents. Conclusively, further research can focus on these most important risk indicators with the aim to optimise risk analysis.

KEYWORD: fire, risk, road, tunnel, analysis

INTRODUCTION

Several methodologies on fire risk analysis in road tunnels with focus on human safety have been developed since the three large fires in the alpine road tunnels in 1999 and 2001 with the aim to evaluate the effects of safety measures [1]. Each methodology considers a unique set of factors which have effects on risks, named here as risk indicators. Commonly, the methodologies express risks by the two risk measures individual and societal risk. Apparently, each risk indicator has different effects on the risk measures. However, only few comprehensive studies on the effects of risk indicators on risk measures exist. For this reason, this study focuses on the analysis of the effects of risk indicators on risk measures and highlights the most important ones with the aim to support further developments of methodologies.

Several experimental and statistical studies describe risk indicators in road tunnels. In general, the risk indicators can be structured in three parts: first, the fire part; second, the evacuation part; and third, the frequency part. Firstly, the fire part focuses on the development of fire, e.g. the heat release rate (HRR). Potential risk indicators are: the width of the road tunnel and tunnel ventilation [2,3]; the flame length and flame spread [4]; various fire-fighting measures [5,6]; and the vehicle type [7]. Secondly, the evacuation part comprises potential risk indicators in the evacuation process: e.g. experiences of tunnel users in fire incidents [8]; alarm signals and signs [9]; or the spread of smoke, e.g. with effects on the walking speed of tunnel users [10,11]. Thirdly, the frequency part considers risk indicators with effect on the frequency of fires in road tunnels. Some risk indicators are: the average daily traffic volume (ADTV), the fraction of heavy goods vehicles (HGV) [6]; the tunnel geometry (e.g. additional ramps) [12]; the day time, location of the fire, or cause of fire (e.g. technical...
defects and accidents), as well as the tunnel slope [13]. In conclusion, complex interactions between the three parts and their risk indicators affect risks in road tunnels.

Due to the complexity of interactions, methodologies on risk analysis in road tunnels consider only some risk indicators analysed in the studies. This study also focuses on risk indicators applied in existing methodologies. Therefore, seven methodologies have been analysed in detail [14–20]. Risk indicators taken into account in most of these methodologies are considered to be fundamental for risk analysis. Conclusively, this study evaluates the effect of the fundamental risk indicators complemented with results from experimental and statistical studies.

To present the results of this study, the paper is organised as follows. The section ‘methodology’ describes the system model of a bi-directional road tunnel with two lanes. The system model comprises twelve fundamental risk indicators as well as external models to analyse the consequences in the upper evacuation area next to the fire source. The section ‘methodology’ also outlines the approach of the screening applied to evaluate the effects of risk indicators on risk measures. The section ‘results’ describes the outcomes of the screening and identifies the most important risk indicators: first, with respect to the effects on risk measures (maximum HRR; number of tunnel users; failure of tunnel alarm); and second, with focus on the three parts of the system model (fire part: maximum HRR; evacuation part: maximum pre-evacuation time; frequency part: specific frequency of fire). The section ‘discussion’ analyses the plausibility of the results of this study comparing the results with experiences from real fire incidents and experimental studies. Together with the discussion of the effects on risk measures, the section ‘discussion’ emphasises the limitations of the results, e.g. due to the tunnel geometry or the exclusion of model uncertainties. Finally, the section ‘conclusions’ focuses, first, on possible effects of safety measures and, second, on refinements of models, both in regard to the most important risk indicators.

METHODOLOGY

This study bases on a system model of a road tunnel. The system model considers twelve fundamental risk indicators identified in existing methodologies as well as parameter domains analysed in experimental and statistical studies [21]. The risk indicators serve as input for two external models to analyse the consequences as well as for a model to analyse the frequency of fire (frequency model). The risk measures are calculated in a Monte-Carlo simulation based on results of the three models. Finally, a screening of risk indicators reveals their effects on risk measures.

Risk Indicators and Fire Scenario

A directed acyclic graph provides the structure for risk indicators in the system model (see Figure 1). Each node in the graph represents a risk indicator with its model and can further contain additional independent variables x. The system model can be divided in three different parts: the fire part, the evacuation part and the frequency part. Each part comprises risk indicators directly linked to the fire, the evacuation or the frequency model. Finally, the three models provide the results to analyse the risk measures.
The fire scenario begins with the ignition of a vehicle after an accident or technical defect in a bi-

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**Table 1** List of independent risk indicators with their default probability distributions (U: uniform (min, max); C: constant (parameter), D: discrete (parameters)).

<table>
<thead>
<tr>
<th>Risk indicator</th>
<th>Distribution</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum HRR ($HRR_{max}$)</td>
<td>$D(5;30;50;100)$ MW with probabilities</td>
<td>[14]</td>
</tr>
<tr>
<td>time to maximum HRR ($t_{HRR}$)</td>
<td>$U(600;1200)$ s</td>
<td>[7]</td>
</tr>
<tr>
<td>maximum pre-evacuation time ($t_{pre,max}$)</td>
<td>$U(100;300)$ s</td>
<td>[8,9,24]</td>
</tr>
<tr>
<td>fraction of HGV with 5% buses</td>
<td>$U(0.05;0.45)$</td>
<td>traffic data, [22]</td>
</tr>
<tr>
<td>ADTV</td>
<td>$U(5000;40000)$ vehicles / day</td>
<td>traffic data</td>
</tr>
<tr>
<td>tunnel length</td>
<td>$U(1;3)$ km</td>
<td>assumption</td>
</tr>
</tbody>
</table>

---

The fire scenario begins with the ignition of a vehicle after an accident or technical defect in a bi-

---
directional traffic tunnel with two lanes. The exponential curve of the HRR depends on the risk indicators maximum HRR and time to maximum HRR [25]. After the fire started, a tailback forms and still more vehicles enter the tunnel. The fire is detected as soon as the HRR reaches five MW (detection time of fire). Immediately after fire detection, forced longitudinal emergency ventilation begins and the tunnel alarm is raised (time of tunnel alarm). The tunnel alarm triggers tunnel closing as well as alerts tunnel users. If the tunnel alarm fails, more vehicles enter the tunnel and each tunnel user gets alerted individually by smoke. Subsequently after the alarm, each tunnel user begins with the evacuation after the individual pre-evacuation time. During evacuation, the tunnel users move toward the closest emergency exit. However, smoke impedes the individual walking speed and combustion products can incapacitate the tunnel users. Finally, the scenario ends when all tunnel users either reached the emergency exit or were incapacitated due to smoke. In conclusion, the fraction of fatalities in a scenario depends on the scenario-specific set of parameters of the risk indicators.

Consequence Model

The system model includes two external models to analyse the incapacitation of tunnel users: the fire model Fire Dynamics Simulator 6.1.2 (FDS) [26] and the evacuation model FDS+Evac 2.2.1 [27]. The evacuation model adopts data on the spatial distribution of gas and soot concentrations from the fire model and determines the fraction of fatalities by the number of fatalities $N_{fat}$ and the number of tunnel users $N_{tu}$ in a scenario.

FDS models the spread of heat and combustion products in a 650 m long domain independent to the risk indicator tunnel length (see Figure 2). A validation study [28] and a grid sensitivity study showed that, firstly, FDS is in principal suitable to model tunnel fires and, secondly, a grid resolution of 0.25 m is sufficient to analyse the incapacitation of tunnel users. The forced longitudinal emergency ventilation maintains a gas speed of less than 1.5 m/s [23]. Therefore, two pairs of jet fans produce a gas flow in downhill direction and stop before disturbing the smoke layer. Furthermore, a parameter screening revealed various effects of the fire source, the tunnel geometry (e.g. domain length, vehicles) and further model parameters on evacuation. As one result of the screening, the fire source is located 200 m from the downhill end of domain burning an arbitrary fuel in well-ventilated conditions with a heat of combustion of 28 MJ/kg [29], a soot yield of 0.1 g/g [30] and a yield of CO to CO$_2$ of 0.05 mol/mol [24]. As another result, FDS considers the two risk indicators maximum HRR and time to maximum HRR as inputs for a scenario.

FDS+Evac models the evacuation process in the upper evacuation area next to the fire source (see Figure 2). Therefore, FDS+Evac adopts scenario-specific data from FDS to determine the incapacitation of tunnel users and to model their individual alarm. The tunnel users are randomly placed on the emergency paths and have an individual pre-evacuation time which is uniformly distributed between 0 s and the maximum pre-evacuation time. To take this randomness in evacuation scenarios into account, the fraction of fatalities for one scenario bases on the mean of 100 evacuation simulations. For validation of FDS+Evac, the individual walking speeds and flows through the emergency exit were compared to experimental data. Additionally, a screening provided information to define the individual alarm (soot density: $10^{-6}$ g/g) as well as the individual minimum walking speed in smoke (about 0.3 m/s in tunnels [11,15,24]). Also based on the screening, FDS+Evac takes
the following three risk indicators into account to analyse the fraction of fatalities in a scenario:
maximum pre-evacuation time, time of tunnel alarm and the number of tunnel users.

The fraction of fatalities is calculated for 800 scenarios in FDS+Evac based on 20 scenarios simulated in the fire model. Therefore, the parameter domains of the risk indicators are:

- \( 25 \text{ MW} \leq HRR_{\text{max}} \leq 100 \text{ MW} \);
- \( 600 \text{ s} \leq t_{HRR} \leq 1200 \text{ s} \);
- \( 100 \text{ s} \leq t_{\text{pre, max}} \leq 300 \text{ s} \);
- \( 30 \leq N_{\text{cu}} \leq 180 \);

and the time of tunnel alarm with and without failure. However, risk analysis has to consider much more scenarios which can not be specifically analysed in the consequence model. Hence, a meta-model is applied to get the fraction of fatalities in these scenarios. Therefore, the meta-model linearly interpolates the fraction of fatalities between the closest scenario-specific parameter sets of risk indicators of scenarios simulated in the fire and evacuation models. The type of the interpolation method as well as the number of scenarios only slightly affected the risk measures. Conclusively, the meta-model determines the fraction of fatalities in arbitrary scenarios not directly analysed in the fire and evacuation models.

**Risk Measures**

Risk analyses in road tunnels usually apply two different risk measures: the individual risk \( R_{\text{ind}} \) and the societal risk [1]. The focus on the upper evacuation area next to the fire source requires adaptions to common definitions [18,31]. Thus, individual risk is here defined as ‘the annual frequency that an unprotected person being permanently present in the upper evacuation area next to the fire source will die’. And societal risk is here ‘the annual frequency that a specified minimum number of persons will die in the upper evacuation area next to the fire source’. The societal risk is usually shown in a \( f_{\text{soc}}/N_{\text{fat}} \)-diagram, named here as societal risk curve, with the frequency \( f_{\text{soc}} \) of scenarios with more than \( N_{\text{fat}} \) fatalities. In conclusion, the adaptions must be kept in mind while interpreting the results of the system model.

The system model determines risk measures based on \( 10^6 \) scenarios randomly chosen by a Monte-Carlo method. The number of scenarios is sufficient to get accurate risk measures. Each scenario results in a fraction of fatalities calculated by the meta-model of the consequence model and a frequency of fire calculated by the frequency model. Therefore, the frequency model considers the risk indicators: specific frequency of fire, fraction of HGV, ADTV and tunnel length and furthermore takes into account that burning vehicles close to the tunnel portals can leave the tunnel [15]. Finally, the fraction of fatalities and the frequency of fire of all scenarios lead to the individual risk \( H_{\text{ind}} \) and the societal risk \( f_{\text{soc}}(N_{\text{fat}}) \) of the system model.

**Screening of Risk Indicators**

A screening evaluates the effects of risk indicators on risk measures. During the screening of a risk indicator, its variable \( x \) is set to a constant parameter \( x_i \). The other risk indicators maintain the default models as described in the section ‘risk indicators and fire scenario’. Thus, the system model considers only scenarios with the parameter \( x_i \), e.g. each HRR develops with \( t_{HRR} = 900 \text{ s} \). Then, the risk measures are calculated for \( x = x_i \), e.g. \( R_{\text{ind}}(t_{HRR} = 900 \text{ s}) \). The calculation is repeated for a set \( x_i \) of \( x_i \) between \( x_{\text{min}} \) and \( x_{\text{max}} \), e.g. \( t_{HRR} = \{600, 900, 1200\} \text{ s} \) leading to the risk measures \( R_{\text{ind}}(t_{HRR} = 600 \text{ s}), R_{\text{ind}}(t_{HRR} = 900 \text{ s}) \) and \( R_{\text{ind}}(t_{HRR} = 1200 \text{ s}) \). The relative effect \( \eta \) for the individual and the societal risk, defined by Eq. (1) and Eq. (2), quantifies the effects of risk indicators on risk measures. Therefore, \( R_{\text{ind, 0}} \) and \( f_{\text{soc, 0}} \) are the risk measures of the system model completely based on default models (default system model). Conclusively, the relative effect \( \eta \) determines the maximum increase of a risk measure in relation to the risk measure of the default system model.

\[
\eta(R_{\text{ind}}(x)) = \frac{\max(R_{\text{ind}}(x_i)) - \min(R_{\text{ind}}(x_i))}{R_{\text{ind, 0}}} \tag{1}
\]
\[ \eta(f_{soc}(x)) = \frac{1}{N_{fat,max,0}} \sum_{N_{fat}=1}^{N_{fat,max,0}} \max\left(f_{soc}\left(N_{fat},\bar{x}_i\right)\right) - \min\left(f_{soc}\left(N_{fat},\bar{x}_i\right)\right) \]

(2)

The following four risk indicators adapt the models during their screening: first, time of tunnel alarm with \(0 \leq p_{fail} \leq 0.1\); second, number of tunnel users with \(30 \leq N_{tu} \leq 180\) (three buses in the evacuation area) independent to the number of vehicles; third, specific frequency of fire with \(0.5 \cdot 10^{-8} / \text{veh.km} \leq f_{fire} \leq 4.5 \cdot 10^{-8} / \text{veh.km}\) [15]; and fourth, traffic speed with \(40 \text{ km/h} \leq v_{tra} \leq 100 \text{ km/h}\). Both latter ones are independent to the fraction of HGV.

Conclusively, these adapted models cause the relative effects on risk measures during screening.

RESULTS

The screening of risk indicators in the system model led to following results. Figure 3 shows the individual risk over the entire parameter domain \(R_{ind}(\bar{x})\) relative to the individual risk \(R_{ind,0}\) of the default system model. Table 2 shows the relative effect \(\eta\) of all risk indicators on both risk measures.

![Figure 3](image)

**Figure 3** Relative individual risk in relation to the default system model (left: fire and evacuation part; right: frequency part).

<table>
<thead>
<tr>
<th>risk indicator</th>
<th>individual risk</th>
<th>societal risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum HRR</td>
<td>(9778)</td>
<td>(9699)</td>
</tr>
<tr>
<td>time to maximum HRR</td>
<td>(2.0)</td>
<td>(5.0)</td>
</tr>
<tr>
<td>maximum pre-evacuation time</td>
<td>(2.0)</td>
<td>(3.0)</td>
</tr>
<tr>
<td>time of tunnel alarm</td>
<td>(0.3)</td>
<td>(7.3)</td>
</tr>
<tr>
<td>number of tunnel users</td>
<td>(0.3)</td>
<td>(727)</td>
</tr>
<tr>
<td>specific frequency of fire</td>
<td>(2.2)</td>
<td>(2.3)</td>
</tr>
<tr>
<td>ADTV</td>
<td>(1.5)</td>
<td>(1.6)</td>
</tr>
<tr>
<td>fraction of HGV</td>
<td>(1.3)</td>
<td>(3.0)</td>
</tr>
<tr>
<td>tunnel length</td>
<td>(1.1)</td>
<td>(1.1)</td>
</tr>
<tr>
<td>traffic speed</td>
<td>(0.0)</td>
<td>(0.0)</td>
</tr>
</tbody>
</table>

The following three risk indicators showed substantial effects on the fraction of fatalities: first, maximum HRR; second, time to maximum HRR; and third, the maximum pre-evacuation time. Thus, these risk indicators strongly affected the individual risk as well as fairly affected the societal risk.
The time of tunnel alarm, in particular the probability of its failure, influenced: first, the number of tunnel users; and, second, the individual evacuation time. Firstly, the effect on the number of tunnel users was small since the tunnel closing had little effect on the number of vehicles in the upper evacuation area. The effect would increase considering the entire tunnel. Secondly, the failure of tunnel alarm extended individual evacuation times of most tunnel users and consequently led to an increased fraction of fatalities. However, the frequency of a scenario with a failure of tunnel alarm was low which caused only little effects on the individual risk. But, only scenarios with failure of tunnel alarm led to high numbers of fatalities. Thus, with a view to the societal risk curve shown in Figure 4, scenarios without failures dominated the left part (high frequencies, small consequences) and scenarios with failures dominated the right part (low frequencies, large consequences). To sum up, the failure of tunnel alarm mainly influences the societal risk but not the individual risk.

![Figure 4](image-url) Societal risk curve of the default system model highlighting the effects caused by failures of the tunnel alarm, as well as the accepted societal risk curve in The Netherlands according to [32].

The number of tunnel users rarely affected the fraction of fatalities in the evacuation model due to the small density of tunnel users ('number of persons in a unit area' [33]) even in case of increased fractions of buses implying small effects on individual risk. Nevertheless, there are substantial effects on societal risk because societal risk per definition considers the number of tunnel users. Consequently, all risk indicators with effect on the number of tunnel users, e.g. the fraction of HGV, had stronger effects on societal risk than on individual risk.

In contrast to the previously mentioned risk indicators of the fire and evacuation part, the following four risk indicators of the frequency part mainly affected the frequency of fire: the specific frequency of fire, the ADTV, the fraction of HGV and the tunnel length. These risk indicators mainly influenced the individual risk and not the societal risk where the frequency of a scenario was less important than the number of fatalities. Among these four risk indicators, the specific frequency of fires caused the largest effects due to its large parameter domain, e.g. see [6]. However, the parameter domains of all four risk indicators could be specified in case of particular tunnel projects which would reduce the effects on risk measures (see Figure 3).

To sum up, the following risk indicators appeared to have remarkable relative effects on risk measures: first, the maximum HRR; second, the number of tunnel users; and, third, the time of tunnel alarm. Firstly, the maximum HRR protruded by a factor from ten to 100 compared the relative effects of all other risk indicators for both risk measures. Secondly, the number of tunnel users stuck out in case of societal risk with a factor of ten to the subsequent risk indicator time of tunnel alarm. Thirdly, the time of tunnel alarm influenced by its probability of failure had, as the number of tunnel users, neglecting relative effects on the individual risk, but revealed the third most relative effect on societal risk. However, its relative effect contrasted only slightly with a view to the remaining risk indicators.
In conclusion, these three risk indicators seem to be most important to reduce risks in road tunnels.

Finally, the different effects of risk indicators affect the importance of the three parts within the system model. Firstly, the fire part, especially the maximum HRR, had exceptional effects on the individual as well as on the societal risk. Secondly, the evacuation part, in particular the maximum pre-evacuation time and the failure of tunnel alarm, also affected both risk measures. However, with a view to the number of tunnel users, some strong effects on the societal risk were not caused by the evacuation model but by the definition of the societal risk. Thus, the evacuation part was less important than the fire part. Thirdly, the frequency part caused only small effects on the societal risk and furthermore, effects on individual risk would be lower for particular tunnel projects. Consequently, the frequency part had the smallest effects on risk measures in the system model. Conclusively, the three parts had following order regarding their effects on risk measures: first, fire part; second, evacuation part; and, third, frequency part.

DISCUSSION

Many models used to analyse individual or societal risk are based on scarce data. Thus, it is necessary to discuss the plausibility of: first, the consequence model; second, the risk measures; and, third, the effects caused by the risk indicators.

Plausibility of the Consequence Model

The number of fatalities determined in the consequence model (CM) was compared to the number of fatalities in real fire incidents (FI) to evaluate the plausibility of the consequence model. For this purpose, the three fire incidents in the alpine road tunnels of Mont-Blanc (1999) [34,35],Tauern (1999) [34,36,37] and St. Gotthard (2001) [37,38] were chosen. These tunnels have comparable cross-sections, and comprehensive descriptions of the fire incidents exist. Also, the spread of heat and combustion products in the upstream part of the tunnels qualitatively correspond to the fire model despite differences in tunnel slope or ventilation. However, only a comparison in terms of the order of magnitude was possible due to the obvious differences.

In a first step, the parameter domains of the risk indicators applied in the consequence model were defined for each fire incident (see Table 3). E.g. the actions of the fire brigade during the Tauern tunnel fire contributed to slow fire development ($t_{HRR} > 900$ s) as well as to rather fast reactions of tunnel users ($t_{pre,max} < 150$ s with tunnel alarm). In contrast, during the St. Gotthard tunnel fire, tunnel users did not properly react on the tunnel alarm. Thus, both, tunnel alarm and no tunnel alarm in the consequence model seemed to be plausible. For each fire incident, the number of tunnel users was estimated by the number of vehicles. Therefore, only tunnel sections were taken into account with comparable conditions to the consequence model. E.g. in the Mont-Blanc tunnel fire, the entire upstream part was considered since no alarm of tunnel users occurred, whereas in the St. Gotthard tunnel fire only vehicles close to the initial fire source were considered. In summary, the three fire incidents differ in particular in the fire development as well as in the reaction of tunnel users.

<table>
<thead>
<tr>
<th>Mont-Blanc</th>
<th>Tauern</th>
<th>St. Gotthard</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum HRR /MW</td>
<td>&gt;75</td>
<td>&gt;75</td>
</tr>
<tr>
<td>time to maximum HRR $t_{HRR}$ /s</td>
<td>&lt;800</td>
<td>&gt;900</td>
</tr>
<tr>
<td>maximum pre-evacuation time $t_{pre,max}$ /s</td>
<td>&gt;200</td>
<td>&gt;150</td>
</tr>
<tr>
<td>tunnel alarm</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>number of tunnel users (FI)</td>
<td>38</td>
<td>50</td>
</tr>
<tr>
<td>number of fatalities (FI)</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>number of fatalities (CM) (min, mean, max)</td>
<td>4;6;11</td>
<td>0;0;1</td>
</tr>
</tbody>
</table>
In a second step, first, the number of fatalities in the fire incident and, second, the number of fatalities in the consequence model were determined. Firstly, in the fire incidents, only fatalities were considered who tried to reach the emergency exit and e.g. not died in a vehicle or in the initial accident. However, in case of the St. Gotthard tunnel fire, too little data were available to determine a definite number of fatalities. Secondly, in the consequence model, the number of fatalities was determined by the number of tunnel users in the fire incident and the fraction of fatalities of scenarios simulated as basis for the meta-model (see section ‘consequence model’). More specific, only scenarios were chosen with parameter domains of risk indicators matching to the parameter domains of the fire incidents shown in Table 3. Thus, the number of fatalities bases on between 13 (Mont-Blanc tunnel fire) to 40 (St. Gotthard tunnel fire) scenarios simulated in the consequence model. As a result, Table 3 shows the minimum, mean and maximum number of fatalities of these scenarios.

Finally, the number of fatalities in the consequence model could be compared to the number of fatalities in the fire incidents (see Table 3). The three fire incidents differed e.g. in fire development as well as in the reaction of tunnel users. Despite the differences, the results of the consequence model are in the same order of magnitude of all three fire incidents. Conclusively, there is no reason to assume that the results of the consequence model are implausible.

**Plausibility of Risk Measures**

The system model focused on the upper evacuation area next to the fire source which had an effect on the risk measures. For individual risk, the fraction of fatalities was assigned on the entire tunnel which led to increased individual risks. For societal risk, the fraction of fatalities outside the upper evacuation area was zero. Thus, the focus on the upper evacuation area caused little effects on the societal risk curve for small number of fatalities. But the frequency $f_{soc}$ might be underestimated for higher number of fatalities. These effects have to be kept in mind for the interpretation of results.

The risk measures of the default system model were compared to accepted risks in The Netherlands [32] to evaluate the plausibility of the system model. The individual risk of the default system model ($2.4 \cdot 10^{-7} \, 1 / y$) was smaller than the accepted risk ($1.0 \cdot 10^{-6} \, 1 / y$). Possible reasons could be the moderate traffic conditions in a rather simple tunnel geometry. Figure 4 shows the societal risk curve of the default system model and the accepted societal risk curve. As explained in the section ‘results’, the failure of tunnel alarm was the reason for the obvious difference between both curves. As Figure 4 shows, the difference between the societal risk curve of the default system model and the accepted societal risk curve increased with growing number of fatalities which corresponded to the expectations explained in the previous paragraph. To sum up, the results produced by the system model are plausible.

**Plausibility and Limitations of the Effects of Risk Indicators**

The effects of risk indicators on the risk measures were compared to general expectations as well as to experimental results to evaluate their plausibility. The maximum HRR had strong effects on the fraction of fatalities and consequently on the individual and societal risk. This effect corresponded to experiences from past tunnel fires, e.g. the three alpine tunnel fires in 1999 and 2001. The effect of the specific frequency of fire on individual risk was also expected due to its large parameter domain as well as the direct effect on the risk measures. Furthermore, the effects of fast fire development (small parameters in the time to maximum HRR) and of fast reaction times of tunnel users (small parameters in the pre-evacuation time) as well as the effect of the number of tunnel users also corresponded to experiences from past fire incidents as well as from experimental studies. However, the effect of the frequency part on risk measures was unexpectedly small. But the fraction of fatalities varied stronger than the frequency of fire which also corresponded to experiences from past fire incidents. Therefore, risk indicators of the frequency part had smaller effects on the risk measures. In summary, the effects of risk indicators on risk measures are in line with experiences from fire incidents and studies.
This study focused on twelve risk indicators with each a definite parameter domain. But due to the complex interactions related to risks in road tunnels, a plenty of risk indicators are available. For this reason, other risk indicators or parameter domains with more effects on risk measures might exist. The system model also applied only one model in each risk indicator, as well as one fire, evacuation and frequency model. In particular, the fire model focused on scenarios in one cross-section, especially height, of the tunnel. Additionally, the system model excluded model uncertainties up to now. The application of other models, cross-sections, or the inclusion of model uncertainties, e.g. after quantitative validations, might have an influence on the results and will be analysed in further steps. However, the results are limited to the assumptions currently made in the system model.

CONCLUSIONS

The screening of risk indicators in the system model revealed their effects on risk measures and consequently allows, first, conclusions in regard to the effects of safety measures and, second, in regard to further developments in risk analysis.

Firstly, the following three risk indicators show notable relative effects on risk measures and thus the potential to reduce risks in road tunnels: first, maximum HRR; second, number of tunnel users; and, third, the probability of failure of the tunnel alarm. Firstly, safety measures preventing large fires, e.g. fixed fire-fighting systems, can lead to exceptional reduction of both risk measures. Secondly, safety measures limiting the maximum number of tunnel users, e.g. by the number of buses, can have considerable positive effects on societal risk. Thirdly, improving the probability of failure of the tunnel alarm seems to have moderate positive effects on societal risk. However, forgoing a tunnel alarm at all would increase both risk measures clearly. In conclusion, it is reasonable to suppose in general that these risk indicators are important for safety measures, but with a view to the assumptions made in the system model further research, e.g. on uncertainties, is still required.

Secondly, the three parts of the system model affect risks in the following order: first, fire part; second, evacuation part; and, third, frequency part. The most important risk indicators in each part of the system model are respectively: first, maximum HRR; second, maximum pre-evacuation time; and, third, specific frequency of fire. Consequently, models applied in each part can be refined to take the different effects into account. Firstly, the fire part should consider different influences on the maximum HRR, e.g. the ventilation or the tunnel geometry as proposed in experiments. Secondly, in the evacuation part, the pre-evacuation time is more important than the number of tunnel users. For this reason, evacuation models should rather focus on the pre-evacuation time than on queues of tunnel users at the emergency exit. Thirdly, in the frequency part, the specific frequency of fire should be based on tunnel specific data and take other traffic conditions into account, e.g. congestions or accidents. Finally, these refinements can optimise risk analysis.

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Evacuation of Modern Rail Tunnels – Emergency Ventilation and Large Fires or Not?

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ABSTRACT

This paper examines whether natural ventilation offers improved tenability for evacuation in the event of a fire on a train stopped in a tunnel. Recent Swedish Metro tests and tests at Carleton University produced fire sizes up to 77MW and 51 MW respectively, for tunnels with longitudinal ventilation and rolling stock ignited using significant volumes of accelerants. The fire sizes seen in these test programs raise the suggestion that longitudinal ventilation systems for smoke control should be sized to accommodate the fire sizes observed. However, improvements in the survivability of rolling stock with a fire on board mean that trains will almost always be able to continue to the next station rather than being stopped in a tunnel. Operational experience over many years supports this view. Further, operation of a longitudinal ventilation system around critical velocity both increases the rate of fire growth and decreases the tenability downstream. By contrast, natural ventilation will rarely lead to full flashover, and allows tenable conditions to exist on both sides of the fire during the evacuation phase, significantly improving the likelihood of escape. The paper argues that the benefits of operating a natural ventilation mode during the evacuation phase of the response to a train stopped on fire in a tunnel should be considered in the design and operation of new and existing tunnels.

KEYWORDS: Train fire, smoke control, natural ventilation

INTRODUCTION

The recent major fire test programs of rail cars in tunnels have challenged the railway operators and design communities as well as fire safety engineers to confront the potential for very large fires in rail tunnels and decide on an appropriate design response. The Swedish Metro tests¹ and the fire test program at Carleton University² produced fire sizes up to 77MW and 51 MW respectively.

At the same time, at least in metro and other urban railways, the statistics show few if any deaths in rail tunnels. Haack and Scheyer³ state that no deaths and few injuries have occurred in Germany in rail tunnels over 40 years. Similar data from in the UK, USA and from rail authorities in Australia also show few fatalities in over 40 years of operation of trains in rail tunnels.

In large part, this appears to be due to improved running capability and more fire resistant modern materials which means if a train fire occurs there is a very high probability of the train reaching the next station, where evacuation, smoke control and fire-fighting is much more efficient.

This leads to 3 key questions facing rail authorities and designers of rail tunnels:
• Should we design fire protection for rail tunnels, including smoke control, for peak fire sizes up to 77MW?
• Do we need tunnel ventilation systems and smoke control in rail tunnels?
If tunnel ventilation is provided, should we operate it for smoke control in the evacuation period?

This paper canvasses these issues through review of the latest fire research, rail standards development, rail operations, fire statistics, risk assessment methodologies and design thinking with the aim of providing a rational approach to development of practical design solutions for rail tunnels.

RAIL TUNNEL FIRE TESTS

There have been only a relatively few, well documented, test programs where rail rolling stock have been subject to fire tests in rail tunnels. The principal recent tests have been:

- Metro tunnel tests\(^1\) in Sweden undertaken by SP and others, based on Stockholm heavy rail metro cars, in 2011
- Carleton University test program\(^2\), involving Korean rolling stock with one metro and one intercity car, in 2011
- Testing of metro cars for Vienna Public Transport\(^4\) in 2010.

The Swedish and the Carleton test programs generated very large fires with full car involvement and peak heat release rates up to 77MW in the first case and 51MW in the second, which was surprise to many fire safety engineers used to basing their designs on much lower design fires. For both test programs, the rolling stock were older versions with limited modern fire resistant materials, the side doors were open, and airflows down the tunnel were at or close to critical velocity, which presumably enhanced the fire spread, fire growth rate and ultimate peak heat release rate.

In the case of the Swedish tests, substantial luggage fire loads were added, which might be typical of a worst case situation for an airport line train, but not common on most commuter trains. And when the older rail car materials were replaced with modern seats and non-combustible wall and ceiling linings in the second Swedish tunnel test, there was very little fire growth until additional fuel was added after one and half hours of fire duration.

For the metro cars tested for Vienna Public Transport, an older U type car did allow fire spread from the underfloor area into the public area or saloon, although significant fire spread leading to full car involvement and substantial temperatures and toxic gas levels did not occur until 30-40 minutes from fire ignition. Interestingly, reported air velocities were of the order of 0.2 to 0.35 m/s.

For the three fire tests of the newer V type rolling stock introduced in Vienna in 2001, none of the tests led to substantial fire spread and fully developed fires, despite using increasingly larger fire sources up to 770kW for 65 minutes and the total fire size never exceeded 3.3MW. This was presumably due to the more fire resistant seating and lining materials in the more modern V type rolling stock, and perhaps due to the doors being closed (apparently) and very low reported air flows.

Overall, what this set of three fire test programs appear to show is that some of the major factors likely to contribute to fire ignition, rapid fire spread and full car involvement (flashover) of rail cars are:

- The size of the initial fire source causing ignition
- The extent of added luggage as a fire load
- The “fire resistance” or ability of rail car seat and lining materials to resist ignition and spread of the fire
- The fire resistance of the floor and its ability to resist fire spread from underbody equipment up into the saloon
- Whether doors are open or not, providing limited or substantial ventilation air
- Whether tunnel ventilation is operational and providing substantial airflows through the rail car via open doors
This fire test research indicates that there is a low likelihood of a train fire going to flashover if rolling stock has reasonably modern “fire resistant” materials, the floor has a reasonable fire resistance, and the doors remain closed, at least until the train gets to the next station.

And if flashover can be avoided in rail tunnels, then very high heat release rates be avoided, and the number of casualties will be minimized. As well, more reasonable and cost effective smoke control design, if provided, will be able to be achieved, based on lower heat release rate design fires.

RAIL FIRE STATISTICS

This low likelihood of fully developed fires in rolling stock, and more particularly occurring in rail tunnels, is reflected in some of the available statistics or other data sourced internationally. For example:

- Devlin\(^5\), in a recent presentation to the 2015 NFPA conference in Chicago, indicated that no flashover fires in rail cars had occurred in US since NFPA 130 introduced the fire performance criteria for rail car materials in 1987 (or some 29 years ago)
- The RSSB data from the UK\(^6, 22\) indicates that no flashover fires have occurred in electric UK rolling stock since BS6853 fire performance requirements were introduced some 29 years ago in 1987.
- In Germany, Haack and Scheyer\(^3\) have stated that no fatalities and few injuries have occurred in Germany in over 40 years of underground rail operations
- Stodola and Lassy\(^4\) have indicated that there has only been one significant fire incident on the Vienna metro and that was an underfloor fire, rather than a saloon flashover fire, in 1991
- No flashover fires have occurred in Melbourne since seating materials were changed more than a decade ago\(^7\), and none have occurred in over 40 years of rail tunnel operations\(^7, 8, 23\).

While internal car (saloon) materials have been a key factor in minimizing the risk of fully developed fires in rail rolling stock, another important factor has been the much more stringent compliance approach to “running capability”, especially in Europe through the TSI process\(^8\). Cables and electrical equipment below the floor of modern rolling stock are designed to minimize the risk of underfloor fires stopping a train in a tunnel section between stations. Multiple unit configurations allow trains to continue even with failure to a motor. This means that even if a fire started in a train between stations, it is highly likely that the train, even in degraded mode, will get to the next station rather than stop in a tunnel section.

None of this data means that fires or casualties do not occur on railways, or that trains cannot be stopped by fires in tunnels. Some examples of fire events or scenarios which have caused or can cause trains to stop, potentially in a rail tunnel section include:

- The recent Washington DC Metro fire in rail tunnel near L’Enfant station, which led to one fatality and a significant number of injuries\(^10\)
- The cable fire on the NY Metro rail tunnel in 1990 which led to two fatalities\(^5\)
- The UK Class 350/2 train fire in 2010 near Leighton Buzzard Station\(^11\). In that event, a person committed suicide by fire in the toilet module of the train, and the fire caused the train to stop on an at-grade section of railway, a short distance from the station.
- The recent underfloor fire on a UK Class 458 train causing it to come to a stop on the at-grade rail network near Windsor & Eton Riverside Station\(^25\). The fire was due to an electrical fault, but by the time the train power had been turned off, the fire had punctured a hole in the vehicle flooring.
- The underfloor fire in Vienna\(^4\) in 1991
- A fire in a traction power converter caused a train to stop on an elevated section of track above a major road in Sydney\(^12\)
- A fire in underfloor traction equipment led to train being stopped at Croxton station in Melbourne, but without casualties\(^13\)
Also the Kaprun, Baku and Daegu train fires as well as the three significant fires in the Channel Tunnel remind us that major fire incidents and disastrous consequences can still occur in special circumstances, although rarely.

Fires may also start, not on rolling stock, but in trackside situations, such as the third rail arcing incident in Washington DC, and with trackside ignition of rubbish, or other external threats.

In summary, the fire statistics for rail rolling stock, and particularly electric passenger rail cars, and rail tunnels would indicate that the probability of a severe fire or one which reaches flashover and stops a train in a tunnel is very unlikely event, particularly if the railway has modern rolling stock with good “running capability” and materials with good quality “fire resistance”.

For most passenger trains, there is a very high probability the train will get to the next station, particularly with metro trains typically having a travel time of 2-3 minutes between stations. An underfloor fire may in extreme circumstances stop the train if the “running capability” is compromised leading to total loss of traction power or having brakes applied, but fires will be small. Fires within the car saloon, such as vandalism and arson, will not stop the train if driver policy/training is to go to next station. If trains do stop in the tunnel, fires are very likely to be small, and casualties are expected to be light.

For modern trains, recent design practice has often been to:

- Provide tunnel ventilation, bi-directional, usually with push-pull system
- Design based on 5-10MW metros, and 10-20MW heavy rail (>20MW for freight and DGs)
- Initiate critical velocity (generally in direction of travel) upon alarm

This seems reasonable approach, and the authors have seen no rail tunnel designs based on 77MW for reasonably modern rolling stock. But is it a case of the rail industry just being lucky so far, with a very large rail tunnel incident just waiting to happen?

RISK ASSESSMENT

The answer in a design sense is to use the best available tools to evaluate the risk of fires in a rail tunnel, and particularly those involving the rolling stock. It appears fires which could stop a train in a tunnel are of low likelihood, and most if not all fires are likely to be small, but there is a very low probability that the consequences could be catastrophic if a large fire grew to flashover on a train with a crush loaded population and stopped in a rail tunnel.

This is a classic risk problem requiring the application of robust quantitative risk assessment (QRA) techniques, based on a clear hazard assessment and multiple scenario and event tree analysis of the type outlined in Australian Standard for Tunnels AS4825. A similar robust process of analysis and risk assessment to support rail station and tunnel designs is set out in a recently published ITA methodology.

Recent designs for new and upgrade of existing rail tunnels, for which the authors have been involved, have utilized extensive QRA studies based on As Low as Reasonably Practical (ALARP) and So Far As Is Reasonably Practical (SFAIRP) frameworks, combined with extensive consultation with a range of stakeholders including rail authorities and emergency service. The risk results generated were, in most cases, combined with cost-benefit analysis based on the value of a life and a grossly disproportionality factor, as input to the final decision making.

In each case, the Swedish Metro and Carleton University fire test data and 77MW/51 MW scenarios were raised and discussed in stakeholder risk workshops. However, the designs and analysis for the rail tunnels were agreed to be based on much smaller peak fire sizes, given clear agreement on
stakeholder safety objectives, the type of rolling stock involved, the running capability, the “fire resistance” of rail car materials, the running times between stations, the fire detection systems installed, distance between exits, expected rail operations and emergency procedures, and the fire statistics for the particular rail systems involved.

CODES AND STANDARDS

The next question is whether railway tunnels require ventilation and smoke control? And if so, is it reasonable to leave smoke control during evacuation to natural ventilation and allow, as far as possible to stratify and spread along the tunnel roof, or better to drive some in a longitudinal direction by mechanical means?

To begin with, fire safety and other railway engineers are very much aware that mechanical ventilation systems for rail tunnels may be required for reasons other than smoke control, including management of heat and humidity as well as control of gases, including methane and other gases entering tunnels due to localized organic materials, and for use in terrorist attacks.

In relation to fire safety and control, the traditional code approach to tunnel fire safety design in many countries worldwide is to follow NFPA 13017, or at least use it as guidance for design. That standard assumes a major tunnel fire could occur, and requires bi-directional emergency ventilation for smoke control. Most designers, in the event of a fire alarm, will initiate smoke control at critical velocity around the annulus of the train in the tunnel in the direction of rail travel. This will typically be 2.5 to 3.0 m/s. Generally, there will be no regard to the impact of ventilation on fire growth and smoke production.

In Australia, the relatively new tunnel standard AS482515 recommends longitudinal ventilation but does not specify whether it needs to be bi-directional or not, and does not clarify whether it needs to be activated during evacuation or not.

The EU TSI on “Safety in Railway Tunnels”8, in contrast, is based on a philosophy that improved running capability (preventing fires and other events stopping the train in the tunnel) and hardened materials for better “fire resistance” means the chances of a major fire in a tunnel is very unlikely, with small fires only expected, and tunnel ventilation for smoke control is not mandated.

This approach is reinforced by the International Tunnelling Association (ITA) which has recently published an “Engineering Methodology for Performance Based Fire Safety Design on Underground Rail Systems”16. The document states “In summary and in most cases, only a train fire in the station needs to be considered with respect to maintaining tenable air conditions during the phases of self-rescue and intervention by fire and rescue services.”

The ITA methodology suggests that for many rail tunnel designs, no tenability assessment in tunnels is required because trains are highly likely to be able to travel to the next station for far more efficient evacuation and fire-fighting. However, the methodology requires a scenario based risk assessment to be undertaken to determine overall fire safety measures. And it highlights the fact that special attention needs to be given and ventilation and mechanical smoke control may be required in rail tunnels where:

- The emergency train brake is not inhibited while the train is travelling through the tunnel, which could cause a train on fire to be stopped by a passenger activating the train brake system,
- The tunnels serve both passenger and freight trains

This approach of the TSI and the ITA is a radical departure from the conventional practice in many countries, where the design of a push-pull ventilation system to be operated in fire mode for smoke
control during evacuation has been the norm for many years for new tunnel design. And designers have grappled with the modelling and interaction between smoke flows and passengers evacuating.

**RECENT RESEARCH**

Tarada\(^{18}\) supports this view of no tunnel ventilation for passenger evacuation when he states:” The provision of emergency ventilation only at stations is deemed appropriate by the ITA to provide a pragmatic design objective that addresses ‘reasonable worst case’ scenarios”. He acknowledges that tunnel ventilation may be required for fire-fighting or control of temperature and humidity, including during lengthy evacuations.

The paper by Tarada is not inconsistent with the views of Carvel in a 2014 presentation\(^{19}\) entitled “Tunnel Design Fires v. Tunnel Ventilation” where he makes the proposition that, in a sense, design fires depend on the ventilation regime adopted, not the reverse. Conventional practice in tunnel design has been to decide on one or more design fires and then undertake an analysis to support the choice of ventilation system design. Carvel argues that, given rail tunnel rolling stock fires are typically ventilation controlled, the effect of forced airflows will only ensure more rapid fire growth and higher peak heat release rates, although the fire durations will be shorter. This could be seen to have a greater impact on evacuating passengers in a stopped train situation in a rail tunnel then if smoke from a train fire is allowed to vent naturally. Thus, ventilation decisions will define the expected fire, not the other way around.

Winkler\(^{20}\) at the University of Edinburgh, with the guidance of Carvel, has now carried out detailed research in relation to evacuation from stopped trains in rail tunnels. His work has included CFD, tenability and egress analysis for long trains in a simulated rail tunnel, with evacuation on one or both directions. He has investigated fires at various rail locations for tunnels with natural ventilation (no forced airflows) and longitudinal mechanical ventilation based on simultaneous and phased evacuation.

Part of Winkler’s work reviewed the Swedish and Canadian fire test research and focused on that fact that the forced airflow of a mechanical ventilation system will promote fire growth and increase smoke volumes and toxicity much more than with natural ventilation, as was seen in the Swedish and Canadian fire test.

Winkler has concluded that for rail tunnels:

- Forced airflows at or near critical velocities in combination with simultaneous evacuation should only be used when the fire is located on the power car or the first adjacent carriage.
- In the case where the fire is located in intermediate carriages or if the location of the fire is unknown, no forced airflows should be introduced – natural ventilation mode.

This work all supports the proposition that, at least for some rail tunnels and for most scenarios, better safety outcomes may be achieved during simultaneous evacuation if natural ventilation is the selected ventilation mode during the evacuation period. In particular, this applies where the fire location is not known precisely, which will be the case for many railways which run a mix of new and legacy rolling stock or do not have the latest train location, digital train radio and other state of the art communication technologies. Even for fires in the first or last carriages, natural ventilation may not be a significantly worse choice than forced ventilation, thereby leading to the simpler operational criteria that would select natural ventilation for all fires in the passenger compartment.

A recent design of the new rail tunnel under Brussels Airport runway identified as the Diabolo project\(^{21}\) has a range of technologies to identify the location of the fire on the train and also the location of the train in the tunnel. These include:

- Duplicated linear heat detection along the tunnel roof
- Train location sensors each 20m
• Tunnel CCTV
• A dynamic evacuation guidance system of flowing green lights to exits
• Bi-directional longitudinal ventilation system
• A complex “intelligent” multi-scenario emergency management and control system

While this Diabolo tunnel control system has the potential to deal with smoke control for all scenarios using longitudinal smoke ventilation, it recognizes the impact of smoke on evacuating passengers where they may be exposed to some from forced airflows. The designers highlight the fact that “In order to allow evacuation of passengers from the ‘shortest’ part of the train, a time algorithm has been implemented to introduce a time delay before starting up the longitudinal smoke ventilation. During this time delay, smoke will stratify at the tunnel ceiling which is more likely to have a less negative effect on the passengers evacuating from the ‘shortest’ part of the train”.

CONCLUSIONS

The 3 key design questions asked at the start of this paper were:
• Should we design fire protection for rail tunnels, including smoke control, for peak fire sizes up to 77MW?
• Do we need tunnel ventilation systems and smoke control in rail tunnels?
• If tunnel ventilation is provided, should we operate it for smoke control in the evacuation period?

While each rail tunnel and its design is different, for most passenger train tunnels design can be undertaken to much lower design fire sizes in the range of 5-20MW, depending upon careful consideration of a large number of factors of infrastructure and rolling stock design as well as details of rail operations and emergency management. Comprehensive risk assessment combined with detailed modelling and analysis as well as stakeholder consultation are the key to appropriate and cost effective design outcomes.

The matter of the need and type of tunnel ventilation for a rail tunnel will depend on consideration of a range of hazards to be managed, and not just fire events. Control of smoke by mechanical ventilation, for example, may be required for fire fighters to minimize asset damage, even if passengers have evacuated before their arrival. However, if mechanical ventilation is not provided, natural ventilation to let smoke stratify and flow along the tunnel roof as far as possible will always be available as a form of smoke control.

During evacuation of a train in a rail tunnel, the evidence seems to point to selecting a natural ventilation approach rather than operating the mechanical longitudinal ventilation system during the evacuation period may provide better conditions overall for escape for many systems. This seems particularly the case where the fire location on the train is unknown, or where the fire is not right at one end of the train or other. The impact of the forced airflow on fire growth, stratification, mixing of smoke and velocity of smoke down the tunnel creates less favourable conditions for evacuation than if mechanical systems are not operated during the evacuation phase. The mechanical system (if installed) may be operated at a later stage to support fire-fighting operations.

This move to natural ventilation during evacuation will be a challenge to some fire safety and rail designers as well as rail authorities and some codes and standards writers who have not considered this matter in detail in the past.
ACKNOWLEDGEMENTS

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Probability of a Large Fire in a Road Tunnel
a Bayesian Approach

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ABSTRACT

Article 13 of the EU Directive on minimum safety requirements for tunnels in the Trans-European Road Network states that a “risk analysis, where necessary, shall be carried out” [1]. In the Netherlands, the risk of death for road users in a tunnel (internal risk) is calculated with a model for quantitative risk analysis, which is called “QRA-tunnels”. The probability of fire that has been used in the model was expected to be too high compared to the probability of fire based on statistics [2]. In this paper a Bayesian approach is presented based on a research study enabling the calculation of the probability of a large fire in a road tunnel [3]. The calculations result in a lower probability of a large fire, enabling QRA-tunnels to be adapted.

KEYWORDS: quantitative risk analysis, QRA, QRA-tunnels, road tunnel, fire, probability, Bayes, statistics, tunnel safety.

INTRODUCTION

The EU Directive on minimum safety requirements for tunnels in the Trans-European Road Network states that “risk analyses, where necessary, shall be carried out... A risk analysis is an analysis of risks for a given tunnel, taking into account all design factors and traffic conditions that affect safety, notably traffic characteristics and type, tunnel length and tunnel geometry, as well as the forecast number of heavy goods vehicles per day. Member States shall ensure that, at national level, a detailed and well-defined methodology, corresponding to the best available practices, is used...” [1].

In the Netherlands, the risk of death for road users in a tunnel (internal risk) has to be calculated with a model for quantitative risk analysis, which is called “QRA-tunnels”. This model (version 2.0) has been developed for Dutch tunnels in particular [6,66]. One of the parameters in the model is the probability of a fire in a tunnel per vehkm. That probability was expected to be too high when compared to the intuitively expected statistical probability of a fire [2]. In this paper a Bayesian approach is presented that enables calculating the statistical probability of a large fire in a tunnel, based on little data. The method has been used for Dutch tunnels and has led to a recommendation to change the current value used in QRA-tunnels for the probability of fire [3].

Problem definition

The current value for the probability of fire used in QRA-tunnels was supposed to be too high. The results from the calculations with QRA-tunnels were therefore thought to be too conservative. TNO was asked to calculate the probability of a large fire in a road tunnel based on statistics: large fires that have actually occurred in the Netherlands. However, at that time only one large fire has happened1. In 1978 a large fire occurred in the Velsertunnel, resulting in 5 casualties [4]. The size of the fire has not been calculated or measured, but has been estimated to be > 40 MW [5] and < 50 MW [1]. Simply

1 In the mean time a large fire has happened on 21st May 2014 in the Heinenoordtunnel with a fire size of 58 MW according to calculations made by Efectis [8].
calculating the probability based on that one fire in a frequentistic manner, seemed to be not reliable.

**Scope**
The scope of the study is large fires in vehicles in road tunnels. A fire is defined as being large when its heat release rate (HRR) is at least 25 MW. Fires in road tunnels not in vehicles, but for example in installations, are outside the scope of this study. Also vehicle fires outside the enclosed part of the tunnel, for example in the tunnel entrance, are outside the scope.

**Approach**
In first instance the basis for the probability used in QRA-tunnels has been studied. Then, since the frequentistic method seemed to result in an unreliable outcome, the Bayesian approach has been chosen. Since at that time only one large fire had happened in The Netherlands, also the small fires in The Netherlands and the large fires in European countries have been included in the Bayesian approach.

**CURRENT PROBABILITY OF FIRE**

The initial probability of fire that is used in QRA-tunnels is the same for cars, buses and trucks and is $2 \times 10^{-8}$ per vehicle kilometre (vehkm) [6]. This is the probability that a fire occurs, regardless the fire size developed over time. To differentiate between the fire sizes, QRA-tunnels calculates the sequential (conditional) probabilities that the fire develops into a certain size, given the initial fire. The probability of a fire with a certain size is therefore the product of the initial probability of fire and the sequential probabilities belonging to a certain fire size. The fire sizes used are: 5 MW, 10 MW, 25 MW, 50 MW, 100 MW and 200 MW. Since the research focuses on large fires, the fire sizes $\geq 25$ MW are taken into account.

In [7] the background of the initial probability of fire of $2 \times 10^{-8}$ per vehkm is given. It states that the probability of fire of $2.3 \times 10^{-8}$ per vehkm has been deduced based on 145 fires in trucks on open roads that have occurred in 1984. The number of vehicle kilometres used in the calculation are the 6200 million vehkm travelled by heavy traffic in the year 1994. Since the numerator of the fraction stems from 1984 and the denominator from 1994, it would have been a better decision to use both numbers from the same year. With probably an increased number of vehicle kilometres in the years between 1984 and 1994, the outcome of the fraction might underestimate the actual probability of fire.

The resulting probability of fire is divided into the probability of a large fire and of a small fire with a ratio of 30:70, resulting in the following numbers:

\[
\begin{align*}
P \text{ (large fire)} &= 6.9 \times 10^{-9} \text{ per vehkm.} \\
P \text{ (small fire)} &= 1.61 \times 10^{-8} \text{ per vehkm.}
\end{align*}
\]

For cars the same probabilities are used, since no data for cars are available. In [6] it is recommended to use a probability of fire of $2 \times 10^{-8}$ per vehkm for cars, buses as well as trucks.

**DUTCH DATA**

The current probability of fire is based on relatively old data from 1984 and 1994. In this chapter an overview is given of the fires that have happened in Dutch tunnels and the number of vehicle kilometres that have been travelled.

**Fires**

We distinguish between small and large fires and between unbroken registered periods and incidental registration of fires. The data has been found by means of literature research and interviews with tunnel administrators. Fires in TERN$^2$ tunnels had to be registered since 2006, resulting in 3 fires.

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2 Trans European Road Network
between 2006 and 2012 [9], [10], [11], [12]. The unbroken registered periods result in 3 fires between 2002 and 2012 [13], [14]. The incidental registration (hereafter non-registered period) results in 2 fires [2], [5], [15]. In theory more fires may have happened than the 2 fires mentioned. In total (at least) 8 fires have occurred of which one was a large fire.

Traffic intensity
Besides the data on fires, also the data on the traffic intensity is needed. Based on [16] and the identification of the number of fires, Table 1 and Table 2 have been composed.

Table 1: Overview of fires in Dutch tunnels (registered periods)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Schipholtunnel</td>
<td>67</td>
<td>6</td>
<td>0,6</td>
<td>238</td>
<td>1</td>
</tr>
<tr>
<td>Beneluxtunnel</td>
<td>47</td>
<td>6</td>
<td>0,8</td>
<td>238</td>
<td>0</td>
</tr>
<tr>
<td>Wijkertunnel</td>
<td>21</td>
<td>6</td>
<td>0,7</td>
<td>85</td>
<td>1</td>
</tr>
<tr>
<td>Thomassentunnel</td>
<td>20</td>
<td>6</td>
<td>1,1</td>
<td>129</td>
<td>0</td>
</tr>
<tr>
<td>Botlektunnel</td>
<td>41</td>
<td>6</td>
<td>0,5</td>
<td>125</td>
<td>0</td>
</tr>
<tr>
<td>Noordtunnel</td>
<td>38</td>
<td>6</td>
<td>0,5</td>
<td>123</td>
<td>0</td>
</tr>
<tr>
<td>Drechttunnel</td>
<td>50</td>
<td>6</td>
<td>0,6</td>
<td>171</td>
<td>1</td>
</tr>
<tr>
<td>Heinenoordtunnel</td>
<td>31</td>
<td>6</td>
<td>0,6</td>
<td>114</td>
<td>0</td>
</tr>
<tr>
<td>Tunnel Swalmen</td>
<td>13</td>
<td>6</td>
<td>0,4</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Roertunnel</td>
<td>14</td>
<td>6</td>
<td>2,0</td>
<td>177</td>
<td>0</td>
</tr>
<tr>
<td>Leidsche Rijn</td>
<td>32</td>
<td>1</td>
<td>1,7</td>
<td>52</td>
<td>0</td>
</tr>
<tr>
<td>Westerscheldetunnel</td>
<td>5</td>
<td>10</td>
<td>6,7</td>
<td>361</td>
<td>3</td>
</tr>
<tr>
<td>Vlaketunnel</td>
<td>16</td>
<td>10</td>
<td>0,3</td>
<td>51</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>1896</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 2: Overview of fires in Dutch tunnels (non-registered period)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All tunnels⁵</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9082</td>
</tr>
<tr>
<td>Drechttunnel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Velsertunnel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

The size of the fires is not known, except for the fire in the Velsertunnel in 1978 with an estimated size of between 40 and 50 MW. It is assumed that the other fire sizes were less than 25 MW, based on the presumption that fires with a size of 25 MW or more would have been published in the media. It is plausible that these fires were even limited to a size smaller than or equal to 5 MW, but to be on the safe side, a limit of 25 MW is used.

EUROPEAN DATA
Since the Dutch data on fires was rather limited, fires in European tunnels have also been included in the analysis. Fires from registered as well as non-registered periods have been identified and a difference between small (< 25 MW) and large (≥ 25 MW) fires. The information on the registered

⁵ In the Netherlands 10.978 mln vehiclekilometers through tunnels have been travelled, of which 1896 in the registered period and 9082 in the non-registered period.
period from references [17] to [47] has been summarised in Table 3.

Table 3: Overview of fires in European tunnels in the registered period

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Length tunnel [km]</th>
<th>Cum. Number vehkm [mln vehkm]</th>
<th>Number of fires (&lt;15 MW) [-]</th>
<th>Period [year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>5,4</td>
<td>891</td>
<td>2</td>
<td>varying</td>
</tr>
<tr>
<td>Germany</td>
<td>41,1</td>
<td>9900</td>
<td>103</td>
<td>6</td>
</tr>
<tr>
<td>Norway</td>
<td>778,5</td>
<td>18470</td>
<td>160</td>
<td>10</td>
</tr>
<tr>
<td>Sweden</td>
<td>1,6</td>
<td>193</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Denmark</td>
<td>5,3</td>
<td>388</td>
<td>1</td>
<td>varying</td>
</tr>
<tr>
<td>France</td>
<td>60,5</td>
<td>2886</td>
<td>47</td>
<td>6</td>
</tr>
<tr>
<td>Austria</td>
<td>348</td>
<td>10454</td>
<td>63</td>
<td>6</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>5,7</td>
<td>144</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>1246,1</td>
<td>43,326</td>
<td>377</td>
<td>varying</td>
</tr>
</tbody>
</table>

Data from other European countries were incomplete or less comparable and have, in accordance with the client, not been included in the analysis.

Table 4: Large fires in European tunnels in the non-registered period

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Age [yr]</th>
<th>Length tunnel [km]</th>
<th>Cum. nr. veh. since opening</th>
<th>Cum. Mln. vehkm</th>
<th>Number of fires</th>
<th>HRR [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mont Blanc tunnel</td>
<td>44</td>
<td>12</td>
<td>62,213,509</td>
<td>722</td>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td>Tauern</td>
<td>37</td>
<td>6</td>
<td>214,729,5008</td>
<td>1374</td>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td>Hovden</td>
<td>20</td>
<td>1</td>
<td>13,870,000</td>
<td>18</td>
<td>1</td>
<td>150</td>
</tr>
<tr>
<td>Ekeberg</td>
<td>17</td>
<td>2</td>
<td>291,635,000</td>
<td>456</td>
<td>1</td>
<td>35</td>
</tr>
<tr>
<td>Mt Blanc</td>
<td>44</td>
<td>12</td>
<td>62,213,509</td>
<td>722</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Pfänder</td>
<td>32</td>
<td>7</td>
<td>205,568,000</td>
<td>1381</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>L’Arme</td>
<td>33</td>
<td>1</td>
<td>100,322,805</td>
<td>110</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Castellar</td>
<td>43</td>
<td>1</td>
<td>221,613,400</td>
<td>126</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Hitra</td>
<td>18</td>
<td>6</td>
<td>8,081,100</td>
<td>46</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Felbertauern</td>
<td>45</td>
<td>5</td>
<td>50,000,000</td>
<td>264</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Frejus</td>
<td>32</td>
<td>13</td>
<td>32,000,000</td>
<td>412</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Porte d’Italie</td>
<td>42</td>
<td>0</td>
<td>1,533,000,000</td>
<td>652</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Moorfleet</td>
<td>49</td>
<td>0</td>
<td>733,285,000</td>
<td>178</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Roldal</td>
<td>48</td>
<td>5</td>
<td>17,520,000</td>
<td>82</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Kingsway</td>
<td>41</td>
<td>2</td>
<td>493,845,000</td>
<td>988</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15</td>
</tr>
</tbody>
</table>

4 The cumulative number of vehkm is calculated as Σ(AADT * #days per year * cum. tunnel length * period/1000000), where the AADT can be found in the references.
5 In a period of two years (2008 and 2009), 3300 mln vehkm have been travelled. It is assumed that in a six year period, three times this number is travelled.
6 AADT from [48], except for the Pen-Y-Cliptunnel, which has been estimated on the basis of the average AADT of the Conwy and Penmaenbach tunnels, since they are in the same highway.
7 All numbers in the columns “Age” and “Cum. Nr. Veh. Since opening”, except the shaded ones, are based on facts
8 Shaded cells: numbers are based on estimations.
In Table 4 the information on large fires in the non-registered period from references [48-65] has been summarised. To be able to use this information, also the overall traffic intensity was needed. In a quick scan an inventory of tunnels in Europe was made, resulting in 1590 tunnels. Since the traffic intensity in the tunnels was not known for part of the countries, it was chosen to use only the information of countries of which the traffic intensity was known. This choice resulted in 1148 remaining tunnels with a travelled distance of 8939 mln vehkm per year.

The average age of Dutch tunnels is 25 years, based on the information in [16]. It is (maybe conservatively) assumed that the average age of European tunnels is the same. Therefore the cumulative number of vehkm follows from: 8939 * 25 = 223.463 mln vehkm. In the registered period 43.326 mln vehkm has been accounted for, resulting in 223.463 – 43.326 = 180.137 mln vehkm in the non-registered period. The presumption is that in the 180.137 mln vehkm travelled no fire larger than about 50 MW has occurred, besides the fires mentioned in Table 4, because these fires would have been identified in studies like DARTS. The HRR has on purpose been chosen larger than compared to the Dutch data, since the probability of overseeing a fire is larger on European than on Dutch scale.

**METHOD TO CALCULATE THE PROBABILITY OF A LARGE FIRE**

**Statistical model**

For the probability of fire in a tunnel having a HRR exceeding a certain size X we assume a model existing of the product of the probability of fire and the conditional probability that the size of the fire is larger than a certain value X:

\[ P(\text{HRR} > X) = p \exp(-X/b) \]  

with:

- \( p \) = the probability of a vehicle fire per million vehkm [1/Mvehkm]
- \( \exp(-X/b) \) = the probability of fire with HRR > X, given a fire occurs [-]
- \( b \) = average value of HRR, given a fire occurs [MW]

For the probability distribution of the HRR, given a fire has occurred, an exponential model has been chosen. This probability distribution suits our expectation that relatively many fires are small and just a few fires are large. On a logarithmic scale the fire size is a linear function of the number of vehkms. A similar relation can be seen with extreme events (storm surges, earthquakes) and is usually assumed to be “conservative”.

The parameters \( p \) and \( b \) in (1) are unknown and need to be estimated on the basis of the available data. The Bayesian estimation procedure has been used to do so.

**Bayesian estimation procedure**

The Bayesian estimation procedure follows the well-known Bayes’ Theorem:

\[ P(A|B) = P(B|A) \cdot P(A) / P(B) \]  

We apply this theorem to the parameter estimation by associating event A with the values to be taken by the unknown parameters \( p \) and \( b \) and event B with the available data [67]. Noted as:

A = (\( p, b \) take certain values ) and B = (occurrence of the data)

Then (2) becomes:

\[ P(p,b|\text{data}) = C \cdot P(\text{data}|p,b) \cdot P(p,b) \]  

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Where C is a normalisation constant, equal to $1/P(B)$ from (2). Further:

- $P(p,b)$ = the “a priori probability distribution” of the parameters $p$ and $b$ if no data is known.
- $P(p,b|\text{data})$ = the “a posteriori probability distribution” of the parameters $p$ and $b$ after the data has been incorporated.
- $P(\text{data}|p,b)$ = the probability that the data occurs at known values of the parameters $p$ and $b$ (usually called “likelihood”)
- $C$ = a standardization constant

In words it says:

$$\text{POSTERIOR} = C \times \text{LIKELIHOOD} \times \text{PRIOR}$$

The value of $C$ can easily be calculated as soon as the likelihood and prior are known. The constant makes sure that the sum of (or integral over) all posterior-probabilities is equal to 1.0, like every proper probability distribution should be.

**Likelihood function**

The likelihood is the probability of finding the available data if the values of $p$ and $b$ are considered to be known. Given the Dutch and European data, we need to set the likelihood function for three types of data (see Table 5):

- there are $n_1$ million vehkm with a fire with a HRR equal to X;
- there are $n_2$ million vehkm with no fire;
- there are $n_3$ million vehkm with a fire with a HRR smaller than X.

The type “larger than” has not been set because no data of that type is available.

In formula:

- $P(\text{data}|p,b) = \left[ \frac{p}{b} \exp\left(-\frac{X}{b}\right) \right]^{n_1}$ \hspace{1cm} (4a)
- $P(\text{data}|p,b) = \left[ 1-p \right]^{n_2}$ \hspace{1cm} (4b)
- $P(\text{data}|p,b) = \left[ 1-p+p\left(1-\exp\left(-\frac{X}{b}\right)\right) \right]^{n_3}$ \hspace{1cm} (4c)

Multiplication of (4a), (4b) and (4c), if necessary for different values of X, gives the likelihood.

Data has been expressed in terms of number of fires per million vehicle kilometres; the occurrence of two fires in the same “package” of 1 million vehicle kilometres has been neglected.

Note: For the unity of “one million vehicle kilometres” in the calculation alternatively 100,000 vehkm has been chosen. This had no influence on the result, which affirms the correctness of the assumption. The reason for choosing 1 million vehkm instead of for example 1 vehkm is purely practical and has to do with the manageability of the numbers in Excel.

**The data**

*The Netherlands*

For The Netherlands the data is limited to a few years and part of the tunnels: most fires are small car fires. Furthermore it is known that there was only one large fire, being the fire in the Velsertunnel in 1978. The HRR is estimated to be between 40 and 50 MW [1], [5]. From the remaining vehkm in the other years is known that no large fire has happened. In the analysis that is taken into account as “smaller than 25 MW”. This seems on the safe side and that is intended. Also the known “car fires $\leq 5$ MW” are taken into account in the “$< 25$ MW” group. It would be best to completely separate car
fires from the larger truck fires, because they are not well-captured with a simple model as in (1). The summarized data results in the following categories (based on Table 1 and Table 2):

Table 5: Dutch Data

<table>
<thead>
<tr>
<th>Data Range</th>
<th>Fire Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 million vehkm</td>
<td>With a fire equal to 40-50 MW</td>
</tr>
<tr>
<td>1890 million vehkm</td>
<td>No fire (this is 1896 - 6)</td>
</tr>
<tr>
<td>9087 million vehkm</td>
<td>No fire or fires &lt; 25 MW</td>
</tr>
</tbody>
</table>

The number of 1890 times no fire is the total of 1896 from the registered period minus the 6 small fires. The number of 9087 times no fire is the total of all 10978 vehkm minus (registered and unregistered periods) 1890 and minus 1 large fire. The 6 small fires are also part of this group.

Europe

In the same way the European data can be summarized (based on Table 3 and Table 4):

Table 6: European data

<table>
<thead>
<tr>
<th>Data Range</th>
<th>Fire Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 million vehkm</td>
<td>With a fire size equal to 300 MW</td>
</tr>
<tr>
<td>2 million vehkm</td>
<td>With a fire size equal to 200 MW</td>
</tr>
<tr>
<td>0 million vehkm</td>
<td>With a fire size equal to 100 MW</td>
</tr>
<tr>
<td>0 million vehkm</td>
<td>With a fire size equal to 50 MW</td>
</tr>
<tr>
<td>2 million vehkm</td>
<td>With a fire size equal to 30 MW</td>
</tr>
<tr>
<td>10 million vehkm</td>
<td>With a fire size equal to 20 MW</td>
</tr>
<tr>
<td>42.949 million vehkm</td>
<td>No fire (this is 43.326-377)</td>
</tr>
<tr>
<td>180.499 million vehkm</td>
<td>No fire or fire &lt; 50 MW</td>
</tr>
</tbody>
</table>

The number of 42.949 times no fire is the total number of 43.326 from the registered period minus the 377 small fires. The number of 180.499 times no fire or a small fire is the total number of 223.463 minus 42.949 and minus the 15 large fires. The 377 small fires are also part of this group.

Here we have, conservatively, chosen for < 50 MW because a larger fire in foreign countries may be easier overlooked than in The Netherlands.

The prior’s

The choice for the a priori probability distribution for the parameters \( p \) and \( b \) needs to be based on the available knowledge. If that does not exist, it is generally accepted to choose a so-called vague or broad distribution. It should however be prevented that knowledge, based on actual data, even if limited, dominates the results of the calculations.

In establishing the prior we assume \( p \) and \( b \) to be independent, so \( P(p,b) \) (see (3)) can be written as:

\[
P(p,b) = P(b) \cdot P(p)
\]

We now discuss both priors \( P(b) \) and \( P(p) \).

For \( b \) (essentially the positive average as well as the standard deviation of the conditional distribution given a fire occurs) often a distribution is chosen in the literature declining according to \( 1/b \). Here we chose a distribution declining according to \( 1/\log(b) \). In this way a priori a lot of space is reserved for large fires, which is, in accordance with the starting points of this analysis, on the safe side. With respect to the numerical calculations, the distribution has been discretized. We use discrete values of 10 MW, 30 MW et cetera until 190 MW. Smaller values than 10 MW are only of importance for car fires and need not be taken into account. Larger values of \( b \) than 190 MW seem extremely unlikely. The resulting distribution (probabilities proportional with \( 1/\log(b) \) and normalised to a sum equal to 1.0) is then according to a-priori-probability (1) in Table 7:
Table 7: A priori distribution for parameter $b$

<table>
<thead>
<tr>
<th>$b$ [MW]</th>
<th>Prior probability $P(b)$ (1)</th>
<th>Prior probability $P(b)$ (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.177655</td>
<td>0.116204</td>
</tr>
<tr>
<td>30</td>
<td>0.120271</td>
<td>0.116204</td>
</tr>
<tr>
<td>50</td>
<td>0.104566</td>
<td>0.116204</td>
</tr>
<tr>
<td>70</td>
<td>0.096285</td>
<td>0.104967</td>
</tr>
<tr>
<td>90</td>
<td>0.090907</td>
<td>0.099104</td>
</tr>
<tr>
<td>110</td>
<td>0.087026</td>
<td>0.094874</td>
</tr>
<tr>
<td>130</td>
<td>0.084039</td>
<td>0.091617</td>
</tr>
<tr>
<td>150</td>
<td>0.081639</td>
<td>0.089001</td>
</tr>
<tr>
<td>170</td>
<td>0.079650</td>
<td>0.086832</td>
</tr>
<tr>
<td>190</td>
<td>0.077961</td>
<td>0.084991</td>
</tr>
</tbody>
</table>

Total 1,00 1,00

Because it is a fact that truck fires with a size of 10 MW will be less frequent from a physical point of view, in column (2) a correction has been applied and the probabilities of a 10, 30 and 50 MW fire have been made equal to each other. The dual role of $b$, being the mean as well as the standard deviation of the conditional distribution of the HRR, requires a small adaptation. The influence on the outcome is small (around 10 percent).

In a similar way a distribution has been chosen for parameter $p$ that is proportional with $-1/\log(p)$. As space 0.001 until 0.1 is chosen. The value $p=0.01$/Mvehkm (or $p = 10^{-8}$ per vehkm) is in the middle of that space. On the basis of the outcome there may be a reason to adapt the boundaries or the step size, especially when the posterior distribution is insufficiently low at the boundaries of the space. The distribution is shown in Table 8.

Table 8: A priori distribution for parameter $p$

<table>
<thead>
<tr>
<th>$p$ [per Mvehkm]</th>
<th>prior probability distribution $P(p)$ for $p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0000100</td>
<td>0.033</td>
</tr>
<tr>
<td>0.0000158</td>
<td>0.034</td>
</tr>
<tr>
<td>0.0000251</td>
<td>0.036</td>
</tr>
<tr>
<td>0.0000398</td>
<td>0.038</td>
</tr>
<tr>
<td>0.0000631</td>
<td>0.041</td>
</tr>
<tr>
<td>0.0010000</td>
<td>0.044</td>
</tr>
<tr>
<td>0.001585</td>
<td>0.047</td>
</tr>
<tr>
<td>0.002512</td>
<td>0.050</td>
</tr>
<tr>
<td>0.003981</td>
<td>0.055</td>
</tr>
<tr>
<td>0.006310</td>
<td>0.060</td>
</tr>
<tr>
<td>0.0100000</td>
<td>0.066</td>
</tr>
<tr>
<td>0.015849</td>
<td>0.073</td>
</tr>
<tr>
<td>0.025119</td>
<td>0.082</td>
</tr>
<tr>
<td>0.039811</td>
<td>0.094</td>
</tr>
<tr>
<td>0.063096</td>
<td>0.110</td>
</tr>
<tr>
<td>0.100000</td>
<td>0.132</td>
</tr>
</tbody>
</table>

Total 1.0

Large a priori probabilities for large values of $p$ have been chosen: the probability of on average 1 fire per $10^7$ vehkm is equal to 0.132, the probability of on average 1 fire per $10^8$ vehkm is equal to 0.066. This approximation is on the safe side.
The predictive distribution
If the prior distributions for $p$ and $b$ are chosen and the likelihood has been calculated from the data, the posterior distribution for $p$ and $b$ can be determined by means of equation (3). To find the probability of exceedance of a certain value of the HRR, we use the Theorem of Total Probability:

$$ P(\text{HRR} > X | \text{data}) = \sum \sum p \cdot \exp(-X/b) \cdot P(p,b|\text{data}) \quad (6) $$

The probability of exceedance is calculated for all possible values of $p$ and $b$, multiplied with the posterior probabilities and then summed up.

The results

The Netherlands
Using the Dutch data according to Table 5, we find with the use of formula (6):

<table>
<thead>
<tr>
<th>Fire size</th>
<th>Interval HRR</th>
<th>Prob. per vehkm (a)</th>
<th>Prob. per vehkm (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 MW</td>
<td>15 – 35 MW</td>
<td>$6.9 \cdot 10^{-11}$</td>
<td>$5.3 \cdot 10^{-11}$</td>
</tr>
<tr>
<td>50 MW</td>
<td>35 – 75 MW</td>
<td>$4.4 \cdot 10^{-11}$</td>
<td>$5.1 \cdot 10^{-11}$</td>
</tr>
<tr>
<td>100 MW</td>
<td>75 – 150 MW</td>
<td>$2.7 \cdot 10^{-11}$</td>
<td>$3.7 \cdot 10^{-11}$</td>
</tr>
<tr>
<td>200 MW</td>
<td>150 – 300 MW</td>
<td>$1.3 \cdot 10^{-11}$</td>
<td>$2.0 \cdot 10^{-11}$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$1.5 \cdot 10^{-10}$</td>
<td>$1.6 \cdot 10^{-10}$</td>
</tr>
</tbody>
</table>

The first column indicates the fire size classes as they are used in QRA-tunnels. The second column states the interval that, in combination with the probability distribution calculated through (6), has been used to calculate the probability of fire in the first column. The third column concern the results of the calculations based on the estimated fire size of the Velser tunnel equal to 40 MW and in the fourth column 50 MW has been chosen. The differences are not significant.

The total probability of all fire sizes $\geq 25$ MW has also been calculated for the a-priori distribution, that is by application of (6) but with $P(p,b)$ instead of $P(p,b|\text{data})$. The result is $2.2 \cdot 10^{-8}$. This confirms the conservative character of the prior.

Europe
Using the European data and the prior’s for $p$ and $b$ we find (per vehkm):

- $P(\text{HRR} > 15 \text{ MW}) = 1.1 \cdot 10^{-10}$ (The Netherlands $1.6 \cdot 10^{-10}$)
- $P(\text{HRR} > 35 \text{ MW}) = 6.5 \cdot 10^{-11}$ (The Netherlands $8.9 \cdot 10^{-11}$)
- $P(\text{HRR} > 75 \text{ MW}) = 2.3 \cdot 10^{-11}$ (The Netherlands $4.5 \cdot 10^{-11}$)

We see that for all fire sizes the probabilities based on European data are comparable to the probabilities based on Dutch data. The European data were meant to contribute to a conservative prior, but that is not the case. The European data will therefore not be taken into account. However, this result is comforting if the probability of a large fire is reduced in QRA-tunnels.

CONCLUSIONS AND RECOMMENDATIONS
TNO was asked to study the probability of a large fire in a tunnel based on statistics. From this research appears that, based on the Dutch data and a conservative a priori distribution, the probability of a large fire (HRR > fire size 25 MW) is as follows:

$$ P(\text{HRR-class} > 25 \text{ MW}) = 1.5 \cdot 10^{-10} \text{ per vehkm} $$
The initial probability of fire that is currently used in QRA-tunnels is $2.2 \cdot 10^{-9}$ per vehkm. This gives reason to change the probability in QRA-tunnels. Based on the conservative approach, the probability could be reduced with a factor 10 or even a bit more.

The European data give a similar result, even with the large tunnel fires in for example the Mont Blanc tunnel. Since we adopted a conservative approach, the European data has not been used. However, this result is comforting if the probability of a large fire is reduced in QRA-tunnels.

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Quantifying the Effect of Input Parameter Uncertainty on the Resulting Risk Level for Fire in Rail Tunnels

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ABSTRACT
A risk analysis for fire safety in rail tunnels can be applied in different ways. One major decision is to choose between a purely qualitative and a quantitative analysis, another big decision is the treatment of uncertainty of the different input variables in the analysis. The advantages of a quantitative risk assessment are clear when the goal is to compare different combinations of fire safety measures and make an assessment if the final fire safety design meets the performance criteria. In previous years, FESG has conducted research on this topic and developed a risk assessment methodology able to quantify the risk for people present in a tunnel [1]. The risk is represented by an event tree and the use of pathway factors in order to take into account variation in design fire, ventilation concept, evacuation concept, and other safety systems. For each branch outcome, the consequences are determined, by means of a FID value. The final risk is presented by the societal risk being visualised by means of an FN-curve. This paper will discuss the importance of having an understanding of the uncertainty of each input parameter and their possible effect before building the event tree. A case-study will show that the focus should be less on the used sub-models, and more on the structure of the event tree as function of the uncertainties. The case-study is the application of a QRA on an existing rail tunnel in Brussels and shows the value of quantifying the residual risk for a combination of safety systems in this project.

KEYWORDS: Quantitative risk assessment, risk analysis, rail tunnel, FID, sensitivity study

INTRODUCTION: FIRE RISK ASSESSMENT IN RAIL TUNNELS
When performing fire risk assessments in rail tunnels, the aspect of human behavior is often taken into account in a very simplified manner. Often designs are being made without questioning the effect of the pre-movement time, the effect of the wider walkway on the walking speed in clear and smoke-filled conditions, or the impact of a dynamic signage system on the wayfinding and walking speed. The effect of a properly designed smoke control system is often simplified to a longitudinal ventilation system.

Figure 1 Safety systems.

Big assumptions on walking speeds are being made, without clear reference to fundamental research. Based on assumptions of walking speed in smoke-free conditions, no optimizations might seem required in terms of properly designed smoke and heat control systems or other safety measures, as
the analysis might show the results are satisfactory. The available research for the effect of external conditions on walking speed are quite scarce, e.g. the data from Yin & Yamada [2]. More recent research projects present data on the effect of lower visibility on walking speeds, the effect of different colors of egress signs on wayfinding [3], or on convergent flows in train cars [4], [5]. It is important for the fire safety engineer not only to make realistic decisions for the input parameters, but also to include the uncertainty of the most important parameters and take them into account in a sensitivity study. E.g. the aspect of human behavior includes many uncertainties, which means a QRA should be structured to allow for sensitivity studies on these assumptions.

![Figure 2](image.png)  
*Figure 2*  
dynamic safety systems.

DETERMINISTIC SCENARIOS IN THE EXISTING QRA FOR RAIL TUNNELS

Performance based design (PBD) in rail tunnels has been generally accepted for 2 decades. When quantifying the consequences in a scenario based approach, the fire engineer has the responsibility to propose a representative set of input parameter values for the specific case and to calculate the consequences in a deterministic way. By comparing these to pre-defined acceptance criteria, an assessment can be made on the acceptability of the design.

A scenario-based performance based design is seen as more transparent than fulfilling a set of prescriptive requirements, as the performance is demonstrated for a specific scenario deemed to be realistic worst-case. The selection of this design scenario requires to agree between all involved stakeholders on a set of design parameters. This is the biggest disadvantage of a scenario-based performance based design, as it is dependent on the level of conservatism of the different input parameters and thus not objective.

At the end of the event tree, the scenarios still need to be calculated on a deterministic way and the matrix below describes which input parameters for a rail tunnel scenario mainly influence both the ASET (Available Safe Egress Time) and the RSET (Required Safe Egress Time). The columns on the right describes how the input parameters were taken into account in the QRA: as “hard input parameters” (i.e. requires a new branch in the event tree to take sensitivity into account) or as “probabilistic input parameters” (i.e. allows to define probability distribution in a pathway factor).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>level of conservatism for:</th>
<th>Input parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>chosen fire scenarios</td>
<td>position of the fire, relative to the emergency exits and the position of the train</td>
<td>“hard” X “prob”</td>
</tr>
<tr>
<td>input parameters for the design fire</td>
<td>growth curve, HRRPUA, soot-yield, CO-yield, …</td>
<td>“hard” X “prob”</td>
</tr>
<tr>
<td>influence factors from proposed mitigating measures</td>
<td>Effect of the ventilation system on the visibility/toxicity conditions</td>
<td>“hard” X “prob”</td>
</tr>
</tbody>
</table>

Table 1  
*Input parameters for QRA.*
The fire engineer is expected to propose additional mitigating measures until the acceptance criteria are met. In order to do this, it is necessary to correctly assess and quantify the effect of the different influence factors and decide how to take them into account in the event tree. In order to take the uncertainty of these deterministic input values into account, the QRA model needed an upgrade. In the following paragraphs, the modifications are presented and shown through a case-study.

**PROBABILISTIC SCENARIOS IN THE EXISTING QRA FOR RAIL TUNNELS**

The advantage of a risk-based design, allows to take the probability of a certain scenario into account in order to define a risk instead of a consequence. When only looking at the consequences without looking at the probability of the chosen scenario, it is not possible to assess the risk level. By adding a probability factor or distribution to the equation, it is clear how the level of conservatism of the chosen input values can be taken into account. The developed QRA gives this possibility, allowing to objectify the consequences of extreme rare events. When the combination of probability and consequences is taken into account, the problem becomes more complex as the uncertainty of variables is translated in probabilities.

In [1] a risk assessment methodology is presented that quantifies the life safety risk in a rail tunnel. The construction of the event tree takes into account factors related to human behaviour; fire growth; ventilation conditions; safety system (e.g. ventilation, detection, voice communication, etc.); population density. These factors are incorporated into the event tree using pathway factors. Frequencies are calculated for each branch outcome based on data from research projects, fault tree analysis and engineering judgement. For the determination of the consequences, the method makes use of three integrated models: the smoke spread, the evacuation and the consequence model.

The output data from the smoke spread model (CFD part) is used as input for the evacuation model, which quantifies the complex interactions between evacuating passengers and combustion products. The purpose of the model is to determine the exposure to heat and toxic gas doses of the different combustion products for each person during their evacuation. Additionally, in case of an evacuation out of the train into the tunnel towards an emergency exit, the effect of merging flow phenomena on...
the walkway can be of importance.

The consequence sub-model converts the exposure as obtained from the smoke spread and evacuation model for each person in the tunnel into a fatality rate per scenario. In the model at hand, the effects of asphyxiating gases, irritant gases and temperature are taken into account by means of correlations formulated by Purser [6].

\[
F_{ED_{IN}} = F_{ED_{CO}} \cdot V_{CO2} + F_{ED_{Io}}
\]

\[
F_{ED_{CO}} = 8.2925 \cdot 10^{-4} \cdot [CO]^{1.036} \cdot t/30
\]

\[
V_{CO2} = e^{-\frac{[CO]}{5}}
\]

\[
F_{ED_{Io}} = \frac{t}{e^{8.13 - 0.54(20.9 - [O2]^1.036)}
\]

with:
- \(F_{ED_{IN}}\) Fractional effective dose for incapacitation [-].
- \(F_{ED_{CO}}\) Fractional effective dose for incapacitation by CO [-].
- \(V_{CO2}\) Multiplier for the effect of CO2 [-].
- \(F_{ED_{Io}}\) Fractional effective dose for incapacitation by hypoxy [-].
- \([CO]\) carbon monoxide concentration [ppm].
- \(V\) volume of breathed air per minute [l/min].
- \(t\) total exposure time [min].
- \(D\) exposure dose for incapacitation [%COHb].

Combining correlations for the different gases, a single value is used to determine whether a person becomes incapacitated or not, namely the FID (Fractional Incapacitation Dose). When the FID value becomes unity it is assumed that the considered person will incapacitate and is likely to lead to a fatality [6]. In the case-study a critical value of 0.3 has been taken as limit, in order to take into account the variability of the population. In the case-study, values have been determined for fast-walking people, with values of respectively 25 l/min for V and a value of 30% for %COHB.

The influence of temperature has been taken into account by looking at the time duration people are subjected to a certain temperature and adding the different doses according to:

\[
F_{ED_{conv}} = \sum_{t=0}^{t} \frac{\Delta t}{5 \cdot 10^2 \cdot T^{-3.4}}
\]

with
- \(\Delta t\) the time period [min]
- \(T\) the temperature of a given time period [°C]

The assumption is that people will evacuate in an area away from the fire and will only be subjected to the convective part of the heat. In the case-study discussed further, a critical value of \(F_{ED_{heat}} = 0.3\) has been used, in order to take the variability of the population into account.

The advantage of using these consequence models instead of the classical visibility or temperature criteria as limit, is that an assessment can be made for all types of scenarios, with variations not only in geometry and materials, but more importantly in functioning and reliability of safety systems and impact on human behaviour. If necessary, even the different susceptibilities of people for smoke can be taken into account. Together, they determine the possible number of fatalities, by means of an FID (Fractional Incapacitation Dose) value, in case of a fire in a rail tunnel. The final risk is presented by the expected number of fatalities, the individual risk and the societal risk. The societal risk is
demonstrated by means of an FN-curve (Frequency/Number of Casualty-curve). The societal risk or the risk to a group of people is demonstrated by means of an FN-curve. The curves are plots of the cumulative frequency (F) of various incident scenarios against the number (N) of casualties associated with the modelled incidents.

LIMITATIONS OF THE EXISTING QRA THROUGH AN EXAMPLE
In [1] the method was applied to an existing underground rail link, and the goal was to determine the societal risk and show the possibility of comparing alternative solutions. The part of the rail link studied was the combination of a 500 m tunnel section and a station. The tunnel contains 6 tracks and has a cross section of about 32 x 5.2 m². The vehicles are 26 m long double-decker rail-way cars (Figure 3).

Different alternative safety systems were compared: a linear heat detection system, a train localisation system, a longitudinal ventilation system and a brake overrule system. Figure 4 presents the determined FN curves. The straight lines refer to prescribed levels (i.e., acceptable levels in Sweden [7] and the Netherlands [8]). As long as the FN curve is below the limit level, the risk is thus considered ‘acceptable’.

On Figure 4 the highest FN the basic case corresponding to the situation where no safety system is in place (i.e., no longitudinal ventilation, no linear detection, no train localisation system). This is clearly
not acceptable, since the FN curve crosses the acceptable criteria line. Adding linear detection and longitudinal ventilation shifts the curve vertically downward and almost leads to a design within the acceptable limits. The addition of the train localisation system results in an acceptable curve. The lowest FN curve is obtained when also a brake overrule system is put in place.

An important assumption in the analysis was that the set of representative scenarios only included scenarios with 1 train on fire stopping in a tunnel and no following trains behind it. When looking at the detailed train data in combination with the train frequency data (400,000 trains per year through the link), it appeared having a train on fire in combination with a following train stuck behind it had a high probability of occurrence during both normal and peak hours. This means that the results were not based on a representative set of scenarios since the boundary conditions had changed.

Another challenge in the existing QRA was that of performing a sensitivity analysis in order to address the uncertainty on the proposed input parameters. An analysis was performed on the individual input parameters, which were visualised in a tornado diagram. The sensitivity of the results to each parameter were studied by varying each parameter individually within certain ranges of the probability distribution. The most important input factors are assigned a possible range of frequencies and probabilities based on fault tree data, historical frequencies and engineering judgment. The result is presented in a Tornado-diagram (Figure 5). The Y-axis shows each parameter and the X-axis shows the standard deviation of the final risk value when each parameter is varied within the specified interval. By means of the diagram, the designer is able to determine the most sensitive input parameters.

![Tornado diagram of the sensitivity analysis with the most sensitive input parameters](image)

Note that on the different FN-curves no horizontal shift is observed because only reliability data are varied, i.e., only probability frequencies are considered and the deterministic aspects (in, e.g., the smoke spread model and evacuation model) are left unchanged. If, e.g., the effect of smoke on the walking speed wants to be added as sensitivity parameter in the evacuation model, also the deterministic part in the methodology needs to change and horizontal shifts in the FN curves would be possible.

We summarize the possibilities for improvement of the existing QRA model: creation of the event tree based on a questionnaire to assure a representative set of scenarios is being taken into account. Adding more events in order to allow for a probabilistic approach in selection of the deterministic scenarios based on uncertainty on both human behaviour (e.g. exit choice selection) and influence factors (e.g. effect of smoke obscuration on walking speed). We will focus on the first in the case-study and on the latter in the next chapter.
NEW QRA TAKING INTO ACCOUNT INFLUENCE FACTORS FOR EVACUATION

Part 1: influence of smoke on walking speed
The effect of smoke on walking speed can be of large importance in rail tunnels, where TSI [9] imposes a maximum travel distance of 500 m to an emergency exit. In [10] a comprehensive overview of the influence of both non-irritant and irritant smoke on walking speeds is given. The paper refers to the experimental data from [11],[12] and stresses the importance of taking the interaction between the occupants and fire effluent. In [13] tunnel experiments were performed in which the relationship between walking speed and smoke density was analysed. It is difficult to compare both sets of data, as the level of irritants were much higher in [11]. Also there were experimental differences and interpretations of the test results might be different.

It is clear that, although the data of [13] is valuable, the fact that the influence of the irritant and toxic smoke has not been fully taken into account makes it less applicable for the scenarios at hand. In [14] data is presented of experiments in a tunnel with artificial smoke and mildly acetic acid with an extinction coefficient between 1 and 3 1/m, where the walking speed varied between 0.4 and 1.8 m/s, with a mean value of approximately 0.9 m/s.

In [15] the relation between walking speed and density of flow consisting of blind and visually impaired people was studied, based on experiments. On unfamiliar horizontal surfaces a walking speed of 0.4 m/s and 0.2 m/s was found for densities of respectively 1p/m² and 3 p/m². For upwards stairs a reduction factor of 0.75 was applicable. The author considers this data as relevant for evacuation through rail tunnels filled with irritant and toxic smoke as this will result in visually impaired people.

<table>
<thead>
<tr>
<th>Source</th>
<th>Velocity [m/s]</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yin &amp; Jamada: takes walking speed to a limit of 0.3 m/s in toxic and irritant smoke</td>
<td>0.3</td>
<td>[12]</td>
</tr>
<tr>
<td>Yin &amp; Jamada: takes walking speed to a limit of 0.5 m/s in toxic and non-irritant smoke</td>
<td>0.5</td>
<td>[12]</td>
</tr>
<tr>
<td>Visually impaired horizontal egress (non-familiar)</td>
<td>0.2 m/s (1 p/ m²)</td>
<td>[15]</td>
</tr>
<tr>
<td></td>
<td>0.4 m/s (1 p/3 m²)</td>
<td></td>
</tr>
<tr>
<td>Frantzich/Nilsson: mildly-irritant smoke: walking speed distribution between 0.2 and 0.8 m/s</td>
<td>0.5</td>
<td>[9]</td>
</tr>
<tr>
<td>No smoke, 55 informed pupils (300 m in 15 minutes)</td>
<td>0.33</td>
<td>[16]</td>
</tr>
<tr>
<td>NFPA 130</td>
<td>Not specified how to take visibility into account</td>
<td>1</td>
</tr>
<tr>
<td>Swedish road standard</td>
<td>PBD: no mention of smoke effect on walking speed</td>
<td>1.5</td>
</tr>
<tr>
<td>Engineering application</td>
<td>Rule of thumb: takes 50 % of the walking speed when evacuating through smoke</td>
<td>0.65</td>
</tr>
<tr>
<td>Engineering application</td>
<td>Often not specified: distribution (child-female-male average)</td>
<td>0.9-1.15-1.35</td>
</tr>
</tbody>
</table>

It is clear that there is a non-negligible uncertainty on the different experimental values about the effect of smoke on the walking speed. It is also clear that due to ethical reasons, it is not something that can be expected to be solved in the near future. As discussed previously, when evaluating the consequences in terms of inhaled dose, depending on the source being used for influence of smoke on walking speed (further called “effective walking speed”), a potential difference of 300% can be expected. It is of utter importance to understand that in terms of dose, this uncertainty has a similar effect as changing a design fire from a 20 MW fire to a 60 MW fire or changing a CO-yield from 7% to a CO-yield of 21 %. Designers would take it for granted that this sensitivity study (e.g. 20 to 60 MW) should be taken into account, but the effect of the effective walking speed is one where
designers and reviewers/authorities might give less attention. On the other hand, it has been shown that in order to realistically assess the consequences of a fire in a rail tunnel, this effect of irritant smoke on walking speed needs to be taken into account. In the example of the QRA analysis, it can be seen that even in the most state of the art QRA, the uncertainty of this influencing parameter (as a variable) is not taken into account.

**Part 2: influence of safety systems on walking speed**

It becomes much more difficult to describe the positive influence of safety systems on the above mentioned negative effect of smoke. There have been experiments comparing different safety systems, but the question is if these are representative as no cases were found with toxic irritant smoke.

In [19] an experimental study was performed showing that the detection rate of a static signage system was approximately 44% longer higher that detection rate for a dynamic signage system. The decision time was also longer with static compared to dynamic signage.

More research has been done on the effect of wayfinding, but for the positive impact of walking speed in an irritant smoke filled tunnel with dynamic compared to static signage no clear data was found.

**Part 3: Proposition to modify QRA**

There is a fine balance between accuracy and completeness. An important question that needs to be asked is: "is it better to perform 1 really accurate calculation knowing that the uncertainty of the scenario or combination of parameters will have an effect of x% on the end result or is it better to perform 100 calculations, taking into account the uncertainty, knowing that y% of the accuracy is being lost?"

Looking at this from a practical point of view, e.g. integrating different effective walking speeds in the presented QRA method, could be done in 3 ways.

- **Option 1:** one way would be to add an extra pathway factor before the evacuation model and perform these calculations for each effective walking speed. The total amount of required evacuation simulations would be multiplied with the amount of effective walking speeds.
- **Option 2:** make a simplified evacuation analysis to take the uncertainty into account by treating the effective walking speed as a variable, with a probability distribution.
- **Option 3:** make a combination of both previous options.

From a time consuming point of view, option 1 seems difficult to manage as all the calculations in both the evacuation model and the consequence model needs to be performed again for each change of values. Especially in full QRA, this can lead to huge numbers of numerical simulations, which are not practical (read: compatible with the cost for the client).

*Figure 6 Trade-off between completeness on the one hand and accuracy and modeling completeness on the other. (Modified from Merci [21])*
In [21] the notions of ‘Available Computing Resources’ (ACR) and ‘Required Computing Resources’ (RCR) were introduced. The discussion in the paper is on CFD and how many phenomena cannot be fully resolved (when ACR \ll RCR), so ‘modeling’ is required, but the idea can be used beyond that scope. Indeed, the graph below (taken from [21]) can be interpreted with following definitions:

- Completeness: this refers to the number of scenarios taken as a set of representative scenarios in the event tree.
- Accuracy: this refers to human behaviour aspects (distributions, group forming, overtaking, etc.) and to modelling aspects (uniform fixed walking speed etc.); to give an example for human behaviour: [22] describes how evacuation through low visibility, is helped by following the wall with one hand. Thus, if it is assumed that overtaking will not take place, the question remains as ‘simple’ as to determine a realistic effective walking speed which can be assumed to be constant in time between leaving the rail carriage and entering the emergency exit. However, if multiple paths come together and complex merging behaviour or queuing is expected, more advanced models might be required.

The proposition for the simplified QRA model for taking uncertainty of influence factors
1. Identify crucial parameters (number of trains, queue when exiting train; merging ratio on walk path; effective walking speed per representative section; exit capacity)
2. Determine constant values for each of the variables in smoke-free conditions:
   a. Effective walking width: data from experiments
3. Determine probability distribution for each of the variables:
   a. Influence of smoke on walking speed: uniform distribution based on limits from:
      i. 0.3 m/s: Jin-Yamada [11]
      ii. 0.4 m/s: Blind and visually impaired [15]
      iii. 0.5 m/s: Light irritant smoke for young people [13]
   b. Effective walking width: 1 person
4. Walking speed multiplication factor for safety system:
   a. 1.5: Dynamic evacuation guidance (continuous light-strip) 2
5. Run all scenarios (combination of fire location and train position) based on the simplified QRA model.
6. Randomly pick 3 scenarios
   a. Compare results in consequences for the 3 scenarios’ with simplified model.
   b. If difference < 20 %, simplified model is validated.
   c. If not, adjust crucial parameters in simplified QRA and go through the 6 steps again.

The advantage of this methodology is that the uncertainty of one of the most important parameters is taken into account. Further improvements could be made, when new information on effective walking speeds would become available. It is also important that the multiplication factor for walking speed when investing in additional safety systems is taken into account in a systematic way. By combining the accuracy of the 3 scenarios with the simplified analysis of the complete set of scenarios, the available computing resources are maximised as a function of the required computing resources.

The proposed improvement is clear for rail tunnels with long travel distances to emergency exits. The methodology could also be applied to rail tunnels with other fire safety strategies, as will be shown in the following case study.

**CASE-STUDY ON THE IMPROVED QRA**
This improved QRA has recently been adopted on the upgrade of the existing North-South rail link in

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1 It has been encountered that, in smoke filled tunnels, people tend to walk in one row behind each other next to the wall in order to have guidance from that wall during evacuation [21].
2 Although discussion can occur on the specific value of the multiplication factor, the author believes a constant value is the most pragmatic approach. If multiple sources of data would be available, a probability distribution could easily be integrated.
Brussels. The goal was to investigate which benefits could be generated by compartmentation of the 6 tracks into 3 separate tubes, taking into account the probability of having a train on fire and a following train in the same section. This requires analysing scenarios with 3000 people evacuating the incident-tube.

The concept was to consider the non-incident tube as a zone of relative safety. Evacuation found place from the incident to the non-incident tube through emergency sliding doors every 50 m. The ventilation of the incident-tube was based on the critical velocity (3 m/s) and the ventilation of the non-incident tubes was based on a lower ventilation (1 m/s), dimensioned to assure no smoke spread would occur from incident to non-incident tube.

The set of representative evacuation scenarios included different exit choices. The analysis took the difference in scenario probability for evacuation where the main advantages of adding a spoken message were to try and improve the guidance of people. An example is given below to estimate the probability that evacuating people would use the ballast as evacuation path, once they reached the non-incident tube. The consequences were calculated for different variations (e.g. effect of presence of a following train). One of the main bottlenecks was shown to be the merging flow when going from the incident tube to the existing flow on the non-incident tube. Even though people reached a place of relative safety once they were in the non-incident tube, they still had a negative effect for the people still queuing in the incident tube due to the bottleneck in the non-incident tube. By adding measures to promote walking on the ballast of the rail track in the smoke-free non-incident tube, the bottleneck was largely reduced.

Another challenge in this project was the evacuation of the people in the scenarios on the outer tracks (track 1 and 6) where no emergency doors were present every 50 m on the walking path. The analysis took the difference in scenario probability (e.g. a scenario in Figure 9) for evacuating over the adjacent track towards the doors leading to the non-incident tube instead of using only the walking path on the outer side of the track. In order to encourage the evacuating passengers to do this, a spoken message was added in the combination of safety systems, resulting in lower probability of the
scenarios with longer evacuation times.

The FN-curve on Figure 10 is the result of adding probabilities to the different deterministic scenarios based on the input from the rail group and the reliability of the different safety systems. The basic case corresponds to the situation where fire compartmentation of the tunnel in 3 parallel tubes, on top of a longitudinal ventilation system and sliding emergency doors every 50 m to the adjacent tubes. This ventilation system in the incident tube and limited ventilation in the non-incident tube is dimensioned on a 35 MW fire and is activated by a linear heat detection system. The reliability of the ventilation system is taken at 99.978%, which almost leads to a design within the acceptable limits for a representative scenario that includes a train on fire and a following train stuck in the same section. It needs to be stated that, if the representative scenario included only 1 train on fire, the provided safety systems would lead to a more than acceptable situation.

The addition of the spoken message system in both the non-incident as the incident tube was required due to the high possibility of having a train no fire and a second train stuck behind the incident-train and Figure 10 visualises how adding the spoken message shifts the curve vertically downward resulting in an acceptable curve.

![Societal risk: FN-curve](image)

**Figure 10** FN-curve case study with compartmentation and ventilation system.

**CONCLUSION**

The paper discussed the importance of taking into account the sensitivity of input parameters in deterministic calculations into account in a probabilistic QRA. Being able to fully take into account the sensitivity of each parameter is future work, but a proposition is made for improving the existing methodology in QRA for rail tunnels. The variation of the input parameters with the largest uncertainty (e.g. exit choice in human behaviour) need to be taken into account in sensitivity studies, preferably in a probabilistic way. The case study shows the application of the new QRA where an optimal combination of passive and active safety measures were proposed in order to achieve an acceptable safety level. Important conclusions are that the boundary conditions of the rail infrastructure (e.g. number of trains in the design based on frequency data) should be taken into account in a QRA. Another important aspect is that the QRA allows the designer to find an optimal balance between reliability of safety systems (e.g. ventilation system) and combination of safety systems (e.g. spoken message).
REFERENCES


Verifying CFD-Calculations with Semi-Empirical Expressions

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KEYWORDS: Fire, tunnel, CFD calculations, semi-empirical expressions

INTRODUCTION

Today CFD-calculations are often used to calculate the conditions at fires in tunnels. Parameters such as temperature distribution over time and height, visibility and toxicity are important decisive tools. The purpose of the calculations is primarily to determine the conditions to secure the evacuation but the conditions for the rescue service can also be studied. A tunnel fires is a complex physical problem and there is a need to validate the calculation results with full scale fire experiments. From practical and economic reasons there are few full-scale experiments with fires in tunnels. But in recent years more and more summaries and analyzes of performed model tests and full-scale trials have resulted in simplified semi-empirical expression. By using these expressions, an indirect verification of CFD-calculations can be performed. The poster will describe a method and initial calculation with comparisons of selected semi-empirical expression and CFD-calculations in a tunnel fire.

METHOD

The poster describes a method and initial calculation with comparisons of selected semi-empirical expression with CFD-calculations (FDS) both from an evacuation perspective. In the poster a case an example of comparison with the semi-empirical and a calculated case in presented. The case is a simulation of a tunnel fire in a tunnel with a length of 2000 meters, HRR = 15 MW and a fire growth rate of 0,003 kW/s². The tunnel section area is 54 m². The simulations are performed with FDS 5.3. Two different cases will be tested where the velocity in the tunnel is 1 m/s and 2 m/s. In the poster suitable measure points and out data in FDS will be discussed.

EXPECTED RESULTS AND DISCUSSION

The results from the FDS-calculations will be verified with a number of semi-empirical expressions from equations presented in "Tunnel Fire Dynamics", Ingason, Li & Lönnermark [1]. Examples on parameters that will be analyzed are temperatures based on a one-dimensional model eq. (8.43-8.46, 8.49) in [1] which calculates the temperature downstream the fire. The stratification will be analyzed according to eq. (12.18) and results presented in [2]. The visibility will be analyzed according to eq. (14.19) in [1]. The flame length will be discussed based on the results from the simulations and the overview concerning flame length described in chapter 8. One of the main questions in tunnel fire analysis is the evacuation analysis and the toxicity. The results and the methods will be discussed and presented in simple charts and diagrams. The aim of the investigation is to discuss a general method and a specific case in order to use the semi-empirical expressions as a tool to verify CFD-calculations indirectly to full scale and model tests. Se figure 1.
REFERENCES

Innovative Solution of Automatic Fire Alarm for Urban Road Tunnels

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KEYWORDS: Fire alarm, fire position, FBG detectors, threshold, on-line evaluation

Introduction
Automatic fire alarm systems combined with active fire protections have been equipped in dozens of road tunnels built in Shanghai during the past 20 years. However some of the systems are not sensitive enough to a car fire, and/or run with higher risk of false alarm. As well known, a temperature sensitive fire alarm system may not able to determine the true fire location with influence of tunnel wind [1]. Besides, administrators are usually unable to do on-line evaluation for alarm sensitivity and system reliability in a running tunnel. To solve those problems, we developed a novel solution for fire alarm by deeply understanding of the physics of FBG (fiber Bragg grating) temperature sensors.

FBG fire alarm system
A line type fire alarm system was equipped in a road tunnel across the Huangpu River, measuring temperature at the tunnel ceiling by FBGs with 1 Hz sampling speed. An optical channel as a segment of the alarm system consists of 20 detectors spaced by about 10 meters in series, and totally 600 detectors for whole system. The fire alarm is triggered by rate-of-rise mechanism rather than by temperature, because in most cases the temperature at tunnel ceiling is unable to reach the threshold in the first minute after ignition [2].

Sensitivity matching stability
Rapid response and correct alarm should be main features for fire detection. However, high alarm sensitivity may result in high risk of false alarm that will damage system’s stability and may cause a traffic disruption in tunnel. In order to balance both features, an optimal threshold needs to be selected. As the threshold differs according to criterion chosen, a clear definition of criteria in rate-of-rise is suggested for the fire detectors. The upper limit of threshold is defined as the minimum peak value of rate-of-rise that is carried out from diesel pool fire tests with 1 MW in the first minute after ignition [3], and the lower limit is considered as 7σ (standard deviation) of all detectable rate-of-rise data for a detector with the tunnel’s operating conditions. To statistics, the 7σ is a value with very low probability, corresponding to a rate-of-rise appeared less than once per year, which is specified as the maximum of acceptable false alarm rate. The criteria of threshold fully depend on environments and operating conditions of the target tunnel, so that optimal threshold may not be a constant, even along a tunnel (see Fig. 1). Based on the new concept, false alarm rate of <1/year • tunnel has been obtained experimentally.

Wind correction
By traditional thermal fire detection, an estimated fire location may be far away from the true fire, particularly in case of strong tunnel wind, because the fire location is determined by searching a peak in temperature profile caused by convection heat [4]. A method to detect radiant heat of a fire in road tunnel is established using FBGs. By wind correction aided program, an acceptable estimation error of < +/-5m is proved, under wind speeds between 0 and 5m/s.
Fig. 1 Alternative zone of alarm threshold, upper and lower limit, for fire detectors at different positions along the tunnel.

Fig. 2 Local temperature variations with time, collected by fire detectors at entrance, middle and exit of the tunnel, respectively.

On-line evaluation
To be an effective fire alarm system, all detectors in tunnel must remain vigilant at all times no matter how the environmental conditions change, which requires on-line evaluation and adjustment. The novel alarm system collects totally hundred millions temperature and rate-of-rise data per day. These data are employed to reveal the major performances of the system, including alarm sensitivity, stability and appropriate threshold all the time within service. For example, temperature variations measured by a detector in short and long period mean system noise of the equipment and actual temperature fluctuation in the tunnel, respectively. The latter reflects local thermal behavior in the tunnel and also characterizes sensitivity of the alarm system (Fig. 2). The on-line evaluation aims at an assistant approach for life cycle maintaining service for the fire detection.

Conclusions
Criteria of alarm threshold, upper and lower limit of rate-of-rise, are defined by on-line mass data analysis for a target tunnel in operation. To a fire in longitudinal wind with a speed up to 5 m/s, the fire position was estimated in an acceptable tolerance of +/- 5 m by wind correction program based on radiant heat response. To satisfy safety of tunnel from fire with long-term service, an on-line evaluation method was developed by analyzing the routine temperature collected from all fire detectors in tunnel.

References
Fixed Fire Fighting System in a Large and Complex Road Tunnel

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KEYWORDS: A safe journey - E4 The Stockholm bypass Project

INTRODUCTION
A tunnel of this magnitude faces various challenges such as risk for congested traffic, driver fatigue due to monotony, complex firefighting operations and a need of quick detection of incidents and fires. See figure below for The Stockholm bypass in brief.

<table>
<thead>
<tr>
<th>Safety features</th>
<th>Facts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency exits</td>
<td>Length: 21 km</td>
</tr>
<tr>
<td>From 100-150 m</td>
<td>Length of main tunnel: 18 km</td>
</tr>
<tr>
<td>Bidirectional traffic</td>
<td>Total length of all tubes: 56 km</td>
</tr>
<tr>
<td>Longitudinal ventilation</td>
<td>Number of lanes: 3</td>
</tr>
<tr>
<td>24h CCTV operation</td>
<td>3-lanes in each direction in two separate tunnel tubes</td>
</tr>
<tr>
<td>Automatic fire detection</td>
<td>Maximum speed: 80/100 km/h</td>
</tr>
</tbody>
</table>

Fixed Fire Fighting System
- Two-redundant water-pressure stations
- Dimensioned for constant water supply for 2 hours
- 100% redundancy for electric, comm. and control systems
- FFFS: System length: 56 km
- FFS: Sections approx: 300
- Electrical valves approx: 350
- Smoke detectors: 250
- Linear heat detectors
- Different operating modes for FFFS
  - Automatic from the Fire Alarm System
  - Temp > 90 Grd. (Cel)
  - Preprogrammed operator interface (HMI)
  - for the traffic operator
  - Operator interface (HMI) from Local DCS
The tunnels are designed with the aim of creating a safe journey, with parallel tunnel tubes without oncoming traffic. Ramp tunnels are connecting the main tunnel to the surface road network, and these are also designed as parallel tubes without oncoming traffic. The tunnel system is to be monitored and controlled by a traffic control center, Trafik Stockholm. To handle this, the tunnels are fitted with a local control and monitoring system. The Control system controls approx. twenty technical systems. For example 24 h CCTV, detection systems such as automatic fire detection system, systems to monitor smoke and heat. Also a system to detect incidents and stopped vehicles. The ventilation concept is based on longitudinal ventilation, both for the environmental and fire ventilation, partly achieved by jet fans mounted in the tunnel ceiling approx. 220. Three air exchange stations, and a specific smoke exhaust tower, divide the tunnel into ventilation sections. Air exchange stations and exhaust towers, as well as the specific smoke exhaust tower, can be used for smoke management. Specific action plans, to be used by the traffic control center, are developed for the operation of the ventilation system during fires and accidents, including consideration of the aspect congested traffic conditions.

**FIXED FIRE FIGHTING SYSTEM (FFFS)**
The specifications for the FFFS is to ensure constant water supply for 2 hours. Here it shows the main layout of the Water Pressure Station where all equipment are doubled; pumps, sensors, UPS, switches and PLC’s. All those systems together has to handle the requirements for uninterrupted operation of the Water Pressure Station. Therefore it is 100 % redundancy for electrical supply, communication network and control system.

There are four different operations mode for the FFFS:
- Automatic from the Fire Alarm System.
- Preprogramed operator interface from the NTS-system (National Traffic System).
- Operator interface from Local Control System.
- Operation Locally from control box in the Emergency Exits

It is also possible to operate the FFFS from different locations:
- Main Traffic Central. Trafik Stockholm.
- With Pre Programmed Action Plan which handles a tunnel fire.
- Locally from Local Control System. With Pre Programmed Action Plan which handles a tunnel fire.
- Locally from Emergency Exits. With On and Off for the FFFS-valves

Our task as specialists is to find the "Single Point of Failure" that could jeopardize a safe functionality and make it correct, from the HMI in the Traffic Center down to activating objects.

**REFERENCES**

A Helium-Technique Experimental Study of Longitudinal Ventilation Control in Sloped, Small-Scale Tunnels

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KEYWORDS: Critical velocity, longitudinal velocity, confinement velocity, backlayering distance, tunnel slope.

INTRODUCTION
There is limited knowledge on how the slope of a tunnel can affect the smoke movement during a fire and thus how the longitudinal ventilation should be controlled. Only very few of the previous reported studies [1–3] consider the slope of the tunnel and how it affects the critical velocity, the backlayering distance and its corresponding longitudinal velocity. Based on the helium-air technique developed by Mégre & Vauquelin [3–5], several experiments in a small-scale rig (scale 1/30 of a tunnel with a section of 6 m by 9 m in full-scale) were conducted in order to study the critical velocity, backlayering distance and longitudinal velocity (confinement velocity) in a tunnel with slope. Several heat release rates were studied, ranging from 0.42-2.6 MW, under two slopes directions (uphill and downhill), and for several slope degrees.

THEORETICAL BACKGROUND
In order to reproduce several phenomena from a full-scale fire to a densimetric small-scale fire, three stages are required: first, a set of formulae based on a semi-empirical model [6] to quantify the parameters that have to be scaled down; second, the application of two sets of scaling principles based on dynamic similarities (Froude modelling) and thermal/densimetric analogy, and third and last the equivalence of the corresponding scaled smoke flow rate to a gas densimetric buoyant mixture of helium-air [5]. The experimental rig and method was validated against full-scale date for a range of 0.42-31 MW to ensure that the method met the theoretical requirement for high fidelity results.

EXPERIMENTAL PROCEDURE
A 4.7 m long model tunnel was designed to allocate a buoyant source of helium-air mixture into the model tunnel section, see Figure 1, and to allow the quantification of the involved parameters and phenomena. Furthermore the experimental rig allowed a wide range of simulated heat release rates, and it also allows for the presence of vehicular blockage. Finally, the modular wall and ceiling construction permits modification of the tunnel slope and the tunnel geometry, making the set-up ideal for parametric studies.

![Figure 1 – Schematic view of the experimental set-up.](image)

The buoyant mixture of helium and air gases are supplied at several flow rates, depending on the heptane pool fire size and hence the fire size. Both gases were supplied from 50 l cylinders and regulated through Bronkhorst mass flow controllers (MFC). In order to overcome the disadvantage of
the colourless buoyant mixture, the flow was seeded in a plenum box with mineral oil particles released from a fog generator. The longitudinal ventilation system was activated when the buoyant plume filled up the small-scale tunnel section, the system consisted in extracting the buoyant mixture with an axial fan (K100M) located at the end of one of the portals. A potentiometer connected to the fan allowed the regulation of the longitudinal flow. Finally an anemometer (VT100E) was used to measure the longitudinal air velocity in the middle of the model tunnel and at several locations; hence an average value was estimated.

THE CASE STUDY

A detailed experimental matrix is shown in Table 1, which contains three sets of experiments; in Set 1 the tunnel had no slope and was aimed to validate the tunnel model and the method, whereas Set 2 and Set 3 had 3% and 6% tunnel slope, respectively. For all sets the tunnel dimensions represented a full-sized tunnel with 9 m width and 6 m height, and the longitudinal ventilation control was studied uphill and downhill. One “X” means that only the critical velocity was measured, whereas “XX” means that the backlayering distance and its corresponding longitudinal velocity were measured in a first experiment, and the critical velocity in a second experiment.

<table>
<thead>
<tr>
<th>Source diameter (mm)</th>
<th>HRR (MW)</th>
<th>SET 1</th>
<th>SET 2</th>
<th>SET 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0 % tunnel slope</td>
<td>3 % tunnel slope</td>
<td>6 % tunnel slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Uphill</td>
<td>Downhill</td>
<td>Uphill</td>
</tr>
<tr>
<td>20.7</td>
<td>0.42</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>26.0</td>
<td>0.78</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>28.0</td>
<td>0.96</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>34.0</td>
<td>1.61</td>
<td>XX</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>41.0</td>
<td>2.62</td>
<td>XX</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

CONCLUSION AND FURTHER WORK

The current method and experimental set-up have been able to reproduce several phenomena in a sloped model tunnel with two orientations (uphill and downhill). Moreover the model has been validated against full-scale data for a certain range of heat release rate, from 0.42 to 31 MW. The tunnel slope seems to have an influence on the critical velocity and backlayering distance, depending on the slope direction, uphill or downhill, where the latter affects the backlayering distance to a greater extent. However, further experiments are required to be executed with higher slope and larger HRR.

The experimental set-up has the advantage to allow a great modularity and thus several scenarios can potentially be studied. Further experiments are planned that include three stages: confinement velocity, tunnel slope and transversal ventilation control.

REFERENCES

Analysis of Tunnel Fire Safety Strategies to Inform the Design, Operation and Emergency Response to Tunnel Fire Incidents

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³Dubai Airports, UAE

KEYWORDS: Fire strategy, fire dynamics, fire plume, smoke movement, tunnel ventilation, road tunnel, vehicle fire

INTRODUCTION
A holistic understanding of the application of the physics involved in the phenomenon of fire dynamics and smoke movement in different tunnel fire scenarios is still limited. The aim of the project presented in this paper is to develop a holistic understanding of tunnel fire safety to inform the design, operation and emergency response to tunnel fire incidents. A hierarchical approach to fire safety is used to compare the fire strategies of a range of international tunnel fire safety standards. The results from tunnel fire comparison are discussed and an example of how the analysis might help inform the application of international tunnel fire standards in design, operation and emergency response is provided and discussed.

TUNNEL FIRE SAFETY CHALLENGE
Dubai Airports intend to implement a plan to significantly increase the capacity of Dubai South International Airport from 6 million passengers per year in 2014 to 120 million passengers per year with an additional four runways. This increase in capacity will require significant expansion of the terminal buildings which will result in a number of extensive tunnel networks, including:
- Road tunnels;
- APM (Automatic People Mover) tunnels;
- Heavy rail (links to Dubai, Abu Dhabi and beyond);
- Services (cable, pipelines…etc.);
- Baggage conveyors;
- Pedestrian walkways; and/or
- Combinations of all or some of these functions.

COMPARISON OF INTERNATIONAL TUNNEL FIRE STANDARDS’ STRATEGIES
To identify the most appropriate fire safety standards for this range of tunnels, a range of international tunnel fire safety standards were compared. The international standards were compared using a hierarchical approach to fire safety (adapted from the approach developed for fire safety in buildings – please see Figure 1). One of the main benefits of this approach is that it can address several different fire safety objectives, whilst recognising the contributions of difference fire safety systems to the achievement of different fire safety objectives. Another benefit of this approach is that it allows different fire strategies (often only implicit in prescriptive standards) to be explicitly considered.
RESULTS OF COMPARISON
International guidance on tunnel fire safety possesses many areas of consensus and consistency of approach. They also have several significant areas of divergence (please see Table 1).

Table 1  Comparison of two road tunnel standards.

<table>
<thead>
<tr>
<th>Fire safety provision</th>
<th>NFPA 502</th>
<th>BD 78/99</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire resistance</td>
<td>2 hours RWS</td>
<td>Based on analysis</td>
</tr>
<tr>
<td>Cross-passage/exit spacing</td>
<td>300m</td>
<td>100 – 150m</td>
</tr>
<tr>
<td>Fixed fire suppression</td>
<td>Can form part of strategy</td>
<td>No – makes conditions worse</td>
</tr>
<tr>
<td>Fire safety management</td>
<td>Some guidance</td>
<td>Informative guidance</td>
</tr>
</tbody>
</table>

For road tunnels for example, one guidance document[1] specifies 300m between cross-passages/exits and indicates that fixed fire suppression can form part of a tunnel fire strategy. Whereas, another guidance document[2] specifies 100m to 150m between cross-passage/exits and precludes the application of fixed fire suppression citing a worsening of conditions in the tunnel on activation. Therefore, knowledge of tunnel fire dynamics and smoke movement was used to inform the application of international good practice guidance for the specific tunnels in question.

DISCUSSION
In the final poster a compilation of the results from the analysis will be presented and a discussion of the possible influence of the main parameters on the tunnel fire safety strategy will be made. The focus will be to determine and discuss differences between the different strategies and how knowledge of context and tunnel fire dynamics can assist in their application.

REFERENCES
Intelligent Lighting Control System in Tunnel Safety

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KEYWORDS: intelligent tunnel lighting control, portal safety, over lighting, under lighting,

INTRODUCTION

Tunnel safety is not limited to fire and other catastrophes that could happen in tunnels. We know that 2/3 of accidents occur at tunnel portal. International recommendations (IEC-088, RP-22 and others) are published and updated since 1973 in order to ensure the most possible safe lighting at tunnel portal and all along the tunnel.

Existing lighting control technologies always “over met” the recommendations with the main consequence that most of the tunnels in the world are over lighted. Tunnel operators are over-lighting tunnels in order to make sure they meet the minimum requirements in the worst case conditions. This over-lighting leads to energy waste but it can also dazzle the drivers and in some case become even more hazardous than under lighting whatever the type of lighting system is used.

As oppose to standard control system, Intelligent Lighting Control Systems (ILCS) can dynamically control the tunnel lighting system per the real needs based on outside natural lighting and inside maintenance factor.

In this paper we will demonstrate the difference between standard and intelligent lighting control system and we will show, how ILCS can improve safety in road tunnels.

THE RELATION LIGHT VS ACCIDENT

Most of the accidents in road tunnels are due to human error. Studies show that most people feel uncomfortable in tunnels. In fact, air, space and light are the factors that influence the feeling of safety and security of drivers in tunnel. A study performed by SINTEF reveals that “30 percent of the population suffers from tunnel anxiety” and that 20% of men and 40% of women in the selection are afraid of driving through long tunnels. It also shows that 45% of the elderly are afraid of driving through long tunnels. The proportion of road users being anxious or afraid of driving through tunnels varies between the different surveys but anxiety always comes out as an important factor that affects the drivers and how they drive.

Tunnel lighting is a very important part of tunnel safety. A proper lighting control lighting system will help reducing the glare of over-lighting. It will also significantly reduce the black hole effect at the tunnel portal that sometimes makes the drivers braking for no reason while entering into the tunnel and becomes a cause of accident.

TYPES OF TUNNEL LIGHTING CONTROL SYSTEMS

Some tunnels have basic programmable logic controller (PLC), that are electro-mechanical control systems, which include relays that turn on a number of luminaires or shut them down based on a schedule.

More advanced systems will switch a group of luminaires ON/OFF as per the real luminance reported by a luminance meter installed at the tunnel portal. Limited by the system architecture, the control is, most of the time, limited to 3 or 4 lighting stages. Photometry is designed for the worst case scenario and tunnels are, again, over lighted. These systems feature basic lighting intelligence.

As opposed to the traditional PLC, the ILCS individually controls and monitors every luminaire.
Using power electronic components instead of simple electric ones, it is possible to more precisely and dynamically adjust the luminaires.

**INTELLIGENT LIGHTING CONTROL SYSTEMS**

The development of electronics during the past decades has drastically enhanced communications and fostered the design of intelligent systems. With two-way communication technologies, the lumens inside the tunnel and at its portal can be individually and dynamically adjusted depending on a signal from other devices. Luminaires can also report their statuses to a main controller so that the latter can react proactively to maintain optimal lighting. These systems reduce over lighting, thus saving energy. They also reduce the under lighting due to dirt accumulation or the luminaires’ failure. Ultimately dynamic lighting adjustment substantially increases safety.

**BENEFITS OF INTERACTION WITH OTHER SYSTEMS**

Communication is key in safety applications. Information and Communication Technology (ICT) provides access to information through media (Internet, wireless, powerline, cell phone, etc.). Cooperative communication now enhances transportation by providing information that will facilitate movements, increase comfort, and improve safety while minimizing the impact on the environment. ILCSs, specifically for road tunnels, are communication systems that exchange information between their components for control and monitoring. ILCSs can also communicate with other tunnel subsystems to share useful information for normal or emergency operations. The use of an open protocol seems to be the best solution to ensure flexibility with any higher control system or any other subsystem in or in related to the tunnel.

**CONCLUSION**

For the Norwegian Public Roads Administration, light conditions in tunnels play a decisive role in how people experience tunnels, light provide safety. An accurate lighting that reduces black hole effect and reduce human anxiety can help preventing accidents. On the other hand, over lighting can cause glare that can be as dangerous as the black hole effect. As opposed to standard lighting control system based on LPCs, ILCS’ now have the capability to adjust the tunnel portal luminance per the per the real human needs and the recommendations, and to communicate with other tunnels’ sub-systems and enhance their benefits in case of accident.

**REFERENCES**

1. AMERICAN NATIONAL STANDARDS INSTITUTE – ILLUMINATION ENGINEERING SOCIETY. RP-22-11 Tunnel Lighting
2. INTERNATIONAL COMMISSION ON ILLUMINATION. CIE 088-2004 Guide for the Lighting of Road Tunnels and Underpasses
Trade-Off between System Robustness and Optimization

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KEYWORDS: scenario approach, stochastic optimization, robustness, CFD, consequence analysis

INTRODUCTION
In every major smoke and heat control design, a trade-off is necessary between the robustness of the system and the possibility to optimize the system in an early stage of the project. An early optimization limits the cost of the overall system whilst fulfilling the same specifications. However, using such an optimized system with complex control logic could possibly lead to a catastrophic failure. In most projects the trade-off between robustness and optimization is performed using good judgement but with a limited analytical background. The failing of one system is usually not critical to the overall safety strategy, but puts stress on the other systems which should be avoided. It is although possible to design a system where no trade-off is necessary between robustness and optimization. This abstract describes the different kinds of optimization and presents a case study in which an optimization is performed without compromising the robustness of the overall system.

DIFFERENT OPTIMIZATION TYPES
There are two different optimization types which typically can be used in a (fire) safety design. Those two are stochastic optimization methods (SO) and scenario optimization approach (SOA).

The difference is that SO focuses on the optimization of a few parameters and usually is very calculation intensive. One or more parameters are changed and an optimal point is chosen related to one or a few criteria. For example, the flux of exhaust air is optimized with the visibility at the exits as criterion. An optimal exhaust flux is thus reached, without looking at the overall system. [1]

A different approach is SOA, where the approach focuses on the whole system and proposes a different scenario usually based on a working and less optimal scenario. This technique has existed for decades, but better and more systematic methods are continuously being developed. SOA is today being used in different fields, such as prediction, systems theory, regression, control, financial mathematics, machine learning, decision making, supply chain and management. [2]

APPLICATION IN A TYPICAL PROJECT PROCESS
The general process starts with defining goals and ends with the realization of the project. In every step of the process stakeholders have an influence and the project is even prone to external influences. An optimization process is often included in the scope of a project. However, this optimization often focuses on the separate technical systems, not the overall system and is often a stochastic optimization. This can for example lead to a decrease in redundancy.

It happens often that choices in different parts of big projects have consequences for the whole project. As most projects have a tight deadline, it is easy to overlook these consequences which lead to unnecessary expenses and necessary redundancy can be lost. Therefore, during every stage of the project, the following questions should be asked and answered.

- What is the estimated cost of the system (component)?
- Is it therefore worth putting time on the optimization of the system (component)?
- What is the role of the system (component)?
- Do we need the system (component)?
- Is it possible to change to a different, more effective system (component)?
- Can the systems functionality be combined with a different system?
- Can we, in an effective way, make the system more local and in this way optimize the costs?
- Is it possible to make the system a general system and in this way keep down the costs?
If the answers lead to a scenario optimization, the level of robustness can be maintained. A risk and consequence analysis should be performed so the general robustness and safety level is not decreased.

**DESCRIPTION OF CASE STUDY**

The designed system which has been analysed in this study is a ventilation system for an underground metro station as shown below:

The blue zones are the part of the exhaust ventilation which is optimized. Right now, all the zones activate in case of fire. The possibility is investigated to sectionize this system in 4 separate zones. The optimization starts with the question list. After answering these questions, it is chosen to make the system more local by using a localized detection system and a localized exhaust system. This is achieved by introducing 6 fire dampers in the existing system. The second step in the process is performing a risk analysis to assess the risk that one of the safety systems partly fail:

Only the changed parts, such as detection and closing of the right dampers, are looked at. The other parts have been evaluated in the basic design.

The third step is the analysis of the wanted and unwanted outcomes and comparing them to the required safe egress time. The system is verified using FDS. The changed scenarios, also the failing ones, with a failing fire damper or detection, are analysed. A different, less severe fire is chosen for the failing scenarios to follow the logic in the Swedish BBRAD guidelines. The motivation for the lesser fire is the acceptable rest risk: the risk level of a failing system in combination with a worst case scenario fire is deemed as very low and as such as a rest risk. Four different ventilation scenarios have been analysed using FDS 6.1.2 [3].

The last step is a comparison of the chosen parameters to the accepted levels of those parameters. At all times and for every scenario, the following equation has to be valid:

\[
\text{ASET} > \text{RSET} \quad [4]
\]

In words, the available safe egress time has to be larger than the required safe egress time. In the case study, the chosen criteria set forward by the stakeholders, such as visibility, were met. Tenable egress conditions were maintained for all analysed scenarios during the 15 minute evacuation time. An optimized system without losing robustness was thus achieved.

**LIMITATIONS**

SOA for the case study is performed with basic methods. More advanced methods are available. No stochastic optimization is performed. Care has to be taken that verifications and analyses encompass all scenarios and follow the highest possible standards.

**REFERENCES**

Performance Based Design of Fire in a Rail Tunnel: Integrating Fire Modelling, Evacuation Analyses and Risk Assessment

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Bahir Dar Energy Centre, Bahir Dar Institute of Technology, Bahir, Ethiopia

KEYWORDS: Rail tunnel, Fire modelling, evacuation analysis, risk analysis and smoke extraction

INTRODUCTION
A tunnel is one of the facilities that requires high safety standard with respect to fire, due to its complexity and the high number of passengers. There have been several tunnel fires, such as the Channel Tunnel, France / Great Britain (1996) [1]; Baltimore Howard Street Tunnel (2001); Leinebusch Tunnel, Germany (1999) [2]; Mont Blanc fire in 1999 that have resulted the severe consequences for people, property and business [3].

The here documented study is conducted on a railway project which is aimed to improve the existing number of rail track from two to four in order to give an opportunity to serve high speed train. The project consists of a tunnel with total length of about 950 m. This includes one station, which is located at the middle of the tunnel, and has length of 351.5 m. There are three platforms at the station, and each has two staircases.

METHOD
The fire size was assumed to be of one single coach of the train having a medium fire growth rate, and reaching a peak heat release rate of 14 MW in 10 minutes. This value agrees with the study made by Ingason [9] on the heat release rate in tunnel fires in Eureka Firetun tests for a German passenger train of IC standard with a steel body. According to the test, a maximum of 14 MW was reached approximately 25 minutes after ignition [5].

While there are various possibilities leading to a fire, three major scenarios were considered for this analysis. The first scenario is assumed to be a fire starts when the train is at the station. The second scenario and third scenario are based on fire that starts while the train enters the tunnel before it arrives at the station. The fire modelling is performed using a CFD (Computational Fluid Dynamics) program FDS (Fire Dynamics simulator) that is developed by the National Institute of Standards (NIST), USA. The geometry of the model is performed on a CAD tool called Pyrosim, which is used as interface for FDS. The fire load on FDS is given as a heat source with HRRPA (Heat Release Rate per Unit area) of 169.5 kW/m². The first two scenarios will be based on an exponential fire growth rate ($\alpha t^2$, where $\alpha$ is the growth constant and t the time) that reach its peak in 600 seconds and continue with this heat release rate until 900 second. In the third scenario HRRPA of 169.5 kW/m² is used for 900 seconds.

The tenability criteria have been used based on NFPA 130 [4] which limits the temperature of the smoke to 80 °C for maximum exposure time of less than 4 minute and 60 °C for maximum exposure time of 10 minutes. In order to protect occupants from excessive radiative flux, the radiation flux should be limited to 2.5 kW/m². A visibility of 10 m should be achieved inside the station and along the evacuation routes. The maximum carbon monoxide (CO) inhalation, according to NFPA 130, is 1150 ppm for the first 6 minutes and 225 ppm for up to 30 minutes.

A single passenger with an occupant load of 100 persons per wagon and carrying 1500 passages in total is considered, and the people on each platform are assumed to be 200.

The evacuation analysis is made analytically according to NFPA 130. NFPA 130 requires the time to leave the platform to be 4 minutes, and 6 minutes to reach points of safety from the farthest point of the platform to the station. NFPA 130 proposes exit capacities of stairs as 0.0555 p/mm – min and 0.0819 p/mm – min for emergency exit doors. Walking speed over platform is limited to 37.7 m/min and over stairs it is reduced to 15 m/m [4].
The quantitative risk analysis is performed by developing event trees considering the fire scenarios and the evacuation scenario. Corresponding frequency of occurrence of the fire, probabilities of each scenario and consequences are calculated. The risk acceptance criterion is selected according to societal risk [6].

RESULTS AND DISCUSSION

The result of the fire modelling displayed in Table 1 shows that the temperature is quite low (less than 60 oC) at the height of 2 m above the platform levels. The Carbon monoxide (CO) concentration is also evaluated. According to NFPA’s recommendation, taking the calculated evacuation period of 15 minutes, a maximum of 450 PPM is allowed. However, the result of all fire scenarios show that the concentration is lower i.e. the CO concentrations are uncritical. According to NFPA, the smoke layer has to be 2.0 m above the floor of evacuation routes. In the analysis, due to very cold smoke, the smoke loses its buoyancy resulting lower smoke free height. However, as the CO concentration and smoke temperature is low, this will not create untenable conditions. Similarly, radiation from the smoke layer was not found to be a problem. The only untenable condition found was visibility. The visibility was found to be less than the required tenable condition (10 m) from 3.5 minutes onwards of the simulation time.

Table 1 Summary of results obtained from evacuation analysis and fire modelling

<table>
<thead>
<tr>
<th>Evacuation Scenarios</th>
<th>RSET (minutes)</th>
<th>ASET (minutes)</th>
<th>Number of people exposed to smoke</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 A</td>
<td>3.3 minutes</td>
<td>More than 10</td>
<td>None</td>
</tr>
<tr>
<td>1 B</td>
<td>10 minutes</td>
<td>More than 10</td>
<td>None</td>
</tr>
<tr>
<td>2A</td>
<td>3.3 minutes</td>
<td>3.5 minutes</td>
<td>None (requires risk analysis)</td>
</tr>
<tr>
<td>2B</td>
<td>15 minutes</td>
<td>3.5 minutes</td>
<td>923 people (highly unacceptable)</td>
</tr>
<tr>
<td>3</td>
<td>15 minutes</td>
<td>15 minutes</td>
<td>None</td>
</tr>
</tbody>
</table>

CONCLUSION

Performance based fire design for a typical rail tunnel is made by integrating fire modelling, evacuation analysis and risk analysis. The smoke movement is simulated with Fire dynamics simulator FDS using various fire scenarios. The fire simulation results are analysed in terms of tenability e.g. smoke layer height, smoke layer temperature, visibility, radiation, CO concentration, etc. Based up on these, the required safe egress time (RSET) is deduced. The analysis of the evacuation conditions according to NFPA 130 approach gives the Available Safe Egress Time (ASET) which is compared with the RSET. The result indicated that visibility is the main cause of untenable condition. Increasing the width of the exit (to reduce ASET) or adding natural or forced smoke extraction system (to increase RSET) is proposed in order to meet the required level of safety. The tunnel risks are assessed in terms of societal risk that is compared with the expected number of fatalities.

REFERENCE

Numerical Investigation on Jet Fans for Fire Control in Short Tunnels

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KEYWORDS: Tunnel Fires, Ventilation, Jet-fan, Smoke confinement

INTRODUCTION

Jet fans are powerful devices for the smoke exhaust and pollution control in tunnels, providing a competitive solution for the ventilation management. Jet fans are commonly employed since they don't require additional construction work, except for their installation under the ceiling: no special ducts are necessary for smoke exhaust, since the tunnel itself works as duct.

Their main field of application are short double tube tunnels [1], in fact, fans produce a pressure rise, pushing the smoke along the traffic direction, so they create a tenable zone in front of the fire, while the cars behind the accident easily run away.

A lot of research on longitudinal ventilation has been carried out [2, 3, 4], by studying the critical velocity, both with numerical simulations and experiment. These studies usually don't consider the three dimensional flow field induced by a jet fan, since ventilation devices are not taken into account and a uniform flow is usually imposed. As well, one dimensional methods, widely used nowadays in the design process, neglect the three dimensional features of the flow and they take into account the jet fan effect by means of empirical correlations [9].

Therefore, referring to a given fire scenario in a double tube short tunnel, in this paper the results of several simulations are compared in order to evaluate the flow field in the close surrounding of the jet fan and the smoke confinement in case of fire.

JET FAN VALIDATION

Before studying the effects of the different jet configurations, it is necessary to assess the reliability of the calculation through a validation process. The jet fan modelling has always been challenging in CFD because of the high number of elements that is required and because of the lack of experimental data. In order to fill this gap the simulations have been validated first on a small scale experiment [5] and later with a real scale one [6].

TUNNEL AND VENTILATION

The validated tunnel [6] has been later used as the base for the simulations, the flow in the tunnel is induced by two jet fan placed at 80 m from the entrance. The overall length of the tunnel is 470 m and its height is 7 m, with a rounded ceiling. Because of the high computational cost and thanks to the results from the earlier validation, just half of the tunnel has been simulated by means of a symmetry plane. The jet fan position will be changed in the different simulations in order to evaluate how the fan's location affect the smoke confinement and the fire plume.
FIRE SCENARIO

The considered fire scenarios refer to a burning Heavy Good Vehicle (HGV) with maximum HRR of 30 MW and a Tanker with a maximum HRR of 120 MW. The fire place has been modelled as a solid block with an uniform burning rate on each exposed surface. The fire has been placed close to the jet fan in order to highlight the local effect of the jet wake on the smoke.

NUMERICAL MODEL

Numerical simulation were performed by resorting to the specific CFD code "Fire Dynamic Simulator (FDS 6)" [7]: this code solves Large Eddies Simulations on a structured cubic grid. The grid size near the fire was chosen basing on the characteristic diameter of the fire D* which is related to the HRR and to the conditions in the compartment. The employed grid element size dx is 0.4 m, which allows to have a ratio D*/dx equal to 9.32, this is enough to provide a good resolution in the fire zone, with acceptable computational time. For the jet fan the grid has been designed basing on the earlier validation work and on the directives provided in [8].

DISCUSSION

The aim of this work is firstly to give information about the capability of FDS to simulate correctly a jet fan. The grid size in this case has been found to be much smaller that the one required for a proper fire modelling. Thus the mesh size becomes a fundamental parameter in the simulation, because it rises the computational time and it strongly affects the results of the simulation. The other goal of this research is to evaluate, with a reliable tool, the effect of the fan position on the air entrainment inside the tunnel. As shown by [9] the jet fan position can change the flow through the tunnel, because of the interaction of the wake jet with the walls. But not only the air entrainment in case of fire has been studied, as well the effects of the jet fan on the smoke confinement have been investigated. The smoke in this case is not uniformly pushed downstream as it would be for a fire far from the fan. The wake discharged by the fan mixes the air with the smoke which interact due to the different velocities and due to the different temperature. With FDS it is possible to evaluate these three dimensional effects and not just to consider them just by using some empirical models.

REFERENCES
