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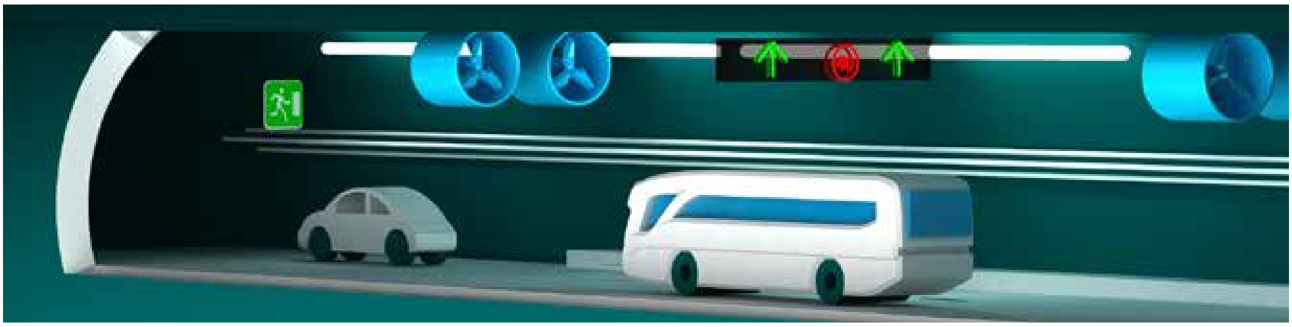
# Fire protection in tunnels: Focus on road & train tunnels

*Catastrophic fires in tunnels have resulted in loss of life, large property losses and relatively long business interruption periods. In the wake of such fires, authorities tend to focus their efforts almost exclusively on addressing fire safety issues. Property conservation and business continuity aspects are generally not considered. From a risk management standpoint (including risk financing/transfer) this situation is not sustainable. Fire protection solutions should be included as part of the overall design of a transportation tunnel.*
*This paper considers the main catastrophic fire events worldwide since 1949. The study begins by providing a full description of tunnel risk, fire hazard, aggravating factors and fire protection considerations. It then investigates loss prevention solutions including fire protection engineering, according to globally recognized standards (National Fire Protection Association – NFPA).*



## Research results

Tunnel walls made of reinforced concrete are known to be fire resistive. However, tunnel linings are vulnerable to large fires, which may result in spalling and/or collapsed concrete. Moreover, the integrity of a concrete structure may be compromised depending on the type of construction involved, including the use of plastic fibers. Thermal barriers and combustible road pavements will add fuel to a fire inside a tunnel.
Evacuation in tunnels is critical and has not been well studied. Various fire detection systems have been developed and some have been adapted for tunnels. Early fire detection systems combined with emergency response crews cannot always ensure life safety or adequate mitigation of property loss.
Research and data on fires in road tunnels is limited, and very limited in the case of rail tunnels. Fire growth rate testing is not sufficiently focused on real fires, including large vehicle fires. Tests are very infrequent and are performed on old vehicles made of less combustible material than modern vehicles. Test information on fire development and the performance of fixed fire protection is often misquoted or misused.
Current available standards for fixed fire protection systems in tunnels provide the framework for a risk-based approach, but not the design criteria for fire protection. Given the difficult access conditions and low visibility in a tunnel during a fire, the manual activation of fixed fire protection systems could be delayed. Consequently, manually activated fixed fire protection systems are deemed to be less reliable than automatically activated ones. Local or partial protection, consisting of water curtains designed to mitigate hot gases and smoke migration in road tunnels, or water spray-protected sections inside rail tunnels (where trains on fire are supposed to be driven) are not considered to be fully reliable solutions. Regarding water mist protection [19], there is no recognized general design method for such systems. The only approved water mist systems are pre-engineered systems for enclosure protection; none exist for large open plan areas such as tunnels. Moreover, there are only a few standards on Water Mist Fire Protection Systems (e.g. NFPA 750[19]) and these neither provide definitive fire performance criteria nor offer specific guidance on

how to design a system to control, suppress, or extinguish a fire. Instead, reliance is placed on the procurement and installation of listed water mist equipment or systems that have performed well in fire tests as part of a listing process. There are no scaling rules for water mist systems. A discharge test is important to verify that a system will operate properly. However, a successful discharge test does not guarantee that the system will provide adequate protection from fire. A change in conditions, the effects of ventilation, and any adverse conditions inside a tunnel in the event of an emergency, would severely challenge the water mist fire protection. As a result, the reliability of such systems is deemed to be questionable.

## Main conclusions and recommendations

Considering the above points, tunnel risks are defined in this study as "systems" consisting of more or less fire resistive buildings "temporarily housing combustible goods in transit". Thus, they correspond to a class of commodity rather than a class of occupancy [3].

Automatic fixed water-based fire-fighting systems should therefore be installed in tunnels as part of an integrated approach to the management of fire and life safety, unless it can be proved that existing early fire detection systems, combined with efficient emergency response, are enough to ensure life safety and to adequately mitigate property loss in a given tunnel. This should be considered on a case-by-case basis.

The following loss prevention and mitigation measures are therefore recommended:

- Use of non-combustible and non-toxic construction materials for the tunnel structure and pavement, in order to ensure safety for people and to prevent severe physical damage.
- Installation of full automatic fixed water-based fire-fighting systems in tunnels where necessary, consisting of automatic wet pipe sprinkler or spray systems as per recognized international standards. This would enable safe evacuation and facilitate control of a fire in its early stages (control mode or surface cooling mode design objectives). Final extinguishment would be achieved through manual fire-fighting.
- Installation of fixed gaseous clean agent type [21] extinguishing systems in the technical rooms of tunnels, approved and adequate as per recognized international standards.
- Provision of emergency ventilation system and smoke control system designed to maximize the exhaust rate in the ventilation zone that contains the fire and to minimize the amount of outside air that is introduced. In all cases, the desired goal is to provide an evacuation path for motorists / people exiting from the tunnel and to facilitate fire-fighting operations.
- Establishment of adequate emergency response planning including all coordination / communications aspects, traffic control, emergency ventilation / de-smoke systems management and fire-fighting operations between the different entities having jurisdiction inside and possibly at both ends of the tunnel, especially for trans-border tunnels [20].

This document sets out key design criteria (density and surface area of application) for the recommended water-based fixed fire protection systems, in accordance with existing recognized international standards (NFPA). This means considering the most challenging combustible load and continuity of combustibles that could possibly enter a tunnel (conservative approach, to be revised in accordance with the vehicles or trains currently allowed to enter a given tunnel). Basic guidance for adequate and reliable water supplies feeding both fixed fire-fighting systems and manual fire-fighting equipment is also given. As there are currently no known, validated methods of predicting the performance of water-based fire-fighting systems, the ability of such systems to meet defined performance objectives under the specific tunnel parameters should be assessed on the basis of full-scale fire testing.

# Fire loss history

177 tunnel events have been recorded in 29 countries worldwide since 1866 (the first being recorded in the UK) caused by electric fire, car crash, bomb attack, fire, derailment, collision, collapse during construction, arson, broken catenary leading to fire, engine fire, electrical train equipment on fire, etc.

Of these 177 tunnel events, 28 major fire events *(see Table 1 on the next page)* were recorded between 1949 and 2008, resulting in more than 700 deaths, more than 1,000 people injured, the loss of more than 500 vehicles (including cars, trucks and trains) and financial loss of more than €1 billion (PD/BI combined).

The top 3 losses were:

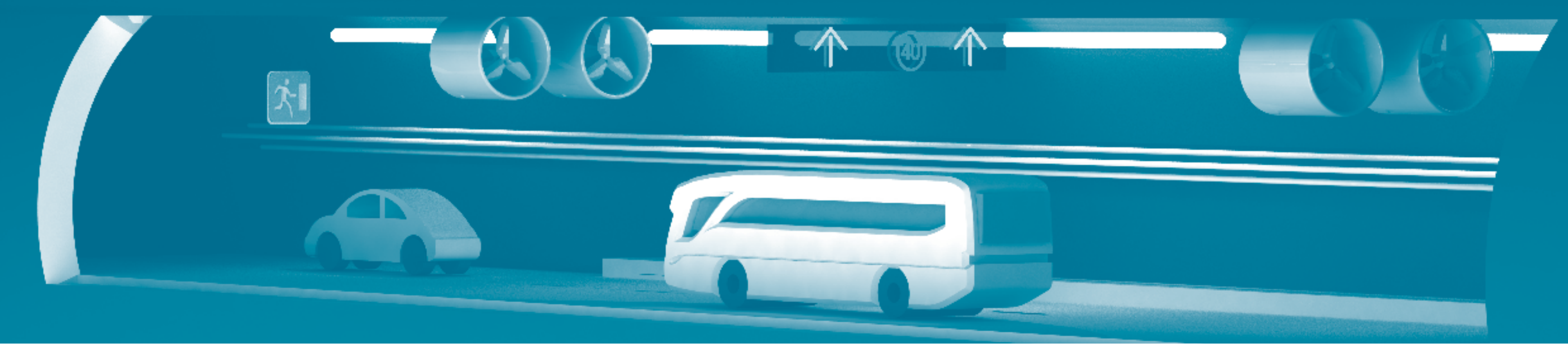
- the Channel Rail Tunnel in 1996 (€ 250M tunnel financial loss),
- the Mont Blanc Road Tunnel in 1999 (39 deaths, many injured and € 392M tunnel financial loss)
- the Channel Rail Tunnel again in 2008 (€ 250-286M loss),

## Lessons learned

In relatively old tunnels, the main purpose of ventilation was to evacuate toxic fumes released from vehicles only; it was not designed for smoke control. In more recent tunnels, in all cases the use of existing emergency ventilation systems intended to remove smoke and heated gases has resulted in aggravated damage to the tunnels' concrete structure and to whatever was inside them (rolling stock, trucks, cars) (i.e. Mont Blanc Road Tunnel in 1999 and in the Channel Rail Tunnel in 1996 and 2008 [25]).

Severe aggravating factors in these events included difficult access, poor visibility and delays due to response time and to the need to de-energize the electric power system for railway tunnels prior to fire-fighting.

The use of non-combustible structural members in the tunnel and non-combustible and non-toxic road



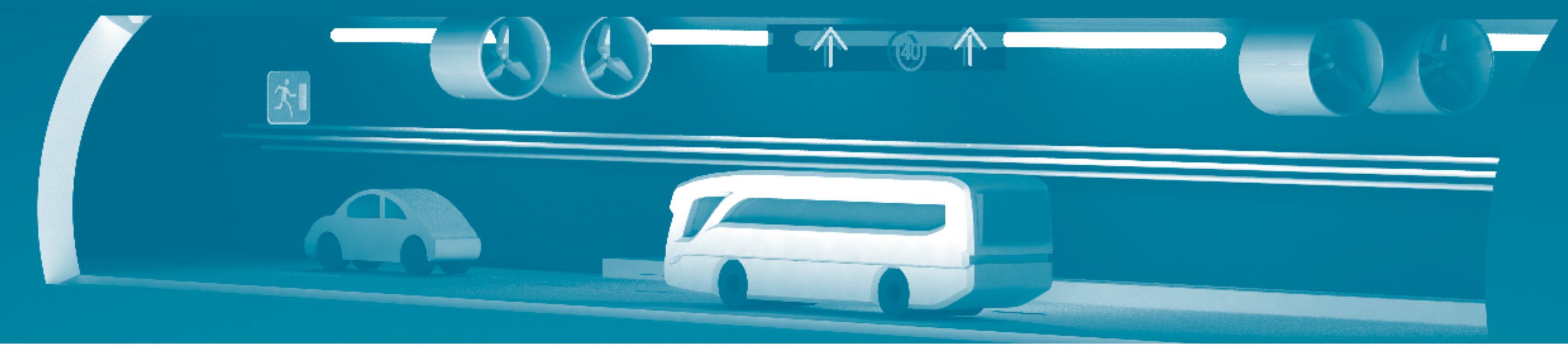
pavements will ensure maximum safety for people. However, concrete itself may be damaged by fire. During the St. Gotthard tunnel's fire in 2001, a 250m long section collapsed, challenging the emergency response. Considering the above, from a risk control standpoint, even with no collapse of the concrete structure, the fire-damaged structural frame of a tunnel may have to be removed and replaced. This leads to expensive operations and relatively long business interruption.

Proper cooling of the structure, as shown during the 2007 Melbourne Burnley Road Tunnel fire, will mitigate damage caused by an internal fire. This 3,400m-long tunnel, built between 1996 and 2000, was equipped with a deluge system which was activated instantly, and a smoke extraction system which reportedly functioned as planned and removed toxic fumes from the tunnel into the open air. Little structural damage was reported.

*Table 1: List of the main tunnel events since 1949 together with their historical economic loss amounts (where data is available) [24] [25] [26] [27] [28].*

| Event Year | Location/Tunnel length/ Construction year | Country | Event/Circumstances/ (Duration & Temperature) | Fatalities | Economic Loss |
|---|---|---|---|---|---|
| 2008 | **Channel Rail Tunnel**<br>2x50km single track tunnels (7.6-metre -25ft diameter rail tunnels) and 1x50 km service tunnel<br>Built between 1988 and 1994 | France / UK | Truck fire on Eurotunnel rail Shuttle roll-on/roll-off vehicle transport<br>(24 hours duration, 1,200°C) | • None reported | € 250-286 M PD BI combined (*):<br>€ 40 M rolling stock<br>€ 53 M tunnel damage<br>€ 193 M BI |
| 2007 | **Los Angeles Road Tunnel Interstate 5**<br>167m long<br>Built in 1975 | USA | Truck blowing a tire before crashing and exploding into flames.<br>The fire was fuelled by about 8,500 gallons of gas | • 3 people died<br>• 10 people were injured | Structural damage reported |
| 2007 | **Melbourne Burnley Road Tunnel**<br>3,400m<br>Built between 1996 and 2000 | Australia | Pile-up in the tunnel involving three trucks and four cars. The crash resulted in an explosion and a subsequent fire which reached temperatures in excess of 1,000 °C (1,832 °F) | • 3 deaths<br>• Approximately 400 people were advised by the tunnel's safety system to abandon their cars, to leave their keys in the ignition, and to evacuate the tunnel after the collision | Little structural damage reported. The deluge system was manually activated by operator. The smoke extraction system functioned as planned and removed toxic fumes from the tunnel and out into the open air |
| 2003 | **Daegu Subway Tunnel**<br>25km long<br>Inaugurated in 1997-1998 | South Korea | Arson fire in a wagon (introduction of gasoline) | • About 130 deaths<br>• 140 injured | No data available |
| 2001 | **Gleinalm Road Tunnel**<br>8.3km<br>Completed in 1978 | Austria | Two car collision in the middle of the tunnel | • 5 deaths<br>• 4 injured | No data available |
| 2001 | **Gotthard Motorway Tunnel**<br>Opened in 1980 | Switzerland | Fire following the collision of two trucks | • 11 deaths<br>• 19 injured | 13 cars and 10 trucks destroyed |
| 2000 | **Kitzsteinhorn Funicular Tunnel**<br>10km<br>Opened in 1974 | Austria | Fire probably due to blow heating system malfunction | • 155 deaths | No data available |
| 1999 | **Mont Blanc Road Tunnel**<br>11.6km (8.6m wide, 4.35m high)<br>Built in 1957-1965 | France / Italy | Truck fire in a tunnel<br>(53 hours duration, 1,200°C) | • 39 deaths<br>• Multiple injuries | € 392 M PD BI combined (*):<br>€ 189 M toll loss<br>€ 203 M tunnel repairs |

| Event Year | Location/Tunnel length/ Construction year | Country | Event/Circumstances/ (Duration & Temperature) | Fatalities | Economic Loss |
|---|---|---|---|---|---|
| 1999 | **Tauern Road Tunnel**<br>6km<br>First bore completed in 1975<br>A second, parallel tube began construction in 2006 and was officially opened in 2011 | Austria | Motor crash in a tunnel (14 hours duration, 1,200°C) | • 12 deaths<br>• 49 injured | € 28.5 M PD BI combined (*)<br>€ 20 M toll loss<br>€ 8.5 M tunnel repairs<br>24 cars and 16 trucks destroyed |
| 1998 | **Gleinalm Road Tunnel**<br>8.3km<br>Completed in 1978 | Austria | Bus on fire | • None reported | Bus destroyed |
| 1996 | **Channel Rail Tunnel**<br>2x50 km single-track tunnels (7.6-metre -25 ft diameter rail tunnels) and 1 x 50 km service tunnel<br>Built in 1988-1994 | France / UK | Truck fire on Eurotunnel rail Shuttle roll-on/roll-off vehicle transport (10 hours duration, 1,100°C) | • None reported | € 250 M PD BI combined (*) |
| 1996 | **Palermo Road Tunnel**<br>148m<br>Construction started in 1972 | Italy | Tank truck (2500 liters of liquid petroleum gas - LPG) collision with a minibus, followed by fire and explosion (presumably BLEVE)** | • 5 deaths<br>• 26 injured | 1 car, 1 truck and 1 minibus destroyed |
| 1995 | **Baku Subway Tunnel**<br>Construction started in 1966 | Azerbaijan | Short circuit in a wagon followed by fire | • 289 deaths<br>• 270 injured | No data available |
| 1995 | **Pfänder Tunnel**<br>6,750 m<br>1 tube<br>Built in 1974-1980 | Austria | Collision,<br>1 truck (Bread),<br>1 minibus, 2 cars | • 3 deaths | 1 truck, 1 minibus, 2 cars |
| 1994 | **Huguenot Tunnel**<br>3,900m long<br>Built in 1984-1988 | South Africa | Electrical fault in gear box in a bus with 45 passenger | • 3 deaths | Serious damage to tunnel structure – Closed for 1 week |
| 1988 | **Herzogberg Tunnel**<br>2,007m<br>1 tube | Austria | Truck | • None | Truck |
| 1987 | **Kings Cross London Subway**<br>Origin 1963 | UK | Accidental ignition (matches) | • 31 deaths | No data available |
| 1987 | **Gumefens Tunnel**<br>340 m<br>2 tubes | Switzerland | Collision 3 trucks, 5 cars; Spilled petrol | • 2 deaths<br>• 5 injured | 3 trucks, 5 cars |
| 1984 | **Felbertauern Tunnel**<br>5,130 m<br>1 tube<br>Built in 1962-1967 | Austria | Bus, brake failure | • None | 1 bus |
| 1984 | **Gotthard Tunnel**<br>16,321m<br>1 tube | Switzerland | Truck fire (Plastic foil) | • None | 1 truck |
| 1983 | **Pecorile galleria Gêne – Savone**<br>662 m long | Italy | Front rear collision of trucks (fish) | • 8 injured | 10 cars |



| Event Year | Location/Tunnel length/ Construction year | Country | Event/Circumstances/ (Duration & Temperature) | Fatalities | Economic Loss |
|---|---|---|---|---|---|
| 1982 | **Caldecott Tunnel**<br>1,028 m<br>3 tubes<br>Built in 1937-1964 | USA (California) | Collision gasoline bulk tank Fire 33,000 l petrol | • 7 deaths<br>• 2 injured | 2 trucks, 1 bus, 1 car |
| 1979 | **Nihonzoka Tunnel**<br>2,045 m<br>2 tubes | Japan | Collision cars, trucks (ether) | • 7 deaths<br>• 2 injured | 87 cars, 102 trucks |
| 1978 | **Velsen Tunnel**<br>768 m<br>2 tubes<br>Built in 1941-1957 | The Netherlands | Collision | • 5 deaths<br>• 4 injured | 2 trucks, 4 cars |
| 1975 | **Guadarroma Tunnel**<br>3,345 m<br>2 tubes<br>Built in 1963 | Spain | Truck fire, pine resin | • None | 1 truck |
| 1972 | **Hokoriku Fukui**<br>13,870 m long<br>double track railway<br>Built in 1957 | Japan | Passenger train, restaurant Car fire | • 30 deaths<br>• 714 injured | 2 rail cars destroyed |
| 1968 | **Moorfleet Tunnel**<br>243m | Germany | Truck fire (14 t polyethylene) Brake failure | • None | 1 truck trailer |
| 1949 | **Holland Tunnel**<br>2,600m<br>2 tubes<br>Built in 1920-1927 | USA (New-York) | Truck fire (carbon disulphide) | • 66 poisoned by carbon monoxide | 10 trucks, 13 cars |

*(*) PD: Property Damage, BI: Business Interruption*
*(**) BLEVE: Boiling Liquid Expanding Vapor Explosion*

## Understanding the risk – Fire hazard

### Ignition sources

There are basically two main types of ignition sources in a tunnel, as follows:

• Sources inherent to the tunnel equipment and appurtenances, such as railway electric power systems, energized equipment for guided transit systems (railway), traffic control and lighting systems (roadway), ventilation systems and any other electric power sources forming part of the tunnel equipment.

• Sources related to transit vehicles (road tunnel) and / or rolling stock (rail tunnels – including standard freight and passenger trains and trains carrying Heavy Goods Vehicles). These include embedded automotive electric power sources (e.g. batteries and lithium batteries if any), electric drivers and lithium batteries if any, and combustion engines, which are typically tested and approved for their intended use. There are also additional ignition sources such as smoking and any other electric powered, gas- / solid fuel-fired equipment that can be found in vehicles (and especially in trucks). A lot of equipment that has been neither especially approved nor tested can be found in gas stations for both trucks and cars. This includes cooking equipment such as 12V/24V microwaves, hot plates, grills, kettles, power transformers and converters.

### Combustible load

The combustible load of a tunnel's structure, equipment and appurtenances is generally relatively low except for road pavements, which are made of combustible material (such as bituminous material) and will fuel an internal fire. Moreover, this combustible material is also responsible for releasing lethal toxic fumes. The combustible load and the continuity of combustibles inside the tunnel consist mainly of vehicles and trains, and of payload in cases where any is transiting through the tunnel.
The combustible load of a car is deemed to be relatively high, corresponding in some cases to up to 80% of the plastic material volume of the vehicle (e.g. polyurethane foam, polyester foam, fiber reinforced plastics, etc.). These can be treated with a fire retardant additive, but they are still combustible and will contribute fuel to an internal fire. The fuel used for combustion engines is

stored in plastic or metal reservoirs. Gasoline considered as flammable liquid (flash point =<38°C), diesel oil considered as combustible liquid (flash point>38°C), any other hazardous liquids (lubricants, some cooling fluids) and any combustible goods (e.g. luggages, material load) will contribute fuel to an internal fire. Moreover, a car powered by LPG and equipped with pressure relief valve or rupture disk on the LPG tank could generate jet fire and in some case explosion if the LPG tank is overheated by fire. However, explosion is more likely to happen in cars not equipped with depressurization systems.

The combustible load of a truck tractor alone (trailer excluded) is deemed to be relatively similar to the truck from the point of view of the materials involved (mostly plastic) but is aggravated by the volume of fuel transported for the combustion engine, which is higher than for a car. When considering the trailer itself, the external shell can be made of either a light non-combustible metal structure or of highly combustible flexible plastic material (similar to tarpoline), thus increasing the combustible load further. Considering the payload, various transported goods should be taken into consideration, from non-combustible goods (e.g. structural metal members, minerals) to highly combustible goods (e.g. wood, coal, plastics, combustible / flammable liquids, flammable and / or explosive gases, molten materials).

The combustible load of a passenger train is deemed to be moderate, mostly consisting of internal furniture on floors, sides, partitions and seats containing a certain volume or weight of plastic material that can be treated with fire retardant additives designed to slow down the ignition rate and the flame spread. However, these plastic-based materials are still combustible and will contribute fuel to an internal fire.

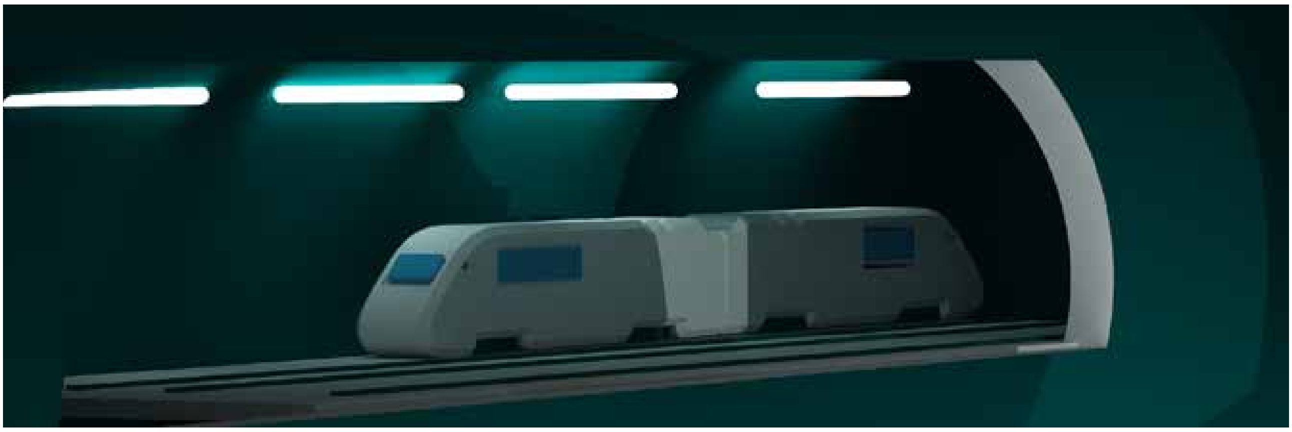
The combustible load of a freight train itself (limited to locomotive and wagon – freight load excluded) is deemed to be light for an electric locomotive and moderate for a diesel engine locomotive. The wagons are basically made of non-combustible materials. However, the above statement should be weighed against the type of freight involved, which can consist of anything from non-combustible goods (e.g. structural metal members, minerals) to highly combustible goods (e.g. wood, coal, plastics, combustible / flammable liquids, flammable and or explosive gases, molten materials). As a result, the combustible load of a train carrying Heavy Goods Vehicles such as trucks is deemed to be very high.

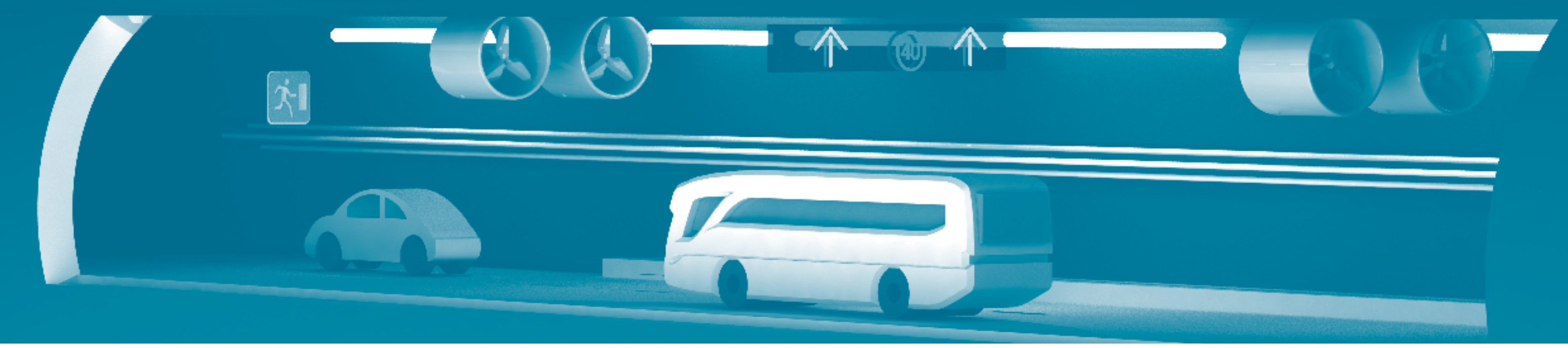
## Challenging fire development

Fire in road and rail tunnels spreads very rapidly due to radiation. For example, a heavy goods vehicle fire needs only 10 minutes to exceed 100 MW and 1,200°C (2,192°F), which are fatal conditions. Charged particles are reflected from the internal surfaces of the tunnel, making it act like a clay oven. Hot gases accumulating in the tunnel can lead to a flashover. Improper use of ventilation in an emergency can lead to "ventilated oven conditions", increasing the convection effect and allowing the fire to gain intensity and to spread inside the tunnel. A fire in a tunnel should therefore be controlled in its early stages, in order to limit its spread.

## Limited access, special hazards, heat, radiation, smoke and adverse conditions

Not all tunnels are provided with service tunnels connected to the main tunnel, and sometimes the driving distance in special vehicles can be relatively long (e.g. up to 25km for the Channel Tunnel using a special fire truck designed for low level ceilings). The electrification system supplying electrical energy (1,500V DC/25kV AC up to 2,000 Amps) to railway trains inside a tunnel needs to be de-energized by people with the proper jurisdiction, authority and knowledge before manual fire-fighting can be organized [18]. This delays the intervention of firefighters. Such intervention may also be delayed by the difficulty involved in identifying the fire area due to heavy toxic fumes, by extremely high temperatures, by obstructions caused by vehicle collision or the derailment of rolling stock, or by unknown hazardous materials that





can result in pool fire or explosion. The improper use of ventilation in an emergency can oxidize an internal fire, causing it to intensify and spread.

### Property damages considerations

Considering the above, property damages resulting from a fire in a tunnel can be very significant, including both tunnel structure and appurtenances. Total loss of vehicles, fixed guided transit system (railways) and rolling stock is usually expected within the fire area.

### Business interruption consideration

A relatively long business interruption period for investigation, debris removal, expertise, partial demolition and rebuild can be expected depending on the extent of the fire. Moreover, in the event of loss of life, people injured or potential ground/air contamination, additional investigation, administrative closure and advanced studies can be requested. The pressure of public opinion on the relevant authorities and the lack of recovery plans can also lead to adverse conditions for the post-loss effective down time, thus increasing the business interruption period further.

## Fire detection

### Purpose and limitation

The main purpose of automatically activating a detection system in a tunnel is to trigger an alarm upon fire detection, which is relayed to a constantly attended location in order to organize prompt emergency response, including evacuation and fire-fighting. Automatic fire detection systems can also be used to trigger automatic fixed fire protection systems. Different systems may be considered, ranging from standard smoke and fire detectors (ionic, optical), flame detectors (UV/IR), laser beam detectors (smoke) and linear detectors (conductors in insulator), to highly sophisticated early detection systems based on air sampling and CCTV imaging software [16] [23]. Other types of detectors such as hydrocarbon detectors can also be installed. Detector selection should be based on the ambient conditions inside the tunnels. Alarms and signals: all fire alarms, supervisory signals and trouble signals should be relayed to a constantly attended location. All fire detection material and equipment should be listed or approved (e.g. UL / FM / VDS) and should be installed by a qualified contractor familiar with recognized standards (e.g. NFPA/FM/APSAD/VDS). The project should be reviewed by a qualified Fire Protection Engineer familiar with the above-mentioned standards.

### Limitation

Based on the highly challenging fire development aspects and adverse conditions mentioned above, an automatic fire detection system should not be considered as a substitute for an automatic fixed fire protection system in tunnels. Such systems can control a fire in its early stage of development.

## Emergency response

### Rescue and evacuation

The designers and contractors should participate in the preparation of the emergency response plan. All typical incidents such as derailment collisions and fires should be considered during the development of facility emergency response plans. [1] [20]

### Ventilation, emergency ventilation & smoke control

Ventilation is installed in most road tunnels in order to limit the concentration of contaminants to acceptable levels within the tunnel. Emergency ventilation systems should be developed in order to remove and control the smoke and heated gases resulting from fire emergencies within the tunnel.

There are various ventilation system concepts for road tunnels. The systems used for mechanical or fan-driven ventilation are classified as longitudinal or transverse. A longitudinal ventilation system achieves its objectives through the longitudinal flow of air within the tunnel roadway. A transverse ventilation system achieves its objectives by means of the continuous uniform distribution or collection of air throughout the length of the tunnel roadway. Many combinations of longitudinal and transverse ventilation systems exist, the desired goal being to provide an evacuation path for motorists exiting from the tunnel and to facilitate fire-fighting operations.

Note: some short tunnels are ventilated naturally (without fans); however, such short tunnels could necessitate a ventilation system in case of fire.

Emergency ventilation systems should be designed to maximize the exhaust rate in the ventilation zone that contains the fire and to minimize the amount of outside air that is introduced by a transverse system. Smoke management is best accomplished by the extraction of air and smoke as close to the incident location as possible.

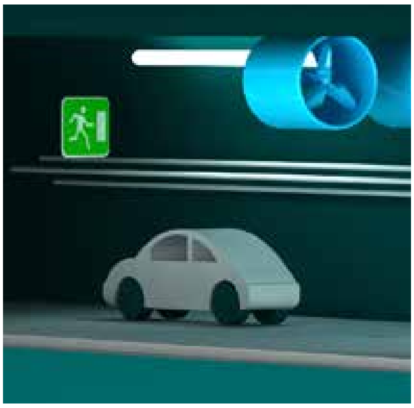
### Manual fire-fighting without water based fixed fire protection

Based on the highly challenging fire development aspects and adverse conditions previously mentioned, safe and efficient manual fire-fighting would be virtually impossible for fires not controlled in their early stage of development by automatic fixed fire protection systems, where the tunnels involved permit this.

## Passive fire protection

### Lack of internal partitions

Tunnels are basically long structures with very few internal fire partitions other than fire shelters (fire doors [17]) and heavy fire doors between the tunnel and the service tunnels (weighing up to 2 tons in the Channel Tunnel), and inside crossover tunnels (e.g. Channel Tunnel crossover tunnels are equipped with a 90-ton fire door). Therefore, a tunnel is an open plan area with a very limited level of feasible passive fire protection compared to other property risks. This allows a fire to spread in the tunnel using trapped fire load as fuel.



As an example of open plan area:
- The longest tunnel in the world is the Japan Seikan railway tunnel at 53.85-kilometre, with a 23.3-kilometre long portion under the seabed. It has been operating since 1988.
- The largest (highest) tunnel in the world is under the river Yangzi in Shanghai, China, with an internal diameter of 13.7 m, housing two stacked levels (upper level for a motorway and lower level for a metro line).

### Fire resistance of the structure

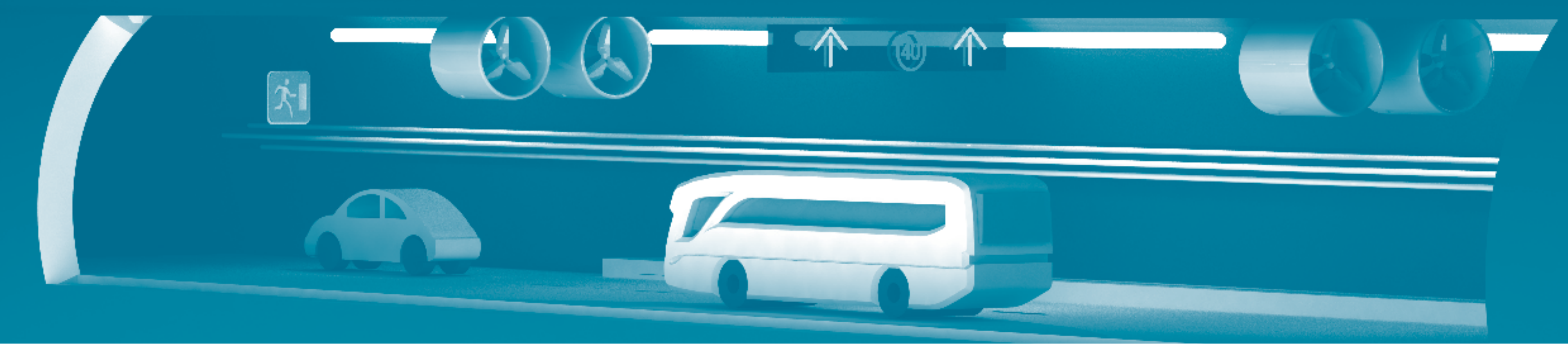
Reinforced concrete installed in tunnels must be fire resistive [2] [22]. However, concrete can actually be damaged by fire (thermal damage: expansion, shrinkage above 300°C due to water loss, decomposition from 450-550°C). Sudden exposure to very high temperatures can result in explosive spalling of the concrete: in a very hot, very quick fire, the water inside the concrete will boil before it evaporates. The steam inside the concrete exerts expansive pressure and can initiate and forcibly expel a spall. This can lead to a situation where damaged concrete needs to be demolished and replaced over a relatively large surface area, resulting in a relatively long business interruption period.

### Electrical equipment

Electrical systems should support life safety operations, fire emergency operations, and normal operations. Emergency circuits installed in a road tunnel and ancillary areas should remain functional for a period of not less than 1 hour for the anticipated fire condition [1], considering one of the following methods: A fire-resistive cable listed for 2 hours, circuits embedded in concrete or protected by a 2-hour fire barrier system in accordance with internationally recognized standards.

Standard acid filled batteries produce highly inflammable hydrogen gas which can accumulate in this room and be easily ignited resulting in explosion and fire. As a result, the UPS acid filled batteries in electrical / IT rooms should be replaced with batteries without hydrogen degassing potential and fire detection should be installed according to NFPA or any other recognized international standard.

All cable openings through floors in electrical rooms, trenches and



walls should be adequately sealed with FM approved and or UL-listed non-combustible material. The use of highly combustible polyurethane foam (even called fire retardant) should be prohibited. All horizontal cable trays running in the tunnel should be provided with large fire breaks of 2m in size, made from FM approved and/or UL-listed non-combustible intumescent paint, applied to cables every 30m. In vertical cable runs, the trays should have a fire barrier installed every 10m.

## Automatic fire protection

### Benefits of water-based fixed fire protection systems - An integrated approach to the management of fire and life safety [1]

Some of the benefits and capabilities of water-based fire-fighting systems include the following:

- minimization of fire spread (prevent fire spread to other vehicles),
- fire suppression and cooling (suppresses the fire and cools the tunnel environment),
- improved conditions for first responders (cooling and radiation-shielding effects of water reducing the thermal exposure),
- improved performance of ventilation systems (cooling of hot products of combustion resulting in higher density).

### Design Objectives [1]

The categorization of water-based fixed fire-fighting systems is based on the following three main performance objectives:

- Fire Suppression System: to reduce and extinguish a fire.
- Fire Control System: to stop or slow the growth of a fire in order to allow safe and efficient final extinguishment through manual fire-fighting.
- Surface Cooling System: to provide direct cooling of critical structure or equipment (exposure).

### Water-based fixed fire protection standards for tunnels

The purpose of the NFPA 502 [1] is to establish minimum criteria providing protection from fire and its related hazards. However, there are relatively few design criteria given in the NFPA 502 standard for fixed water-based fire protection. Consequently this paper has considered other NFPA standards relating to automatic fixed water-based fire protection, in order to define the key design criteria to be considered for tunnels as described in the following sections.

### Design criteria – Tunnel risks as commodity rather than occupancy

There is no real process for tunnels compared to other property risks. Moreover, there are no obvious classes of occupancy which could correspond to tunnel risks. Vehicles and trains in transit in the tunnel are relatively similar to combustible goods (vehicle and train materials such as plastic, metal and payloads for trucks) and to hazardous materials (gas, fuel for tankers) in transit. People driving cars, trucks and trains can introduce/induce ignition sources which are considered as special hazards (human factor related). As shown by the loss history, in-transit vehicles/trains on fire in the tunnel will stop somewhere inside the tunnel before the fire can spread to other surrounding vehicles/wagons.

Consequently, this paper's analysis of the design of fixed fire protection is based on the assumption that tunnel risks are similar to fire resistive buildings housing combustible goods and/or hazardous materials (i.e. tunnel content). The resulting main commodity storage classes, as per NFPA [3] [14] [15] are shown in *table 2* below and consider conservative scenarios in terms of combustible load and hazardous material.

*Table 2: Tunnel risk content and corresponding commodity storage classes*

| Tunnel risk content | Commodity storage classes |
|---|---|
| Cars (considering FRP resin-based shell) | Exposed non-expanded plastic |
| Trailer trucks (considering trailer shell made of highly combustible flexible plastic material and carrying expended polyurethane / polystyrene foam) | Exposed expanded plastic |
| Tanker truck (carrying flammable liquid such as fuel) | Flammable liquid |
| LPG bullet tank truck | Liquid pressurized gas |
| Freight trains (carrying expended polyurethane / polystyrene foam) | Exposed expanded plastic |
| Passenger trains | Class IV |
| Train carrying Heavy Goods Vehicles (considering trailer shell made of highly combustible flexible plastic material and carrying expended polyurethane / polystyrene foam) | Exposed expanded plastic |

*Notes: Class IV commodity: contains within itself or its packaging no more than 25% by volume or 15% by weight of plastic in ordinary corrugated cartons.*
*Plastic commodity: contains within itself or its packaging more than 25% by volume or 15% by weight of plastic.*
*Expanded (foamed or cellular) plastics: plastics where the density is reduced by the presence of numerous small cavities (cells), interconnecting or not, dispersed throughout their mass.*

## Design criteria – Sprinkler design density

The design criteria for fixed fire protection systems, hose demand and fire water supply duration should be based on the actual tunnel risk content, in order to give the most demanding sprinkler density as shown in *table 3* below. The criteria should thus consider commodity classes [3] [14] [15], maximum height up to 7.6-metre based on Channel Rail Tunnel single tube diameter (should be revised according to NFPA standard when higher ceiling conditions) and maximum "storage" height (i.e. car, truck, train) up to 6.1m.

The design criteria for the fixed fire protection systems, hose demand and Fire Water Supply Duration should be based on the actual tunnel risk content resulting in the most demanding sprinkler density as enclosed in *table 3* below.

**Considering**

- The above commodity classes [3][14][15]
- Maximum height: 7.6-metre based on Channel Rail Tunnel single tube diameter (should be revised according to NFPA standard when higher ceiling conditions)
- Maximum "storage" height (i.e. car, truck, train): Up to 6.1m

*Table 3: Design criteria for the fixed and manual fire protection systems*

| Tunnel risk content | Assuming commodity storage classes [3] | Sprinkler type [3][9] | Sprinkler density LPM/sqm² (GPM/sqft) | Hose demand LPM (GPM) | Fire water supply duration (min) [7] |
|---|---|---|---|---|---|
| Cars | Exposed non-expanded stable plastic | Automatic control mode<br>High Temperature (141°C)<br>Wet Type sprinkler | 28.5<br>(0.7)<br>[5] | 1,900<br>(500)<br>[7] | 150<br>[7] |
| Trailer trucks | Exposed expanded stable plastic | Automatic control mode<br>High temperature (141°C)<br>Wet type sprinkler | 32.6<br>(0.8)<br>[6] | 1,900<br>(500)<br>[7] | 150<br>[7] |
| Tanker truck | Flammable liquid (pool fire and vessels) | Automatic spray sprinkler | 12.2<br>(0.30)<br>[9][10][11] | 946<br>(250)<br>[12] | 60<br>[12] |
| LPG bullet tank truck | Liquid pressurized gas (vessels exposure protection) | Automatic spray sprinkler | 10.2<br>(0.25)<br>[9][11] | 946<br>(250)<br>[12] | 60<br>[12] |
| Freight trains [18] | Exposed expanded stable plastic | Automatic control mode<br>High temperature (141°C)<br>Wet type sprinkler | 32.6<br>(0.8)<br>[6] | 1,900<br>(500)<br>[7] | 150<br>[7] |
| Passenger trains [18] | Class IV | Automatic control mode<br>High temperature (141°C)<br>Wet type sprinkler | 12.2<br>(0.30)<br>[4] | 1,900<br>(500)<br>[7] | 150<br>[7] |
| Train carrying Heavy Goods Vehicles [18] | Exposed expanded stable plastic | Automatic control mode<br>High temperature (141°C)<br>Wet type sprinkler | 32.6<br>(0.8)<br>[6] | 1,900<br>(500)<br>[7] | 150<br>[7] |
| Train carrying Heavy Goods Vehicles [18] | Exposed expanded stable plastic | Automatic control mode<br>High temperature (141°C)<br>Wet type sprinkler | 32.6<br>(0.8)<br>[6] | 1,900<br>(500)<br>[7] | 150<br>[7] |

*Notes:*

*LPM: S.I. Units - Liters Per Minute, GPM: U.S. Customary Units - Gallons Per Minute.*

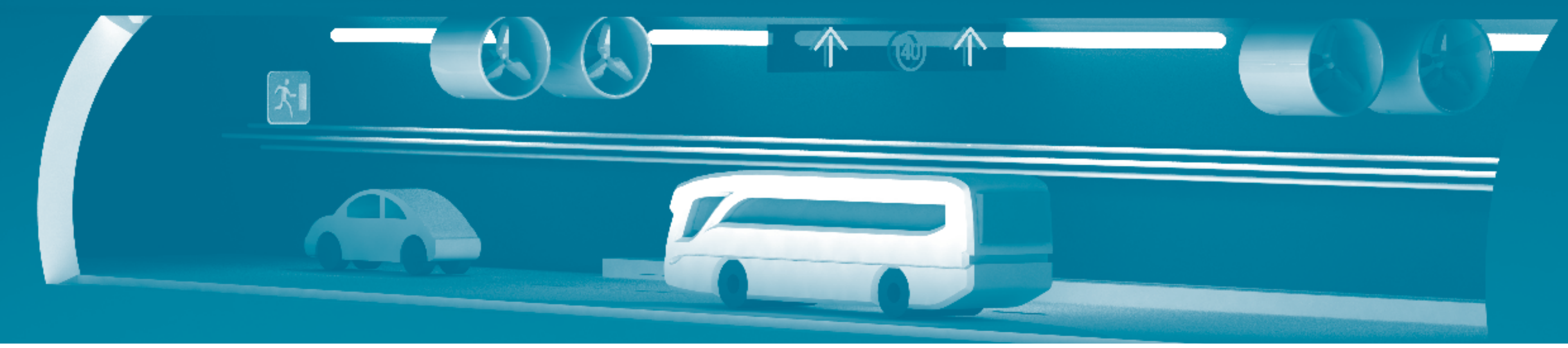
*LPM/sqm: S.I. Units - Liters Per Minute per square meter, GPM/Sqft: U.S. Customary Units - Gallons Per Minute per square foot, min: minutes.*

*Control mode sprinkler: limiting the size of a fire by distribution of water so as to decrease the heat release rate and pre-wet adjacent combustibles, while controlling ceiling gas temperatures to avoid structural damage.*

*Spray sprinkler: open head sprinkler. The water is discharged by a pilot line detector consisting of a standard spray sprinkler or thermostatic fixed-temperature release device, which is used as a detector to pneumatically or hydraulically release the main valve controlling the flow of water into a fire protection system.*

*Automatic sprinkler: fire suppression or control device that operates automatically when its heat-activated element is heated to its thermal rating or above, discharging water over a specified area.*

*High temperature sprinkler (141°C): closed sprinkler heads capable of withstanding high temperatures for long periods of time. This reduces the number of sprinklers triggered in the surrounding area, so that the area of sprinkler operation remains reduced compared to lower temperature-rated sprinklers (up to 25%).*



## Design criteria – Surface area of application

The surface area of application is equal to the zone length multiplied by the zone width of the tunnel.
Zone length depending on the type of vehicle permitted to enter the tunnel [1]. This study recommends a zone length of 100m for both road and train tunnels. This would be the equivalent of the three longest wagons of the Channel Tunnel trains designed for Heavy Goods Vehicles, each carrying one complete truck and trailer. The same zone length of 100m is recommended for road tunnels, based on a scenario of vehicle collision and pile-up resulting in a continuity of combustibles identical in length to that of trains carrying HGVs (conservative view).
The maximum width has to be measured at the largest section of the tunnel.

## Design criteria – Fire Water Supply

Both fixed fire protection systems and manual fire-fighting equipment (hoses) inside the tunnel should be fed from two identical adequate and reliable Fire Water Supplies installed at both ends of the tunnel. Each of the two Fire Water Supplies should consist of a set of (electrically-driven) FM-approved / UL-listed main fire pump(s) able to supply the full water demand as indicated in *Table 3* above. The main pump(s) should take suction under head from a reservoir above, providing the required duration indicated in *Table 2* above. Moreover, a set of (diesel engine-driven) FM-approved / UL-listed back up pump(s) with the same capacity as the main fire pump(s) should be provided for each of the two Fire Water Supplies. The backup pump(s) taking suction under head from the above reservoir feed the main pump(s). The capacity of the fire pumps should be defined considering the full combined fire water demand, including the fixed fire protection systems and the manual fire-fighting equipment located in the most remote area from the Fire Water Supplies inside the tunnel. This takes into account pressure loss due to elevation and friction inside piping. [13]
The installation of fire water supply should be compliant with NFPA-20 [13] or any other recognized international standard. All equipment should be FM-approved and/or UL-listed. All alarms and supervisory / trouble signals should be relayed to a constantly attended location. Plans should be reviewed by a qualified Fire Protection Engineer familiar with NFPA / FM standards or any other recognized international standard prior to installation.
The installation of booster pumps inside the tunnel should be considered in case of loss of pressure.
The fire water main running from both sides inside the tunnels and the fixed fire water protection systems and manual fire-fighting networks should be looped and gridded when possible for greater reliability. The fire network should comply with NFPA-14 [8] or any other recognized international standard. The fire network should be pressurized by jockey pump(s) provided for each Fire Water Supply at both ends of the tunnel. Where areas are subject to freezing conditions, this should be taken into account. Water heating, recirculation and heat tracing and insulation should be considered where necessary.

## Performance evaluation [1]

Fire test protocols should be designed to replicate and evaluate the entire range of application parameters associated with transportation tunnels. The ability of such systems to meet defined performance objectives under the specific tunnel parameters should be assessed on the basis of full-scale fire testing.
Caution: human safety requirements for evacuation and rescue can be different from the requirements designed to protect the structural components of the tunnel. This should be carefully and seriously taken into account.

## Water based fixed fire-fighting systems installed in tunnels around the world – Design parameters & testing results [1]

In Japan fixed water-based fire fighting systems have been installed in road tunnels for more than four decades. Fixed fire suppression systems are required in all tunnels longer than 10,000 m (32,808 ft) and in shorter tunnels longer than 3000 m (9843 ft) with heavy traffic. A serie of tests were reportedly conducted involving pool fire and bus fire, with various types of spray systems investigated. The results of these tests showed that the activation of the spray system rapidly decreased the air temperature in the tunnel to the ambient air temperature.
In North America, six road tunnels are now equipped with water-based fixed fire-fighting systems such as spray of 10 mm/min (0.25 gpm/ft2), Spray Foam Sprinkler of 6.5 mm/min (0.16 gpm/ft2) and wet pipe sprinklers.
In some road tunnels in Europe, fixed fire suppression systems have been used for special purposes. Catastrophic road tunnel fires have encouraged a re-evaluation of these systems for use in future road tunnels.
In Australia: 11 road tunnels have fixed water-based fire-fighting systems.

## Fixed fire protection of electrical rooms

Gaseous extinguishing total flooding fire protection could be installed within all critical electrical rooms (e.g.; IT room for signaling systems and other rooms housing electrical equipment). Gaseous extinguishing agent: carbon dioxide ($CO_2$) is very dangerous for human (lethal). Consequently, for any normally occupied or occasionally occupied areas, an automatic system using a safe gaseous extinguishing agent for personnel is strongly recommended, such as "Inergen" or "Argonite" or approved clean agent such as FE227 and FM200, in accordance with NFPA 2001[20] or any other international recognized standards. The recommended extinguishing agent density should be such that the oxygen concentration in the room does not drop below the safety limit. If a carbon dioxide system is selected for raised floor, a special low-velocity discharge system should be used so that the carbon dioxide does not rise above knee height in the room. Under-floor halocarbon agent systems (e.g. FE227 and FM200) are not permitted when the space above the raised floor is not equipped with a halocarbon agent system. A fire in the space above the raised floor could draw the discharged halocarbon agent up, causing it to decompose and become very toxic. Only equipment tested and approved by a recognized laboratory should be accepted.

All cable vaults and cable tunnels should be protected with adequate and reliable automatic wet pipe sprinkler protection in accordance with NFPA. The sprinklers should be designed in order to provide 10mm/min. water density over the cable vault area. The sprinkler heads should be rated at 30°C above the ambient temperature. All fire alarms should be connected to a constantly attended location.

Ventilation Interlock: the ventilation system should be interlocked with the fire protection system in order to shut down automatically upon fire detection. All fire alarms, supervisory and trouble signals should be relayed to a constant attended location.

Materials and equipment: all fire detection/protection material and equipment should be UL-listed or FM approved and should be installed by a qualified contractor familiar with NFPA/FM standards or any other internationally recognized standards.

Plan Review: the project should be reviewed by a qualified Fire Protection Engineer familiar with NFPA standards or any other international recognized standards.

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2. NFPA 1 Fire Code
3. NFPA 13 Standard for the Installation of Sprinkler Systems
4. NFPA 13 FIGURE 14.2.4.
5. NFPA 13 Table 15.2.6(a) or (b) Column E
6. NFPA 13 Table 15.2.6(a) or (b) Column B
7. NFPA13 Table 12.8.6.1
8. NFPA 14 Standard for the Installation of Standpipe and Hose Systems
9. NFPA 15 Standard for Water Spray Fixed Systems for Fire Protection
10. NFPA 15 7.3.3 Flammable and Combustible Liquid Pool Fires.
11. NFPA 15 7.4.2 Vessels.
12. NFPA 15 Hose allowance 7.2.3.1.4 and 7.4.4.3.6
13. NFPA 20 Standard for the Installation of Stationary Pumps for Fire Protection
14. NFPA 30 Flammable and Combustible Liquids Code
15. NFPA 58 Liquefied Petroleum Gas Code
16. NFPA 72 National Fire Alarm Code
17. NFPA 80 Standard for Fire Doors and Other Opening Protectives
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