SOLIT Safety of Life in Tunnels

Engineering guidance for a comprehensive evaluation of tunnels with fixed fire fighting systems

Scientific report of the SOLIT² research project, prepared by the SOLIT² consortium

Annex 1:
Status analysis

Gefördert durch:

Bundesministerium
für Wirtschaft
und Technologie

aufgrund eines Beschlusses
des Deutschen Bundestages

All to this document related activities were supported with funds by the German ministry of economics and technology (Code No. 19S9008). The content of this publication is within the responsibility of the authors.

This document was produced with best knowledge and with great care. These documents and its annex documents are for the use of experienced fire protection experts. The reader has to evaluate the application of this document for each specific case separately.

Classification:
The scientific research project SOLIT² - Safety of Life in Tunnels was promoted by the German ministry of economics and technology (BMWi; Code No. 19S9008) based on a decision of the German Bundestag. All members of the consortium have set up separate scientific reports related to their aim of study. Most outstanding outcomes have been concluded in the present Guidance. The Guideline has been set up jointly among the consortia members and presents the common final report in terms of the guiding principles of the BMWi. The Guideline is part of the work package. All individual reports are available on behalf of the project coordinator.

Imprint:
Engineering Guidance for a comprehensive evaluation of tunnels with fixed fire fighting systems

The following annexes pertaining to this guidance are also available:
Annex 2: Selected Results from Full Scale Fire Tests
Annex 3: Engineering Guidance for FFFS in tunnels
Annex 4: Application Example for a Risk Analysis
Annex 5: Safety evaluation of Operating Technology
Annex 6: Lifecycle Costs of Operating Technology
Annex 7: Fire tests and fire scenarios for Evaluation of FFFS

The following people contributed to the production of this document:

BUNG AG – Engineering Consultants
Wolfgang Baltzer
Uwe Zimmermann

FOGTEC Brandschutz GmbH & Co KG
Tobias Hoffmann
Max Lakkonen
Dirk Sprakel
Sascha Wendland

Ruhr University Bochum – Chair of tunnel construction, line construction and construction management
Markus Thewes
Götz Vollmann

STUVA – Research Association for Underground Transportation Facilities
Frank Leismann
Roland Leucker
Antonio Piazzolla

TÜV Süd Rail GmbH
Jürgen Heyn
Jakob Zaranek
Lutz Neumann

IFAB Institute for Applied Fire Safety Research
Stefan Kratzmeir
Rajko Rothe

Institut der Feuerwehr Sachsen Anhalt
Mario Koch
Horst Starke

The members of the research consortium would like to thank the Scientific Advisory Board for their valuable comments and suggestions previous to the fire tests: Felix Amberg (ITA-COSUF), Frank Heimbecher, Jürgen Krieger (Federal Road Research Institute), Ingrid Ortlepp (Thüringian Ministry of the Interior), Werner Thon (Hamburg Fire Brigade), Bernhard Koonen (Project Administrator for Mobility and Transport), Robert Sauter (ADAC e.V.)

Edited by:
SOLIT² Research Consortium, consisting of:
BUNG AG – Engineering Consultants
FOGTEC Brandschutz GmbH & Co. KG
Ruhr Universität Bochum – Chair of tunnel construction, line construction and construction management
STUVA Research Association for Underground Transportation Facilities
TÜV Süd Rail GmbH

Printing and publication:
The documents form part of a private publishing venture and can requested via contact@solit.info or the editor.

Cologne
Version: 1.1; Status: November 2012
This Engineering Guidance will be further revised by the SOLIT² Consortium. Future versions can be requested from the consortium via contact@SOLIT.info.

Project coordinator: FOGTEC Brandschutz GmbH & Co. KG, Schanzenstraße 19, 51063 Cologne - Germany

Contents

Part 1 Introduction

An extensive collection of data on “Fire Fighting Systems (FFFS) in Tunnels” has been produced in work package 2 – status analysis – of the SOLIT2 research project. These data were obtained by means of detailed researching of reference sources, the Internet, written surveys among representatives of all ITA[1] member countries through questionnaires as well as direct questions posed to generally recognised experts and companies in the field of tunnel safety (personal/ by phone/ by e-mail).

The research results are included in the closing report of work package 2 (unpublished). It contains a documentation of applications of fire fighting systems (FFFS) in road tunnels that have been produced and publicised worldwide followed up by a description of applications in rail and Metro tunnels. In addition, findings with operating FFFS as well as fundamental expert opinions on this topic are brought together. The closing report contains the latest level of knowledge pertaining to technical-physical interrelationships for fire fighting systems based on a compendium of the principles. Furthermore, the guidelines and codes of standards available throughout the world are evaluated whilst reference data and substantial recognitions of fire tests carried out in the past are documented (Solit2 2009).

In this short report, excerpts of the described status analysis are made available to the general public in compact form in considerably less detail. This short report largely ignores presentation of the principles as well as all information relevant for competition.

[1] International Tunnelling and Underground Space Association www.ita-aites.org

Part 2 Principles

2.1 Fixed Fire Fighting Systems (FFFS)

Definition of PIARC
The PIARC[2] applies the following definition for "Fixed Fire Fighting System (FFFS)" as equivalent to the German term "Brandbekämpfungsanlage (BBA)" (PIARC 2008):
Fixed fire fighting systems (FFFS) in road tunnels are defined as fire fighting equipment, which is permanently installed in the tunnel with a pipe system to be constantly supplied with water or another extinguishing agent. By activating the fire fighting system and releasing the extinguishing agent, it is intended to reduce the heat release rate and fire spreading. Sprinklers[3], water spray and water mist systems are examples of FFFS.

Reasons for installing a fixed Fire Fighting System
The main aim of such a fire fighting system in road tunnels is to combat and suppress fires, until they can be completely extinguished by the fire brigade. As most fires inside vehicles take place within the confines of the engine, passenger or loading area, it is generally not possible for a FFFS installed in the tunnel (and not directly in the vehicle) to completely extinguish the fire.

The main tasks of a fixed fire fighting system are:

- Restricting or reducing the heat release rate and in turn reducing the production of smoke gas, especially during the self-rescue phase in the first 5 to 10 minutes after the fire ignites,
- Reducing the temperatures at the fire seat and in turn reducing the smoke gas volume [Kratzmeir 2008],
- Preventing fire flash-over to other vehicles,
- Improving the deployment conditions for the fire brigade, maintaining the operating conditions for other safety systems, e.g. preventing the ventilation system from overheating,
- A secondary factor is protecting the structure by lowering the effects of temperature [Bettelini and Seifert 2009].

Available Systems
It is customary practice throughout the world to apply pure water or water with additives as extinguishing agents in FFFS. Theoretically gases can also be applied as extinguishing agents, in the case of which the extinguishing effect is based on the application of inert gases (carbon dioxide CO_2, nitrogen N_2) or partially halogenated CO_2, CHF_3 or CF_3CHFCF_3. The latter systems are used for special application in buildings. Application in tunnels is not possible owing to the prevailing general conditions as extinguishing systems based on gas require a largely gas-tight closed area [Haack 2007].

Regardless of the type of FFFS, extinguishing systems in tunnels usually comprise a system of jet nozzles arranged on the ceiling.

Water-based extinguishing systems can be split up into three groups [Häggkvist 2009]:

- Conventional sprinkler systems with wet lines
- Systems with dry lines, which are further differentiated according to the water drop size
  - water spray systems
  - water mist systems
- Foam extinguishing systems.

Sprinkler systems are highly popular in the building construction segment. In this connection, the corresponding pipeline system filled with water is permanently under pressure (wet line). The nozzles open via a thermally activated element. Usually this relates to a glass vessel, which releases the jet nozzle when it bursts after reaching a defined temperature. The extinguishing effect of sprinkler systems depends by and large on wetting and in turn cooling the fire load located beneath the nozzle jets with water.

Sprinkler systems are inappropriate for use in tunnels for two reasons:

- The fire's heat is guided away from the fire seat by the air movement normally prevailing in the tunnel, which leads to sprinkler jets far away from the fire seat being activated.
- A tunnel fire rapidly produces large amounts of heat so that too many sprinklers irreversibly open at the same time so that ultimately not enough water can be fed with economic pipeline cross-sections and pumps.

A water spray system in contrast to a sprinkler system comprises a system of permanently open jets. The system is divided into zones, with their length being roughly the equivalent of that of a truck – some 30 m. In the event of fire, an electronic control opens the valves in the particular zone above the fire and in the two neighbouring sections. As a result, water is released from all the nozzles in the activated zones.

Conventional sprinklers as well as water spray and water mist systems use water as an extinguishing agent in order to restrict or control the fire. The released water removes heat directly from the fire, cools the hot combustion gases or the surface of the fire load. The water vapour that ensues displaces the oxygen in the fire zone. These characteristics by and large make water a suitable extinguishing agent. The principle manner of operation largely depends on the water drop size and in turn, the water pressure and the nozzle jet geometry. Figure 1 clearly shows the relationship between size of drop and cooling effect.

[2] World Road Association
[3] In English, water spray and sprinkler systems are practically synonymous because the water is delivered by sprinkler nozzle jets. As a result "sprinkler" may also be used in place of "water spray systems" in this report.

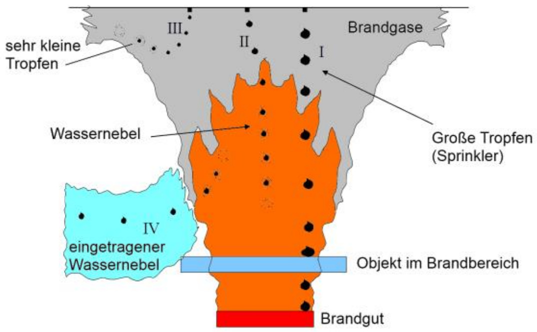

Figure 1: Manner of operation and location of various water drop sizes [UPTUN 2006].

Large drops, as presented at point I in Figure 1, are characteristic for conventional sprinkler systems. The drops fall through the flames, largely cooling down the fire seat and moistening fire loads that remain unburned. The combustion gases are scarcely cooled given the amount of water applied as the specific surface of the large drops is low. Large drops are furthermore not suitable for extinguishing liquid fires: particularly when the burning liquid is non water-soluble and possesses a lower density than water, a burning pool of released extinguishing water accrues.

Drops of a smaller size, as presented in point II in Figure 1. penetrate the flames and hot gases (plume) and reach the flammable material to a certain extent as well. They cool and largely restrict the combustion process and can also extinguish the fire given the right circumstances. Small drops possess a large specific surface compared to the applied amount of water and in turn, good thermal exchange capacity, as the heat exchange takes place on the surface of the drops. The water drops can vaporise very quickly on account of the high specific heat capacity and the high enthalpy of vaporisation (E=2.634 KJ/l) of water involved with the extremely large cooling effect of water mist systems. Drops of such a small size are produced by water mist systems, which represent the objective of the SOLIT2 project.

As the diameter of the drops diminishes, as is presented at point 3 in Figure 1, the vaporisation process is accelerated over-proportionally leading to cooling and restricting the response bias. At the same time, the drops' capacity to penetrate the flames decreases as the diameter diminishes [Häggkvist 2009].

2.2 Mode of Preparation of Water Mist Fire Fighting Systems

Temperature Reduction

The cooling effect of water mists has been proved in various test series [Kratzmeir 2008]. The fall in temperature is largely based on the exchange of heat between the hot smoke gases and the water drops. The vaporisation of the water drops absorbs a part of the thermal energy. In addition, the temperature level in the tunnel is reduced through a fall in the fire's heat release rate through the effect of the water mist.

Activation of a water mist system inevitably causes the air to mix combined with a certain adjustment of the temperatures along the entire height of the tunnel. A possibly previously existing stable smoke gas layer is disturbed by the cooling process occurring in the activated sections. Smoke particles are pulled downwards by the drops thus strengthening the proclivity of turbulences. The change in temperature distribution causes the lower section of the tunnel to heat up slightly.

Increase in Air Humidity

The fall in temperature caused by the application of a water mist system is accompanied by an increase in the relative air humidity. Larger quantities of water in the tunnel atmosphere impede survival conditions in the tunnel. The danger of burns to the skin or the respiratory system persists given temperatures in excess of 120 °C. This limit value falls to 60 °C given air partially enriched with water. A temperature of 60 °C can be sustained over a period of some 30 minutes when the air is completely saturated with water.

Reducing the Heat Radiation

Water mist exerts a reducing effect on the spread of radiation heat. The drops floating in the air form a kind of shield against the heat radiation produced by the fire and partly absorb the energy. The maximal absorption occurs in the wave range commensurate with the drop diameter [Cetu 2010].

Preventing the Fire Spreading

A reduction of the heat radiation combined with diminished air temperature leads to a clear decrease of the risk of the fire spreading, i.e. of fire flash-over among vehicles in the tunnel. This effect has been verified for solid fires.

Liquid fires can spread on account of the combustible liquids flowing on the ground depending on local circumstances. The release of water on burning liquids increases the amount of liquid and thus tends to encourage the spread of pools of liquid, especially under unfavourable circumstances, as e.g. inclined tunnels [Cetu 2010].

Generally, however, gutters are installed in the tunnel, to which the liquids are relatively quickly transferred over a short distance thanks to the inclined road surface. As a result, the unrestricted spread of pools of liquid is considerably hampered. At the same time, the addition of extinguishing water also leads to diluting the burning liquid so that less liquid can be burned per time unit.

Heat Release Rate (HRR)

A water mist FFFS possesses a restricting effect on the fire's heat release rate. The reduction of the HRR is strongly influenced by the type of combustible material (liquid or solid state) as well as just how the fire is coped with [Cetu 2010].

Visibility Conditions
The visibility depends on the concentration of smoke particles and the water drops in the air, the size of the water drops and the light conditions in the tunnel. Elution of smoke particles through the water mist, which occurs to a certain degree, exerts a favourable effect on the visibility conditions. However, this can only be determined with great difficulty in measurement technical and theoretical terms. Consequently the smoke gas elution effect has so far not been regarded as verifiable.

A further potential effect influencing the visibility conditions exists if water vapour produced close to the fire recondenses on the exhaust air side and then produces mist.

The visibility conditions can be worsened by activating a water mist fire fighting system should there be no smoke gas layer given (small) fires in the tunnel as an extremely turbulent current is produced through the impulse of water and cooling of the smoke gases. The smoke is virtually carried to areas, which were previously smoke-free by the water drops [Cetu 2010]. However, a smoke gas layer cannot be depended on either in the case of larger fires owing to the turbulences and thermal effects without applying a FFFS.

In smoke-gas free areas within the tunnel the visibility conditions worsen through activating a water mist system only to an uncritical extent so that the conditions for self-rescue for tunnel users are only affected to a lesser degree [Kratzmeir 2008].

Toxicity of Smoke Gases
The production of toxic gases during a fire is a function of the heat release rate, the ventilation conditions (oxygen supply) and the nature of the combustible materials. Under these circumstances, the production of carbon dioxide (CO2) practically entirely depends on the heat release rate whereas carbon monoxide (CO) and nitrogen oxide (NOx) also depend on the vaporisation rate of the combustible material. This for its part is influenced by the nature of the combustible materials and the oxygen supply. As a consequence, the application of a water mist system reduces the production of CO2 owing to altered combustion reaction.

The qualitative and quantitative estimation of the effects of a water mist system and the production of CO and NO_x is also extremely complex. These gases are practically insoluble in water under the conditions prevailing in the tunnel, something which was proved during fire tests for the A86 tunnel (please see Chapter 4.7). On the other hand, other toxic gases, which can be released during a fire in the tunnel, such as e.g. hydrogen chloride (HCL), sulphur dioxide (SO_2) or hydrogen cyanide (HCN) are completely water-soluble. Dissolving these gases in water leads to the formation of hydrochloric acid, sulphuric acid and prussic acid. Analysis of the water collected on the road surface after carrying out the above mentioned fire tests for the A86 indicated a low pH value for area 2.

The current level of knowledge does not permit a quantitative prognosis of these phenomena under the temperature and visibility conditions prevalent in the tunnel. Ultimately the spatial distribution of the smoke gases is more important than the toxicity of the smoke gases for assessing the dangers posed to users and restrictions on self-rescue. Consequently, the deliberations on the smoke gas layer in the previous chapter dealing with “Visibility Conditions” are referred to. Establishing the suitable threshold time is of particular importance in this respect [Cetu 2010].

Structural Protection
Thanks to the restricting effect of a water mist system on fire development (temperature, heat radiation, heat release rate) and the spread of fire, the tunnel structure heats up to a lesser extent. In this connection, an early threshold time enhances the effectiveness of structural protection although it must not impede the aim of self-rescue and evacuation by a third party. Thus structural protection is not regarded as a top priority. Essentially the activation criteria for sustaining life must be accorded higher priority than those for protecting the infrastructure [Cetu 2010].

Fire Brigade Deployment combined with Fire Fighting Systems
The tactics of the fire brigade and the approach for deploying the emergency services can basically change through the installation of a FFFS (water spray or water mist system) and thus must be subject to extensive investigation. The suitable deployment tactics can differ depending on the system and how it is controlled (manually, automatically). Essentially, the aim of a fire fighting system is also to improve the fire brigade’s deployment conditions [Hjelm, Ingason and Lönnermark 2010].

Part 3 Level of Technology for Applying Fire Fighting Systems – Use world-wide

The research results on the state of the art pertaining to the worldwide use of fire fighting systems in tunnels are collated in the following.

3.1 Case Studies on Road Tunnels

3.1.1 Europa

Currently there is no European country with national regulations, basically promoting the use of FFFS. Regardless of this situation, there is a growing recognisable tendency to equip tunnels, especially new ones with such systems.

Belgium
As far as is known, no road tunnels in Belgium are equipped with FFFS. No new projects have been cited since publication [PIARC 1999].

Bulgaria
It appears that in Bulgaria the fact that whether FFFS are available, planned or under construction in tunnels, is regarded as relevant to safety. As a result, no information is forthcoming in this respect [Georgieva 2010].

Denmark
Currently there are no road tunnels in Denmark fitted with a FFFS although retrofitting the Øresund Tunnel is being contemplated. The Øresund Tunnel is an underwater tunnel, 3,510 m in length, consisting of 4 bores (2 for road traffic each with 2 lanes in each direction and 2 for rail transportation) and a technical service passage between the road tunnels. This passageway is already equipped with a water mist system to protect it against cable fires, in contrast to the running tunnels. According to the existing safety concept, the emergency exits leading to the neighbouring tunnel bore, set up 88 m apart, afford a sufficient level of safety for protecting people in keeping with the regulations.

The operator believes that a FFFS can be advantageous for avoiding major damage to the tunnel structure, whereby the maintenance costs must be considered in addition to the costs for installation alone. The tunnel operator (in this case Øresund Bridge Consortium) is responsible for selecting the tunnel safety system following approval by the responsible authorities [Eskesen 2010].

Furthermore, it is intended to install a water spray system for the planned permanent Fehmarn Belt Crossing. According to the planning status in 2012, the Fehmarn Belt Crossing (construction time 2015 to 2021) will in all probability be devised as a 17.5 km long submerged tunnel with in each case separate bores for cars and trains as well as a utility connecting passage [Fehmarn 2011].

Germany
So far in Germany only one road tunnel has been equipped with an automatic fire fighting system within the scope of a pilot project (as of 2011). The 1,140 m Pörzberg Tunnel in Thuringia is Germany's longest tunnel on a highway. It links the towns of Rudolstadt and Stadtilm and was provided with a compressed air foam system in 2010. The Pörzberg Tunnel is split into 48 activation areas each 35 m long. Three rotors are arranged in each area by means of which the foam is distributed. In the event of fire being detected, the rotors in the affected area and its two neighbours operate automatically over a total distance of 75 m [Märkische Allgemeine Zeitung online 2012].

Tenders were invited for a FFFS for the 3 km long Jagdberg Tunnel as part of the upgrading of the A4 motorway to form six lanes in mid-2012. The official draft for the tender foresaw a foam extinguishing system although other types of extinguishing system were permitted. So far it has not been made public whether the tunnel will be equipped with a fire fighting system and which system (foam/water/water mist) will be chosen (as of Nov. 2012).

The approval authorities have shown an interest in basic research and the further development of FFFS, which is documented through sponsorship of the SOLIT (2004-2006) and SOLIT2 projects. The results of research projects will be incorporated in future decisions pertaining to the installation of automatic fire fighting systems. However, at present, neither concrete measures nor the inclusion of explicit requirements in guidelines are planned [BAST 2011].

Finland
The first road tunnel was provided with a fire fighting system on a water mist basis at the end of 2009. It was installed in the 2 km long "Keskustan huoitotunnell, KEHU" – Helsinki Service Tunnel. This links up several shopping centres in the city centre including the related parking facilities and supply tunnels with the University of Helsinki. The tunnel is located at a depth of some 30-40 m and is in part, reserved for parking purposes and supply trips. The tunnel's average clear height amounts to 5.50 m with widths varying from 70 to 20 m. Four roundabouts of varying dimensions are integrated in the tunnel system.

The emergency services carried out several tests and drills in 2009 and evaluated the findings obtained as positive. Low temperatures in winter did not result in problems. Using the system is described as easy and attractive. Lower investment costs were incurred compared to conventional sprinkler systems [Järvinen 2010].

The possibility of a water mist system is being examined for several unnamed projects (two motorway tunnels outside of Helsinki and six tunnels within the Helsinki limits). A risk analysis will be undertaken to decide whether to plump for a system of this kind or alternative safety installations.

France
Practically nothing has changed in France regarding the application of water mist systems in road tunnels compared to the circumstances described in the last PIARC Report (please see Chapter 4.1) in 2008. The A86 tunnel in Paris is still the sole project, involving a FFFS (water mist system).

The A86, aka the super-périphérique or Périphérique de l'Ile-de-France, is a motorway ring around Paris some 78 km in length. The final construction section completing the ring in the west is designed as a "duplex" car tunnel with the driving lanes on top of each other and is equipped with a FFFS.

The A 86 tunnel's total length amounts to roughly 10,300 m and it was opened to traffic in 2008. Taking the related connecting tunnels and the two driving levels into account, around 24 km of tunnel bores had to be provided with fire fighting measures. The A 86 Tunnel's special feature is that it possesses a circular cross-section driven by a tunnel boring machine, which is used for two traffic levels. This results in a clear ceiling height for the traffic levels of only 2.55 m so that as a consequence no heavy goods vehicles are allowed to use the tunnel. Three driving lanes are available per traffic level and direction with one-way traffic. The two traffic levels are linked to one another every 200 m by means of stairwells and there is an evacuation route leading into the open every 1,000 m. The tunnel is equipped with a ventilation system, which provides fresh air to the two traffic levels through special air ducts. Air exhaust and fresh air ducts run along the ceiling and in the area below the carriageway (Figure 2).

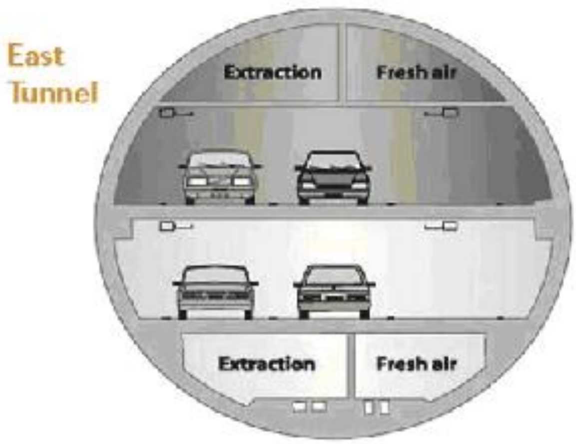

Figure 2: Ventilation system in the A86 Tunnel (http://www.fhwa.dot.gov/)

The extinguishing system in the A86 Tunnel – with a total of 850 zones and 16,000 spraying heads [Vuolle] – was applied under real conditions for the first time in December 2010, when a car caught fire. The system worked as planned and the tunnel was able to return to busy as usual only one and a half hours after the fire broke out. All those involved assessed the findings obtained during this deployment as extremely positive [Le Parisien 2011].

Greece
No FFFS have yet been installed in tunnels in Greece. Currently no corresponding projects are under construction or planned.

Great Britain
Two projects involving FFFS in road tunnels have been implemented in Great Britain:

- Tyne Tunnel (Fogtec 2009)
- Dartford Tunnel

Tyne Tunnel
The Tyne tunnels in the Newcastle upon Tyne region cross beneath the River Tyne linking the town of Jarrow on the south bank with North Shields and Howdon on the north side of the Tyne. The crossing consists of a pedestrian and cyclist tunnel opened in 1951 as well as two road tunnels opened in 1967 as part of the A19. The New Tyne Road Tunnel was opened in 2010. The volume of traffic using the tunnel currently amounts to 38,000 vehicles per day with a predicted increase to 43,000 vehicles per day by 2021.

The New Tyne Tunnel project has become a pioneer in the field of tunnel fire fighting through the decision to install a FFFS to suppress fire for protecting a road tunnel 3.2 km in length. It more than conforms to current legislation in the United Kingdom as well as European standards. The decision to invest in the New Tyne Crossing project was reached following a recommendation by a group of experts based on a quantitative risk assessment and a cost-benefit analysis. According to the study the investment costs for a fixed FFFS are well worthwhile over the service life of the project.

Both the new road tunnel and the original tunnels are fitted with FFFS on a water mist basis. The protected areas are divided into a total of 130 sectors each 25 m long. In the event of fire, three neighbouring sectors are activated at the same time. Solely open systems are applied as jets so that the full flow rate and in turn, the maximal effect of the water mist is activated and attained from the very outset in all operational sectors. The basis for dimensioning was provided by 1:1 fire tests with truck fires [Fogtec 2009].

Dartford Tunnel
The Dartford River Crossing Tunnels are located some 25 km from the centre of London and link Dartford on the south bank of the Thames with Thurrock on the north side. The Thames crossing as part of the M25 London motorway ring comprises two road tunnels and the Queen Elisabeth II Bridge and is used by around 150,000 vehicles per day. The two tunnels are altogether 1.43 km in length. The first tunnel was opened for traffic in 1963, the second followed in 1981.

The Highways Agency decided to retrofit a stationary high-pressure water mist system from 2010-2012, to enhance protection for motorists, the service staff as well as emergency services in the event of fire [fogtec].

Iceland
There are no FFFS in Icelandic road tunnels, neither are they planned or under construction as only a slight accident risk prevails in most tunnels < 1,000 vehicles per day on account of the low traffic frequency [Haraldsson 2010].

Italy
At present (as of early 2011 only one tunnel, the Virgolo Tunnel as part of the Brenner Motorway), is provided with a water mist system. Within the scope of the UPTUN research project sponsored by the EU (please see Chapter 4.8), initially a part-section of the 887 m long tunnel was fitted with a water mist system for a large-scale demonstration. The demonstration was a success so that the entire tunnel was subsequently equipped with the high-pressure water mist system [Häggkvist 2009].

In addition, the local operator of a tunnel in the Veneto area is considering installing a water mist system.

Netherlands
Two projects involving fire fighting systems in road tunnels have been pursued in the Netherlands. Both projects are elements on the newly built A73 motorway in the south-east of the Netherlands and were opened in 2008. Both these tunnels possess twin bores with one-way traffic, equipped with a longitudinal ventilation system:

- Roer Tunnel (length 2,450m)
- Swalmen Tunnel (length 400 m)

The decision approving the installation of fire fighting systems in the two tunnels was taken in 2003 based on a resolution by the Dutch Ministry for Transport, Public Works and Waterways (Rijkswaterstaat). The aim was to avoid:

- major truck fires,
- fire spreading downstream in the event of traffic jams in the tunnel,
- exploding tanks as a BLEVE (Boiling Liquid Expanding Vapour Explosion).

Initially (2004-2005), a pilot system with “Compressed Air Foam” (CAF) was planned and tenders correspondingly invited. A CAF unit comprises a standard system on a water basis, which also possesses intakes for compressed air and a foaming agent to produce foam as extinguishing agent. The CAF unit design was modified several times during the project design stage in order to come up with optimal foam distribution. In 2005, it was tested in the Runehamar Tunnel in conjunction with 150-200 MW fire tests.

The high costs for the installation led, however, to the Dutch Ministry for Development deciding against pursuing the CAF system any further and to apply a water mist system. The pumps for the system installed in 2007 and 2008 are located in three rooms, the main lines and distributor valves in the service tunnels. Altogether, the system comprises 10,000 nozzle heads and 25 km of stainless steel pipes [Aquasys 2010].

Installing the FFFS is regarded as an additional safety feature without replacing other safety measures foreseen by legislation in Dutch tunnels [Meijer 2008, Both 2010; Jonker 2010; PIARC 2008, Lemaire 2008].

Norway
Two tunnels are equipped with FFFS in Norway:

- Fløffjell Tunnel (3.2 km long, average daily traffic frequency (DTV) 26,000 vehicles, two tunnel bores)
- Vālreng Tunnel (800 m long, DTV 37,000 vehicles, two tunnel bores)

Water without additives is used in both tunnels as extinguishing agent. The lines are devised as a dry system to avoid the lines freezing in winter when low temperatures prevail.

The decision to install a FFFS in the Vālreng Tunnel was brought about by problems occurring with the tunnel waterproofing, which were subsequently resolved through polyurethane injections. Water spray jets were then installed to protect the waterproofing system regarded as critical under fire protection aspects.

In the Fløffjell Tunnel a water spray system was installed at the behest of the fire brigade. Accordingly those responsible had the choice between the alternatives in the form of a tunnel lining with the product “Etafoam” on a shotcrete basis or installing a fire fighting system in the tunnel. Experience revealed problems with the formation of ice in the winter months as well as a high number of false alarms involving the system (70 false alarms within half a year, as of 1999) [PIARC 1999].

According to current research (as of January 2012) no further tunnels in Norway have been equipped with FFFS in the interim. The findings for the above mentioned projects are assessed negatively based on high maintenance costs and problems with frost protection [Grov 2012].

Austria
Two fire fighting systems are operating in Austria (as of 2011):

- Felbertauern Tunnel
- Mona Lisa Tunnel in Linz

The Federal Ministry for Transport, Innovation and Technology (BMVIT) is responsible for the installation and operation of a FFFS. Ultimately it must also issue approval for using the tunnel. Here too, the view is shared that a FFFS increases the safety standards and can possibly replace other safety-related installations (e.g. a lack of evacuation routes, major distances between cross-passages, etc.) on the basis of a safety analysis. It is of prime importance that the operator accepts the planner’s proposals. This is followed by applications for a permit from the BMVIT [Sturm 2010].

Felbertauern Tunnel
The Felbertauern Tunnel is an Alpine tunnel at an altitude of 1,650 m ASL consisting of a two-way bore 5.3 km long possessing a transverse ventilation system. The intake air ducts, which are in part, used for evacuation purposes, were the reason for installing a water mist system. This concept requires special protection for the intermediate ceiling structure.

There is no particular need to increase the safety level in the Felbertauern Tunnel, as the tunnel has an extremely small cross-section and possesses a high difference in pressure between the portals because it crosses the Alps over a distance of 5.3 km. These general conditions lead to high air speeds of up to 10 m/s, which is problematic especially with regard to two-way traffic operation. The extinguishing system is activated automatically following a predetermined delay, should the service personnel not intervene in the process. Activation simultaneously affects three sections totalling 100 m in length [PIARC 2008].

The system possesses two pump rooms; the main lines and branch valves (diverters) are arranged in the fresh air ducts. Altogether the system consists of 8,000 spray heads and 20 km of stainless steel lines [Aquasys 2010].

Mona Lisa Tunnel
The Mona Lisa Tunnel near Linz operates with two-way traffic. It is 775 m long and possesses a longitudinal ventilation system. Jams occur frequently in the tunnel on account of traffic lights close to one of the portals. As a result, it was decided to install a water mist system in keeping with “class I” of the NFPA 750. The system is fitted with a self-actuating fire detection system, which automatically gets in touch with the fire brigade and emergency services. The decision for activating the extinguishing system (currently only on a manual basis) is the responsibility of the fire brigade. It is planned to install remote activation sometime within the next few years. Owing to the cold climatic conditions prevailing in the city of Linz area suitable frost protection measures were required for installing the FFFS using water as extinguishing agent [PIARC 2008].

The water mist system was installed in 2003/2004 within the framework of a demonstration project by Messrs. Aquasys [Aquasys 2010].

Romania
There are no findings or plans available for equipping road tunnels with fixed fire fighting systems [Arghirou 2010].

Sweden
Two tunnels are equipped with FFFS in Sweden [Häggkvist 2009]:

- Tegelbacken Tunnel
- Klara Tunnel

According to a report dating from 1999 the Tegelbacken Tunnel system was activated under real conditions and functioned perfectly. In spite of the FFFS being installed, the tunnel is closed for the transportation of hazardous goods. The FFFS operates as a water spray system and is activated section-by-section by temperature sensors. No particular problems have occurred during maintenance [PIARC 1999]. More recent reports on findings are not available.

It is planned to install a FFFS in the “Norra Länken” Tunnel project (due to open in 2015) in Stockholm. As no regulations are in force in Sweden, which govern the installation of a FFFS in road tunnels, there are no specifications pertaining to the FFFS design. The system planned for the Norra Länken Tunnel could thus be freely developed with regard to savings costs for the project’s specific conditions.

The planned system is not intended as a new standard solution in future Swedish road tunnels. It will only be used in tunnels with enhanced safety demands, for instance long tunnels, tunnels transporting hazardous goods or in urban tunnels with longitudinal ventilation affected by tailbacks. All these above-mentioned general conditions exist in the Norra Länken Tunnel [Lundström 2011].

Spain
So far two tunnel projects in Spain have been fitted with water mist systems:

- Vielha Tunnel in the Pyrenees, Province of Lleida in the north-east of Spain
- M30 Tunnel in Madrid

Vielha Tunnel
The new Vielha Tunnel, opened in December 2007, was built to replace an existing tunnel, which will only be used as an evacuation tunnel and for transporting hazardous goods in future. The new tunnel is altogether 5,200 m in length with varying gradients (550 m with +1.7% and 4,550 m with -4.5%). It operates with a two-way, three lane system with a total width of 14 m. The ventilation operates in accordance with the semi-transverse flow system and is divided into four ventilation sections. These are connected to ventilation stations set up at the portals. Cross-passages leading to the original tunnel that serves evacuation purposes are arranged at 400 m gaps.

The FFFS is solely activated by manual means by the tunnel operations centre via remote control. At present, activation is only foreseen once all tunnel users and the emergency services have vacated the fire zone. In addition, activation of the fire fighting system is coordinated with the fire detection and ventilation system.

M30 Tunnel in Madrid:
The M30 (Figure 3) forms Madrid’s inner motorway ring and represents one of Europe’s biggest urban road tunnel projects undertaken so far with an approx. 56 km tunnel length. The project was tackled between September 2004 and summer 2007. Parts of the tunnel as well as technical operational rooms are protected by

water mist systems from the manufacturers Fogtec and Marioff.

Figure 3: M30, 4-lane section and position on motorway network around Madrid [Wikipedia]

Hungary
No automatic fire fighting systems are currently installed or planned in Hungary. This negative approach is explained in PIARC publications dating from recent years [PIARC 1999] [Horvath 2010].

The fire brigade proposed the installation of a fixed fire fighting system on a foam basis in a tunnel on the M6 motorway, however, it was abandoned during the planning process. It was decided to concentrate on the application of conventional and mobile extinguishing systems.

3.1.2 America

USA
Currently six tunnels in the USA are equipped with automatic fire fighting systems. The decision to install FFFS in these tunnels is based on allowing hazardous goods to pass through them as well as to protect the buildings above the tunnels [Häggkvist 2009]:

- Boston Massachusetts CANA Northbound and CANA Southbound*),
- Settle Washington Battery Street,
- I90 First Hill Mercer Island*),
- Mt. Baker Ridge*),
- I-5 Tunnel*).

*) Water spray system without foam-forming additives

Canada
In Canada, an automatic fire fighting system in the form of a sprinkler system on a water basis in installed in the British Columbia George Massey Tunnel in Vancouver. The 630 m long tunnel is part of the Highway 99 and was commissioned in 1959 as a submerged tunnel with two lanes in each direction. The directional tubes are separated from each other by a concrete wall [Häggkvist 2009].

3.1.3 Australia

The safety philosophy prevailing in Australia is based on the fact that small fires, if not suppressed in time, can easily develop into large uncontrolled conflagrations. This type of fire development actually takes place far more frequently than the sudden occurrence of large fires. As a consequence, the prevailing safety philosophy in Australia advocates that the FFFS are activated as soon as possible so that the full capacity of the FFFS takes effect during the first few minutes of an incident. In this way, the fire's growth is impeded during the initial phase so that the probability of it becoming a large fire is reduced [PIARC 2008]. These positive factors outweigh potential disadvantages of the FFFS such as destroying the smoke layer, increased flow of heat and the production of vapour.

FFFS are applied as follows in a number of road tunnels in Australia:

- FFFS are only installed in tunnel of significant length in urban areas. These tunnels were opened after 1990.
- The FFFS's field of application now includes rescuing persons in addition to the original aim of structural protection. This alteration / addendum is restricted solely to tunnels.

Table 1 contains a survey of road tunnels in Australia, which are fitted with automatic fire fighting systems.
Additional safety features are:

  - Control room with operators, who are not simply responsible for traffic management but also for safety in the tunnel.
  - Video cameras and/or automatic accident detection, which enables the operator to localise the incident immediately in a precise manner as well as identify it [Häggkvist 2009].

- All tunnel ventilation systems, which are foreseen along these lines, are at least partly provided with a smoke removal system.

Burnley Tunnel
The Burnley Tunnel is 3.4 km long and possesses three driving lanes per bore and direction. A mix of car and truck traffic uses the tunnel. The ventilation system operates in transverse mode with smoke gas removal. A water spray system is installed as FFFS.

In 2007 a fire accident occurred in the Burnley Tunnel. The findings that were obtained from this accident can be summed up as follows:

A fire was caused by a traffic accident resulting in the deaths of three people on March 23, 2007. It was detected by means of digital image evaluation and activated the emergency ventilation and FFFS two minutes after the fire broke out. The system worked perfectly so that backlayering was prevented through quickly attaining the speed limit in the air flow. The fire was controlled until the fire brigade arrived so that the fire did not spread to any extent. There was only slight damage to the structure. Only persons involved in the accident were harmed. No victims resulted from the fire.

Name of the Tunnel	Location, year of construction	Lenght	Description
Lane Cove Tunnel	Sydney, 2007	3.6 km	3.6 km, twin tube, 2 & 3 lanes, deluge 10 mm/min, no DGV's, 2 zones of 30 m covering 60 m of roadway
M5 East	Sydney, 2002	4 km	twin tube, 2 lanes, deluge 10 mm/min, no DGV's, 2 zones of 30 m covering 60 m of roadway
Cross City Tunnel	Sydney, 2006	2 km	twin tube, 2 lanes, deluge 10 mm/min, no DGV's, 2 zones of 30 m covering 60 m of roadway
Sydney Harbour Tunnel	Sydney, 1992	2.8 km	twin tube, 2 lanes, deluge 10 mm/min, no DGV's, 2 zones of 30 m covering 60 m of roadway
Eastern Distributor	Sydney, 2000	2.1 km	twin tube, 2 & 3 lanes, deluge 10 mm/min, no DGV's 2 zones of 30 m covering 60 m of roadway
Burnley Tunnel	Melbourne, 2000	3.4 km	3 lanes, deluge 10 mm/min, no DGV's 2 zones of 30 m covering 60 m of roadway
Kemp Place Tunnel	Brisbane, ~1980	0.5 km	bi-directional (1 lane each way), fire sprinklers, 5 mm/min, no DGV's
Inner City Bypass (Tunnel A)	Brisbane, 2006	0.6 km	twin tube, 3 lanes, foam sprinkler (due to DG vehicles) 6.5 mm/min
Inner City Bypass (Tunnel B)	Brisbane, 2006	0.3 km	twin tube, 2 lanes, foam sprinkler (due to DG vehicles) 6.5 mm/min
Inner Northern Busway	Brisbane, 2008	1.2 km	bi-directional dedicated Busway with underground station, deluge at station platforms only, 10mm/min, individual zones covering each platform stop
Southern Crossing Tunnel Adelaide Hills	Adelaide		
North/South Busway Tunnel	Brisbane, 2004		
City Link, Mitcham / Frankston Tunnel	Melbourne		
N/A North/South Tunnel			
Graham Farmer Tunnel	Perth		
M5 East Tunnel	Sydney		
M4 Tunnel			
M7 Clem Jones Tunnel	Brisbane, 2010	4.8 km	twin tube, 2 lanes
Airport Link	Brisbane, 2011 under construction	6.5 km	

Table 1: Road Tunnels in Australia with FFFS [Bagis 2010], [Häggkvist 2009].

3.1.4 Asien

Japan
FFFS, usually water spray systems, are applied in Japanese road tunnel according to national standards. Tunnels are classified according to traffic volume and length. FFFS are prescribed for tunnels in Class A (more than 10 km long) and B (more than 3 m long and in excess of 40,000 vehicles per day).

Since the late-1970s more than 80 tunnels have been fitted with fire fighting systems. This development was triggered by a mass pile-up with resultant fire in the Nihonzaka Tunnel on July 11, 1979. A total of 187 vehicles were involved resulting in 7 fatalities. Generally speaking, systems are installed, whose extinguishing water is permanently under pressure. The only exception regarding the extinguishing agent is the 9.5 km long Trans-Tokyo Bay Tunnel, which has a water spray system with foam additive option. The FFFS's aim is structural protection by reducing the temperatures that occur and improving the evacuation conditions [Häggkvist 2009, Iwata 2001].

Experiences in Japan
Experiences gained in conjunction with the FFFS can be summed up as follows:

- In 1999, two fires occurred in the Tokyo Metropolitan Expressway underwater tunnels. The fires were caused by a delivery van and a medium-sized truck. In both cases the tunnel operator activated the FFFS installed in the tunnel.
- Evaluations of video recordings of fires in tunnels confirm the assumption that the FFFS are not in the position to extinguish vehicle fires completely. However, the evaluations show that the fire is effectively prevented from spreading and the positive effect of cooling the structure.
- After long-standing Japanese experiences it can be presupposed that installing FFFS in tunnels does not bring about disadvantages with regard to safety. The decision taken for a given tunnel project generally relates to Japanese safety standards and cost effectiveness considerations.
- The time delay in activating a FFFS depends on the tunnel operator's decision. In the past, the FFFS was activated immediately after discovering the fire. In other cases, it was first activated after the last motorist had vacated the tunnel tube in order to preclude the danger of injury through hot water vapour. The decision is made by the tunnel operator on the basis of an estimation of the better chances of survival. In the interim, proper activation of the system is governed by a risk analysis [PIARC 2008].

Generally no foam-forming additives are used in Japan in order to avoid costs and an increased need for cleaning after application. The water supply is geared to a deployment period of at least 40 minutes. Regular inspections and trials are carried out every year. No perceptible damage resulting from aging of the installations was observed on the spraying systems [Ingason 2066].

However there are also critical assessments of the effectiveness of sprinkler systems in Japan. Yoshikazu Ota, OTA, OTA Engineering, Chlyoda Engineering Consultants Co., Ltd., a top Japanese expert in the field of ventilation and FFFS, was commissioned with designing many FFFS in Japan since the 1960s. In a report, he doubts the cost-benefit ratio of the FFFS on account of high installation and maintenance costs.

He believes that the ventilation system's performance must perhaps be increased when a FFFS is installed to make up for aerodynamic losses, which are attributable to water drops and water mist. He feels investments in passive fire protection measures and active safety measures to improve evacuation are more advisable than installing FFFS. On this basis, he as a planner does not foresee any more FFFS as safety equipment in tunnels in Asia [Ota 2010].

Taiwan
The decision to apply FFFS in Taiwan is made individually.

In the case of the East Coast Freeway Tunnel in Taiwan (opened 2006), one of the first road tunnel projects in the east Asian region, the Taiwanese Highway Authority, responsible for the project, had no intention of installing a FFFS as part of the safety equipment [Ota 2010]. This decision according to one of the Japanese engineering offices involved in the planning was due to the following aspects:

- The national Taiwanese regulations contain no corresponding requirements for the installation of a FFFS.
- The cost effectiveness of installing a FFFS in Taiwan continues to be regarded as unclear based on Japanese experiences. Weighing up the costs for installation and maintenance against the realised effect does not suffice for making a decision.
- The tunnel possesses an effective ventilation system.
- Both the tunnel and its furnishings possess high temperature resistance.

South Korea
The safety concept in South Korea is geared towards Japanese guidelines. As a result, FFFS are foreseen for Class A tunnels [Ota 2010].

3.1.5 Other Countries

Egypt
There are no FFFS used nor planned in road tunnels in Egypt. Existing installations are restricted to sprinkler systems in business and shopping areas.

Abu Dhabi
A low pressure water spray system was installed at the Yas Island Southern Crossing Tunnel project in Abu Dhabi.

The 698 m long road tunnel connects the island of Yas with the mainland. Originally it was planned to split the cross-section up into 5 cells (2 bores for road traffic, 1 rail tunnel and 2 evacuation tunnels) to secure the required safety level. Cross-passages with fire protection doors, in keeping with the UK Design Manual for Roads and Bridges, were originally foreseen at 100 m intervals from the running tunnels to the evacuation tunnels. Based on a risk analysis the concept of the evacuation tunnels was abandoned and the resultant extension of the escapeways was approved through the application of a low pressure water spray system given the same potential danger level. The maximal escapeway length is 294 m taking the rescue shafts set up at both sides of the river into account. As this escapeway length is evaluated as permissible according to the risk analysis, the tunnel cross-section was reduced to 3 cells (2 road tunnel bores and 1 rail tunnel) [Tarada 2009].

3.2 Other Use

Indirect Application of FFFS in Road Tunnels to cool Smoke Gas
A water mist system is applied for cooling smoke gas in the Austrian Gleinalm Tunnel on the Pyrn motorway A9 Linz-Graz. The Gleinalm Tunnel is a single bore, two-way tunnel totalling 8,320 m in length, which operates with transverse ventilation. There are 6 ventilation sections with 6 air intake and exhaust machines (axial fans), 2 ventilation caverns as well as 84 exhaust air flaps.

The original fans dating back to the year of construction 1978 are geared to a temperature load of 250°C over a 60 min period. However, according to the valid RVS Guidelines, smoke gas temperatures up to 400 °C have to be controllable over a period of 120 min. Consequently, it is essential that the exhaust air temperature in the exhaust air duct is restricted prior to the fans. This is effected in the event of fire by adding water mist to the smoke gas current between the smoke gas flaps and the axial fans. Through the vaporisation of the water mist in the hot smoke gases, heat is extracted from the air stream and the temperature diminished [Aquasys 2010].

Application in Rail Tunnels
Betuwe Route (Netherlands)
The tunnels on the Betuwe Route in the Netherlands provide an example of using a water mist system in a rail tunnel. The Betuwe Route is intended for carrying goods traffic between Germany and the Port of Rotterdam. Hazardous goods transportation is also permitted on the line but there are no plans for passenger services. The continuous twin-track route possesses five tunnels as well as an overhead noise barrier with one-way traffic.

The goals of combining FFFS with other safety measures are:

- Reducing the temperature around a burning tanker with the aim of preventing a LPG-BLEVE (Liquefied Petroleum/Propane Gas, Boiling Liquid Vapour Explosion),
- Preventing concrete spalling in the event of fire,
- A reduction in the production of smoke near the portals.

Risk analyses indicate that all safety requirements could also have been adhered to by applying alternative measures such as additional ventilation, without using water mist systems [Both 2010].

SAFE Stations in the Channel Tunnel
The Euro Tunnel is a rail tunnel between France (Calais) and Great Britain (Dover), carry all kinds of road vehicles on shuttle trains. Basically the general conditions regarding a fire occurring are comparable to a road tunnel.

In 1996 and 2008, two fires causing great damage to the tunnel structure (segmental lining) took place. The affected section of tunnel had to be closed for seven months in 1996; in 2008, the bore affected by fire was closed for several weeks. Even although no lives were lost, a fire protection concept based on a water mist system was developed on account of the high economic losses incurred, to diminish the effects of future fire incidents.

During the fires in 1996 and 2008, temperatures in the tunnel reached roughly 1,000 °C and led to critical damage to the concrete tunnel shell. Fire service units, who combated the fire in 2008, were unable to get close enough to the fire seat. As a result, they were unable to prevent 30 trucks on the shuttle train being destroyed by fire and a major portion of the extinguishing water from reaching the blaze.

To enable fire to be fought by means of a water mist system, two so-called “SAFE stations” were set up per running tunnel in 2011, in which the affected train must stop in the event of fire. Each of these SAFE stations is 870 m long thus offering a 70 m tolerance for the maximal 800 m long trains if they are forced to stop. Heat sensors on the tunnel ceiling activate the jets of the water mist system automatically in one or several sections. Each of these sections is 30 m long and equipped with 15 jets at both sides of the train.

The total costs for retrofitting the tunnel with FFFS systems amount to roughly € 20 million. The bulk of the costs is spent on the subsequent extremely complicated setting up of the technical rooms at the side of the Service Tunnel. The technical rooms’ cross-section corresponds to the dimensions of the cross-passages [Railway Gazette].

Application in Rail Vehicles
Fighting fire actively in rail vehicles has only really caught on in recent years. Previously, this topic was confined to clear normative requirements. The Greek national railway for instance, equipped its diesel-operated fleet of traction vehicles with extinguishing systems on the basis of valid approval specifications back in the late 1970s.

For some years now, active fire fighting measures have been advocated internationally based on concrete approval specifications. There are requirements for fire fighting measures in rail vehicles e.g. in the UK, Greece and Italy. Italy in particular, has adopted a special place on the approval market for years now with its call for fire extinguishing systems. In keeping with UNI CEI II170 requirements, technical sectors in trains with medium and high-voltage systems as well as combustion engines must generally be equipped with fire alarm and fire extinguishing systems. For this reason, extinguishing systems are even to be found there in locomotives that are 30 or almost 40 years old, even although they may not be as efficient as modern systems.

If one looks in comparison to the passenger area application sector, in the past, only a few innovative operators introduced fire protection systems in their vehicles. The Hamburg Hochbahn and the Madrid Metro are among the pioneers. Both operators have gone into this problem complex in great detail and have come up with a fundamental approach for modern application. The increasing number of fire incidents caused by vandalism was according to the operators a major reason for implementing such extensive measures.

The Hamburg Hochbahn decided to apply a system based on low pressure with water as extinguishing agent back in the mid-1980s, whereas the Madrid Metro came out in favour of creating water mist by means of high-pressure technology in the passenger area. Both operators use water as medium as it poses a minimal danger to nearby persons. A frost protection additive on account of possible low temperatures is added to the water in the case of the Hamburg Hochbahn vehicles, which in some cases travel on the surface. In Madrid on the other hand, there is no need to apply such measures because all trains travel underground and a temperature level in excess of 0 °C is always prevalent in the underground transportation system [Heyn 2010].

Currently (2011) the idea is being mooted of fitting older Stadtbahn Düsseldorf vehicles with FFFS. Similar notions have been put forward for other urban rail systems in the Ruhr District. Appropriate systems have already been integrated in some vehicles of the Munich Metro.

Stops in Metro Stations
There are over 2,000 areas such as escalators and technical control rooms in more than 200 stations fitted with water mist systems on the Madrid Metro [Marioff]. Further FFFS in Metro systems are used in Metro stops (e.g. Osaka, Milan) or the main exit areas (Helsinki) [Blennemann 2005].

The Budapest Metro has equipped 2 complete lines with high pressure water mist fire fighting systems at the track sector of the stops as well as in technical rooms and elevators [fogtec].

3.3 Assessment and Reservations

The application of FFFS still continues to be a bone of contention among experts. A reason often encountered for the lack of acceptance of such systems in tunnels can be attributed to the very unsatisfactory results of the first experiments carried out back in 1965 in the Ofenegg Tunnel (Switzerland) (please see Chapter 4.1).

In this case, immediately after the ignition of 1,000 l of diesel on a 95 m² surface, a water spray system was activated, which caused a swift reduction in temperature. The fire appeared to be extinguished after 10 minutes. However, then the remaining fuel vapours resulted in an explosion in the tunnel, which caused three technicians to be injured and seriously damaged the test set-up. Development of vapour was already registered for smaller fires without the above described dramatic events occurring.

The problems encountered (danger of explosion, vapour development) were also reflected in PIARC recommendations (please see Section 3.4), which opposed fire fighting systems being installed in road tunnels throughout from 1983 (Congress in Sydney) and 2004. Although the PIARC no longer generally rejects the installation of such systems but bases this on the outcome of a risk analysis, this negative approach is still found in most national guidelines for tunnels [Bettellini and Seifert 2009].

The mentioned reservations against FFFS in general and water mist systems in particular do not comply with the present level of knowledge and can be assessed as follows:

Thesis 1:
Water without suitable extinguishing agent additives can cause explosions, should it come into contact with fuel or other chemical substances during a fire.

Assessment:
- There are a few substances, which are unsuitable for combating fire with FFFS with water as extinguishing agent. Diesel and petrol in particular, however, represent no danger after assessing extensive tests.
- Water mist is a generally accepted extinguishing agent for fighting fire in technical rooms and machine rooms, in which the danger stems from various fuels.
- In the case of substances, which cannot be extinguished by water, the tunnel could theoretically be closed to loads carrying hazardous goods of this nature. This includes substances belonging to

Dangerous Goods Class 4.3, which form inflammable gases in combination with water. Examples: sodium, carbide, zinc dust and trichlorsilane. According to the valid ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road) no classification is foreseen for the above mentioned hazardous goods category. In such a case, a tunnel can only be closed for “all dangerous goods” (Category “E”).

Figure 4: Pictogram of Dangerous Goods Class 4.3 for substances, which form flammable gases in contact with water

Thesis 2:
There is the risk that although a fire is largely extinguished, inflammable gases continue to be produced, which can result in the danger of an explosion.

Assessment:
- As long as there is an open fire, inflammable gases will be burned directly.
- Once the fire is extinguished the extinguishing agent provided by the FFFS combined with the tunnel ventilation causes harmful vapours to be distributed, resulting from leaks in transport containers or fuel tanks or from pools of escaping liquids. In this way, gas concentrations, which are critical for explosions, are avoided.

Thesis 3:
Water Vapour that develops can harm persons in the tunnel

Assessment:
Water vapour and in turn, temperatures of over 100 °C occur but are only locally restricted in the direct vicinity of the flames.
- Persons, who are located close enough to the fire seat that they could be scalded by the vapour produced locally, would already have sustained serious injuries from radiation heat from the fire (i.e. without vapour development).

Thesis 4:
A water mist system’s efficiency is low when applied against concealed fires within vehicles.

Assessment:
Concealed fires in an open room represent a challenge for all FFFS. The purpose of a water mist system FFFS is:
- Preventing fire spreading to other vehicles in the vicinity,
- Making better and safer evacuation conditions for users in the tunnel as well as improved deployment conditions for the fire brigade,
- Protecting the tunnel and the tunnel equipment.

Thesis 5:
When activating a FFFS (water mist system) the smoke gases are cooled down and an existing layer destroyed. As a result, the entire tunnel section fills with smoke over a major distance in a short time.

Assessment:
- A smoke layer is produced for a few minutes under favourable conditions given an undisturbed thermal in the case of an unrestricted fire in a tunnel (in other words, without the application of FFFS). The zone of this layer close to the floor affords a time-restricted possibility to escape while free from smoke gas. However, the fire smoke layer is massively disturbed through the tunnel ventilation and the cooling of the smoke gases that occurs on the tunnel walls, in such a way that the smoke gases are swirled around after only a few minutes even without FFFS application depending on the production of fire gas (size of fire) and the air current. Should the longitudinal air speed exceed values of some 3 m/s, the uprising fire gases are completely swirled over the tunnel cross-section even without FFFS and a smoke gas layer is unable to form [Schneider 2006].
- Activation of a water mist system mixes and cools the smoke that is present. At the same time, less smoke gas and heat are produced through fire development being suppressed.
- The so-called pros and cons have to be considered when evaluating the effects of FFFS on the survival conditions of tunnel users, whose self-evacuation close to the fire seat was not possible prior to activation of the FFFS. The fire-suppressing effect of the FFFS is advantageous in this case. This stands opposed to the disadvantage of a possibly curtailed time span with prevailing smoke gas layer.

Thesis 6:
Visibility is reduced by applying a water mist system.

Assessment
- Sufficient orientation is assured even with an activated water mist system in spite of reduced visibility. This was verified in numerous tests even with fires of 60 MW.
- In the event of fire, the visibility in a tunnel is strongly affected by the general conditions within a short time even without application of a FFFS.

Thesis 7:
Maintaining a water mist system involves high costs.

Assessment
- No global evaluation of the maintenance costs is possible, instead each individual case must be taken under consideration of the project-specific general conditions on its own (please compare Appendix 6 of the Guidelines). By assessing

existing installations, the costs actually incurred are known. Accordingly, the maintenance costs are reasonably geared to the overall investment costs and the benefit provided by the system.
- Components made of high-grade stainless steel possess an extensive service life and only require limited maintenance outlay [Vuorisalo].

3.4 International Codes of Practice and Guidelines

The current level of regulations on safety equipment in tunnels is presented as follows. First of all, general provisions are examined in detail and subsequently explanations provided on fire fighting systems found in these guidelines and regulations. Table 2 provides a corresponding list. It should be said at this point that with the exception of Japan there were no legal regulations or norms for installing fixed fire fighting systems in tunnels [Ingason 2006].

General codes of practice on safety systems in the form of FFFS and water-mist-FFFS from the fields of structural engineering and industry, which can partially be applied in tunnels include:

- FM 5560: “Approval Standard for Water Mist Systems” [FM Approvals 2009],
- TS 14972: “Water Mist Systems – Design and Installation” [CEN European Committee for Standardization German version CEN/TS 14972:2011],
- EN ISO 14847: “Rotary Positive Displacement Pumps - Technical Requirements”,
- EN 12259-1: “Components for Sprinkler and Water Spray Systems”,
- prEN 14816: “Water Spray Systems – Design and Installation”,
- 97/23/EC: “Pressure Equipment Directive” [European Parliament and Council 1997],
- NFPA 13: “Installation of Sprinkler Systems” [NFPA 13]
- NFPA 20: “Standard for the Installation of Stationary Fire Pumps for Fire Protection”[NFPA 20]
- NFPA 25: “Standard for the Inspection, Testing and Maintenance of Water-Based Fire Protection Systems” [NFPA 25],
- NFPA 750: 2006: “Standard on Water Mist Fire Protection Systems” [NFPA 750].

European Tunnelling Guideline

In 2004, the European Union published the Guideline 2004/54/EC “on minimum requirements for safety in tunnels in the Trans-European Road Network” (so-called EU Tunnel Guideline) with the aim of accomplishing a standard, high protection level in road tunnels. As is the case with many other European legislative initiatives, however, this too (as of 2011) has not been adopted in national law as foreseen, as differing views prevail on the measures to be specified. Early drafts of the Guideline were rigidly formulated; the final version is more flexible leaving room for decisions. As a result, alternatives approaches are permitted instead of solutions to regulations, if a risk analysis is able to show that at least an equal level of safety is achieved (please see Appendix 1, Section 1.2.1 of the cited European Guideline).

Land	Title	Abreviation	Type	Publisher / Year
Australien	Fire Safety guideline for road tunnels	-	Guideline	Guideline Australasian Fire Authorities Council (2001)
Österreich	Richtlinien und Verordnungen für den Straßenentwurf RVS 09.02.22 – Tunnelausrüstung – November 2010 RVS 09.02.51 - Ortsfeste Löschsysteme – März 2006	RVS	Guideline	Forschungsgesellschaft Straße - Schiene - Verkehr (FSV)
Frankreich	Circulaire interministerielle N° 2000- 63 DU 25 aout 2000 relative à la sécurité dans les tunnels du réseau routier national (Inter-ministry circular n°2000-63 of 25 August 2000 relating to the Safety of tunnels in the national highways network)	Circ 2000/63A2	Regulation	Ministry for infrastructure, transport, spatial planning tourism and the sea (2000)?
Deutschland	Richtlinie für die Ausstattung und den Betrieb von Straßentunneln Guideline regarding equipment and operation of road tunnels	RABT 2006	Guideline	Forschungsgesellschaft für Strassen- und Verkehrswesen (2006)
Japan	Design Principles, Volume 3 (Tunnel) Part (4) (Tunnel Safety facilities)	-	Guideline	Japan Highway Public Corporation (1998)
Korea	National Fire Safety Codes Guideline for Installation of Safety facility in road Tunnels	NFSC GIST	Regulation Guideline	Korean National Emergency Management Agency (2005) Ministry of Construction & Transportation (2004)
Norwegen	Road Tunnels	Handbook 021	Guideline	Norwegian Public Road Administration (2010)
Schweden	Tunnel 2004	Tunnel 2004	Guideline	Swedish national road administration (2004)
UK	Design manual for roads and bridges, Volume 2 Highway structure design Section 2, Part 9, BD 78/99: Design of road tunnels	BD78/99	Guideline and requirement	Highway Agency (1999)
USA	Standard for road tunnels, bridges and other limited access highways	NFPA 502	Standard	National Fire Protection Association (2011)
EU	Directive2004/54/EC of the European parliament and of the council	2004/54/EC	Directive	European Parliament and the Council (2004)
PIARC	Fire and smoke control in road tunnels, Road Tunnels, Assessment of fixed fire fighting systems (Brand- und Rauchbeherrschung in Straßentunneln, Straßentunneln, Beurteilung von festen Brandbekämpfung-sanlagen)		Guideline	PIARC (1999 PIARC (2008)
UNECE	Recommendations of the group of experts on safety in road tunnels (final report)		Guideline	UNECE Ad hoc Multidisciplinary Group of Experts on Safety in Tunnels (2001)

Table 2: Overview of relevant regulations and guidelines regarding safety equipment in tunnels

TSI – Technical Specifications for Interoperability

On December 20, 2007, the European Commission passed the “Technical Specifications for Interoperability” (TSI). The TSI deal with “safety in railway tunnels” in the conventional trans-European railway system and in the trans-European high-speed railway system. Paragraph 17 determines their scope:

“These TSI apply to tunnels in the country with low traffic frequencies as well as to tunnels in the centre of urban areas with a large number of trains and passengers. Only minimum requirements are laid down: TSI conformity on its own does not afford a guarantee for safe commissioning and safe operation.

All those involved in safety matters are required to work together to attain the appropriate safety standard for the tunnel in question according to the regulation of the TSI and the Interoperability Guidelines. The member countries are requested to ascertain whether the local circumstances (including nature and frequency of traffic) call for additional measures, which extend beyond those contained in the TSI, each time a new tunnel is opened or when an existing one is used by interoperable trains. This examination can be carried out by means of a risk analysis or another method commensurate with the state of the art. The tests represent a part of the process of issuing safety certificates and granting safety permits in accordance with Articles 10 and 11 of the Guideline on Railway Safety” [EU Commission 2008].

Depending on the local circumstances, the above-mentioned additional measures can also relate to installing an automatic fire fighting system.

NFPA Standards (National Fire Protection Association)

In the United States, the NFPA 502: Standard for Road Tunnels, Bridges and Other Limited Access Highways represents an important norm in conjunction with fire fighting systems for tunnels. The association's members are representatives of tunnel operators, scientists, consultants and other technical experts so that the regulations worked out at the committee stage form a balance among the various interest groups. Furthermore, many of the association's members also belong to PIARC committees (working groups) so that the NFPA 502 document and PIARG position papers (please see below) mutually influence each other and usually develop harmoniously [Brinson 2010].

The current new edition of the NFPA 502 dating from 2010 deals with water-based fire fighting systems in a separate chapter (9). It depends on the tunnel category whether such a fixed system is installed. Normative references in NFPA 502 relate to the technical equipment, which is dealt with in the following codes of practice [Häggkvist 2009]:

Abbreviation	Title
NFPA 11	Standard for low, high, medium expansion foam
NFPA 13	Standard for the Installation of Sprinkler Systems Remark: The standard deals with many fundamentals concerning hardware, design and requirements.
NFPA 15	Standard for Water Spray Fixed Systems for Fire Protection Remark: This standard gets a bit more specialized and often refers to NFPA 13. So the best usage is to combine NFPA 13 and 15.
NFPA 16	Standard on the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems Remark: NFPA 16 only applies for systems using low expansion foam. Furthermore, it does not stipulate were foam systems are required.
NFPA 18	Standard for Inspection, Testing and Maintenance of Water-Based Fire Protection Systems
NFPA 750	Standard on Water Mist Fire Protection System Remark: NFPA 750 contains the minimum requirements for design, installation, maintenance and testing of water mist fire protection systems. The standard shall not be seen as a design handbook with definite solutions but more like a guide. It instead relies on good engineering practices.

Table 3: Overview of NFPA Codes of Practice

Positions PIARC Position Papers

The World Road Association (PIARC) – formerly "Permanent International Association of Road Congresses" – is essentially a non-political, non-profit association with members in the form of national governments and authorities as well as individuals from 142 countries. The PIARC consensually publishes so-called position papers, which are valid for most European governments as the basis for their approaches to tunnel safety.

For a long time, the PIARC adopted a negative stance on fire fighting systems. In its 2008 position paper, however, the PIARC revealed it had altered its approach on assessing FFFS. The PIARC basically concluded that the application of fixed fire fighting systems makes sense under certain circumstances.

Since publication in 2008, no more official indications have been forthcoming (on the subject of FFFS). According to a verbal account by the German representatives in working group C4.4 of the PIARC, no publication dealing with FFFS is planned during the cycle (2008-2011). The discussion is nonetheless continuing. The cycle embarked on in 2012 is to see a study worked out (Best Practice of Fixed Fire Fighting Systems in Road Tunnels) [BAST 2011],

UPTUN Guidance

The "Guidance for Water-Based Fire Fighting Systems for the Protection of Tunnels and Subsurface Facilities" [UPTUN 2008c] was drafted as part of the European UPTUN research project.

The Guidance contains details relating to the design, installation and maintenance of water-based fire fighting systems for use in tunnels. It discusses various aspects from water supply to water disposal. The UPTUN Guidance relates to the previously mentioned NFPA norms as well as other corresponding standards. These include the norm parts of the DIN EN 12259: Fixed Fire Fighting Systems – Components [Häggkvist 2009].

3.5 National Guidelines

Australia

Australia is a federation consisting of federal states. The federal states regulate legislation with regard to tunnel safety. As a result, there are no standard legal regulations, applying for the whole of Australia. This weakness was recognised by the independent supervisory authorities of the federal states and continental territories as well as Australian tunnel experts and a series of recommendations published as a counter-measure (AUSTROADS, Australian Standards). However, these are non-binding although they are contractually agreed on in individual cases [ITA COSUF 2011].

Bulgaria
The Republic of Bulgaria's Ministry of Transport established the minimal safety requirements for road tunnels on national roads belonging to the trans-European road network in an enactment (No. 1 of 04.04.2007) Supplements to the enactment followed in the "State Gazette", issues 58/2007 and 102/2008.

The enactment does not commit itself with regard to installing of a FFFS. According to Article 3 of the corresponding enactment, the managing director of the national road agency is responsible for the choice of safety concept, which also entails fire fighting systems [Georgieva 2010].

Denmark
There are no national guidelines with explicit demands relating to FFFS in Denmark. The specifications of Directive 2004/54/EC have been integrated in Danish law [Eskesen 2010].

Finland
There are national Finnish guidelines for road tunnels (only available in Finnish), which are issued by the road administration authorities. They foresee, although do not call for, solutions involving water mist systems as well as alternatives.
Essentially the responsibility for the choice of the safety installations lies in the hands of the tunnel operator (city, state or private operator).

France
A circular from August 25, 2010 issued by the responsible French ministry contains neither requirements nor details on FFFS [Ministry of Interior 2000], [Ministère Equipement 2000].

A FFFS is installed on the basis of a decision in each individual case. National guidelines define the safety level to be observed. The CETU (Centre d'Etudes des Tunnels) published a position paper on the application of FFFS in tunnels with the focus on water mist systems [Ponticq 2010].

Great Britain
Section 8.55 of the "Design Manual for Roads" [Highway Agency 1999] evaluates automatic fire fighting systems as unsuitable for traffic zones. Spraying systems with gaseous extinguishing agents and foam systems are accordingly not to be used if persons are to be found in vehicles. Although the positive influence of FFFS as spray water systems for cooling and washing smoke gas is recognised, these systems are rejected on account of the possible production of explosive air/vapour mixtures.

The negative attitude based on the above mentioned guideline from 1999 is, however, not actually observed in practice. In 2010, the Highway Agency authorised the Dartford Tunnel to be retrofitted with a fire fighting system. Recently fire fighting systems were also installed in the (privately operated) Tyne Tunnels (please see Chapter 3.1.1).

Iceland
The Icelandic highway authority is responsible for selecting the safety measures in tunnels. Guidelines are determined by the Ministry for Transport and Communication. There are no special guidelines relating to FFFS [Haraldsson 2010].

Italy
The National Autonomous Roads Corporation (ANAS) describes systems for damage limitation in Section 3.3.2.5 of its guidelines. It is stated that various types of fire fighting systems must be subjected to a special risk assessment for concrete application, which confirms the level of safety, the choice and the function of the equipment. The guidelines, however, only apply for roads, which are actually operated by ANAS [Arditi 2010].

Japan
In 1967, the fire brigade announced Standards for Highway Tunnels as a consequence of the fire damage in the Suzaka Tunnel and published them the same year.

Netherlands
Generally, the tunnel operator is responsible in the Netherlands. However, as no tunnel in the Netherlands is privately operated, the responsibility lies with local or national authorities (road tunnels: Rijkswaterstaat RWS, rail tunnels: prorail). No basic requirement to install fire fighting systems exists in the Netherlands. The existing guidelines by and large reflect the negative attitude towards installing fixed fire fighting systems that existed some years ago.

Norway
The "Statens Vegvesen" authority responsible for the safety equipment in road tunnels issued a revised version of the manual 021 "Vegtunneler" in March 2010. It does not include details or requirements for installing fixed fire fighting systems [Statens Vegvesen, Norway 2010].

Austria
The tunnel equipment in Austria is governed by the Guidelines and Regulations for Highways [FSV 2011]. No demands or details relating to FFFS are to be found in them. There is also a technical bulletin RVS 09.02.51 – Fixed Fire Fighting Systems – (March 2006) [FSV 2010], which defines protective goals of FFFS and related requirements on fire fighting systems in detail. In addition, the bulletin examines technical aspects and verifications of efficacy of the systems are cited.

Sweden
The technical specification to be applied in Sweden "Tunnel 2004" only mentions sprinkler systems as possible safety equipment and points to NPA 502 regulations [ASTRA 2000].

Spain
There are no national regulations regarding FFFS in Spain [Del Rey 2010].

Hungary

No national guidelines for applying automatic fire fighting systems exist in Hungary. According to the ITA Hungary, so far there has been no need to apply international regulations [Horvath 2010].

Romania

In Romania, Law No. 277 from October 10, 2007 contains the minimal demands for tunnels as part of the trans-European road network pertaining to the required safety equipment. This law implements the European Parliament's specifications in Guideline 2004/54/RC from April 29, 2004 [Arghirou 2010].

Part 4 Fire Tests

An overview of fire tests involving the use of FFFS, which have already been carried out and published will now be provided in chronological order. A major portion of further research projects was, however, obtained within the scope of industrial research projects. The results from such sources are usually not published and thus inaccessible.

4.1 Ofenegg-Tunnel (1965)

Initial tunnel fire tests were undertaken in 1965 in the Swiss Ofenegg Tunnel, an abandoned rail tunnel with a clear height of 6 m and a floor width of 4 m [Haerter 1994]. A partition was set up to close off the cross-section 190 m from the portal. The fire source was 130 m from the portal or 80 m from the partition wall. Two rows of sprinklers were installed in the vicinity of the fire with a specific capacity of 19 l/s·m².

The sprinklers were activated immediately after the pool fire was ignited and led to the temperature quickly being reduced. The fire appeared to be extinguished after 10 minutes. However, at the test set-up involving 1,000 l of diesel, the fuel vapours remaining the tunnel subsequently exploded causing three technicians to be injured and massive damage to the test set-up. A similar effect was observed in the case of smaller fires, albeit without dramatic consequences. All in all, strong vapour development was registered during all the tests [Bettelini and Seifert 2009].

4.2 Japanese Test Series (1960-2001)

Numerous model and in situ tests have been held in Japan since the beginning of the 1960s to assess the effectiveness of sprinkler systems in tunnels. There are no more precise results of the tests carried out available as the relevant reports are only written in Japanese.

4.3 VTT Test Series in Finland (1990)

In 1990, the Finnish Technical Research Centre (VTT) undertook series of tests with liquid fires and water, without adding foam-forming additives [Kokkala 1990]. Ten different inflammable liquids with flame points ranging from -6° to 234 °C combined with seven different sprinkler and water spray jets were applied. The pool fire area amounted to between 0.4 m² and 12 m² and the jets were set between 3 and 8 m apart.

4.4 US Tests in the Memorial Tunnel (1993-1995)

The "Memorial Tunnel Fire Ventilation Test Program (MTFVTP)" embraced a total of 98 full-scale tests. The total costs for the programme amounted to almost $40 million thus making it the most extensive research project ever tackled by the Federal Highway Administration and the Massachusetts Highway Department. The fire tests were carried out in the Memorial Tunnel, located some 80 km from Charlestown, West Virginia (USA). The two-lane, 850 m long rock tunnel with a horseshoe-shaped cross-section on the Interstate 77 with a 3.2% gradient, was closed for operational reasons in 1988 [Sergui and Luchian].

A main objective of the test was to examine the effectiveness of different ventilation systems and ventilation rates in the event of fire (simulated with diesel pool fires with heat release rates of 10, 20, 50 and 100 MW), in order to set up a resultant data bank containing information on temperatures and the spread of smoke. Furthermore, the influence of various nozzle set-ups, the ventilation conditions within the tunnel and the fire's heat release rate on the effectiveness of the different sprinkler systems was to be ascertained. Five tests with sprinklers, in which case a foam-forming additive was added to the water, are of particular significance for assessing FFFS. An attempt was made here to establish whether the extinguishing foam, (2% Aqueous Film Forming Foam) was swept away from the fire seat by high air speed given longitudinal ventilation.

4.5 Benelux Tunnel Tests (2001)

Full-scale fire tests were undertaken in the Second Benelux Tunnel in Rotterdam in November 2001 under the aegis of the Centre for Tunnel Safety of the Dutch Ministry Rijkswaterstaat (RSW) in collaboration with TNO (Centre for Fire Safety), Arcadis, Nagtglas Versteeg Inspection and Strukton Systems. Towards this end, all unnecessary installations were encased or demolished to protect them against damage or contamination. Furthermore, a heat-resistant coating was installed over a distance of 70 m around the fire seat.

Altogether 28 fire tests were carried out over a four week period:

- 6 pool fires,
- 4 vehicles fires,
- 6 tests with piled fire loads (partly covered by tarpaulins),
- 10 tests on fire detection.

A water spray system with two sections (17.5 and 20 m in length) was installed as fire fighting system in the proximity of the fire load and the adjacent downstream sector. The water discharge rate amounted to 12.5 l/m²/min.

The following conclusions relating to FFFS were drawn from the tests:

- Visual condition worsened downstream to the fire at a distance of 100 to 200 m in all probability with as well as without longitudinal ventilation in the investigated fires without the application of the FFFS. The sight of users can be impaired to such an extent that escapeway markings can only be registered with difficulty or not at all. The rise in CO concentration does not exceed the permissible limit values.

- A water spray system reduces the air temperature in the vicinity of other vehicles near to the fire seat. The measured temperatures of the fire loads applied would not have been fatal are no fire flash-over occurred between vehicles. Furthermore, practically no vapour formation was observed. By activating the extinguishing system visibility was reduced to such an extent that escapeway signs are practically or completely indiscernible.
- Simulation of fire cycles by means of CFD analysis provides qualitatively adequate results. Quantitative evaluation results in clear deviations, which underline the need for fire tests to verify the calculations [Ministry of Transport 2002].

4.6 CETU-Versuche (seit 2002)

The French Centre d'Etudes des Tunnels (CETU) is the French government organisation responsible for tunnels. Since 2002, it has been engaged in a research programme, which pursues the following goals with respect to FFFS:

- Improving the conditions for self-rescue of users, which are capable of extending the time span for sustainable conditions securing survival for users depending on third-party assistance and the emergency services.
- Better understanding of the basic physical interrelationships as well as an evaluation of the effectiveness of FFFS.
- Improving measuring methods for significant parameters (as e.g. temperature or visibility measurement with sensors), which are or are not protected from water drops in each case.

The related test programme was set up in two stages. Phase 1 involved model tests on a 1:3 scale on the premises of the French Institute for Construction Research. Phase 2 saw major tests carried out on a full-scale basis. According to our source, only Phase 1 was implemented until 2008, further publications are not known. The test programme comprised 30 tests with uncovered and partly covered fires in the form of heptane pool fires or solid matter fires consisting of wooden pallets.

4.7 Hagerbach Test Gallery A86 (2003)

In 2003, fire tests were executed in the Hagerbach Test Gallery (Switzerland) to assess the effectiveness of a water mist system, intended for the A86 tunnel in Paris (France) (please also see Chapter 3.1). The directional carriageways are superimposed on top of one another there (Figure 5). As no trucks are allowed to use the A86 tunnel on account of the low clearance height, only cars were used for the tests. Figure 6 displays the basic set-up.

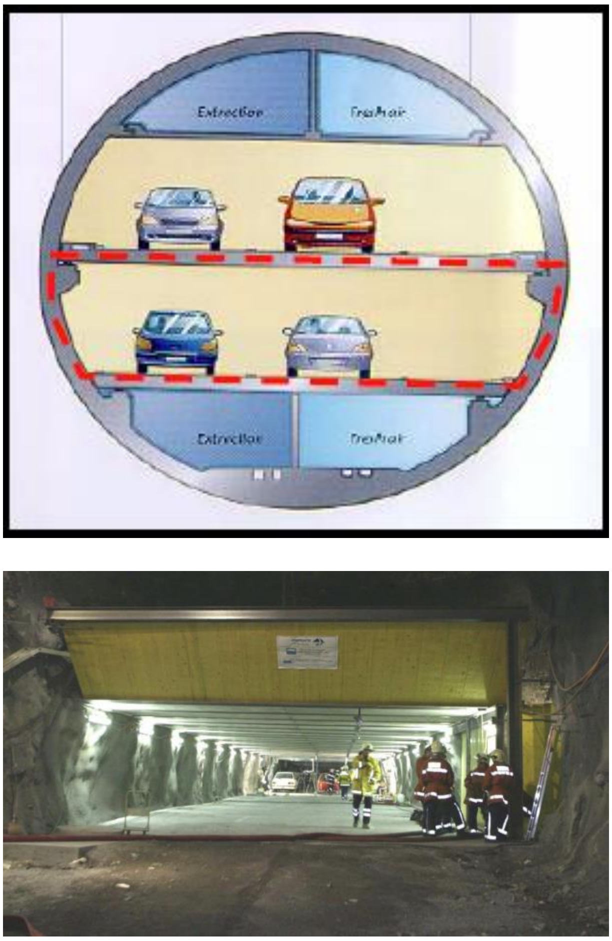

Figure 5: A86 cross-section and set-up at the Hagerbach Test Gallery (VSH)

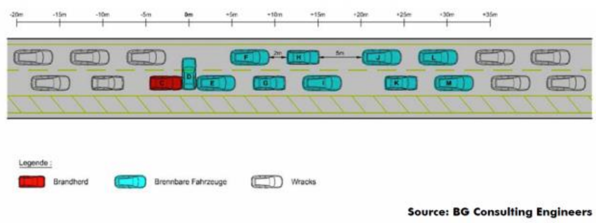

Figure 6: Test set-up for the A86 fire tests in the Hagerbach Test Gallery

Altogether 16 fire tests with an intermediate pressure water mist system (12.5 to 35 bar) as well as a high pressure system (> 35 bar) were carried out in two series. The tests were aimed mainly at assessing the efficacy of the systems in preventing fire flashing over from car to car [CETU 2010]. More extensive information and results for the executed tests were not published.

4.8 UPTUN (2002-2006)

The UPTUN research project (cost-effective, sustainable and innovative Upgrading methods for fire safety in existing TUNnels examined the application of water mist systems in tunnels in addition to basic research. The project entailing a budget of some € 13 million was sponsored within the EU's 5th framework programme (FP5) and carried out by 41 European partners from 14 countries.

Two extensive test programmes were undertaken in this project, namely fire tests in the Runehamar Tunnel in Norway (non-operative tunnel) and in the Vigolo Tunnel in Italy (operational tunnel). High pressure water mist systems were also taken into consideration in the process. Further results were obtained from test tunnels in Dortmund and Oslo (Norway).

4.8.1 DMT (2004)

Test series involving current fire fighting technologies in road tunnels were undertaken within the scope of the UPTUN project in the Deutsche Montan Technologie (DMT) test facility in Dortmund. The 150 m long test tunnel possessed a 9.7 m² cross-section. The test series were executed to determine the capabilities of the following systems [UPTUN 2008a]:

- Water curtain,
- Water spray system (drop size approx. 1 mm) and
- Low pressure water mist system.

A trough filled with diesel (pool fire) split into four compartments was used as the fire source. Each trough compartment was roughly 2 m² in area (1.5 x 1.2 m) enabling heat release rates of 5 to 20 MW to be produced. The trough was partly covered by a roof structure so that a car could be simulated (see Figure 7). Diesel floating on water was used as fuel, involving between 60 and 240 litres per attempted test duration.

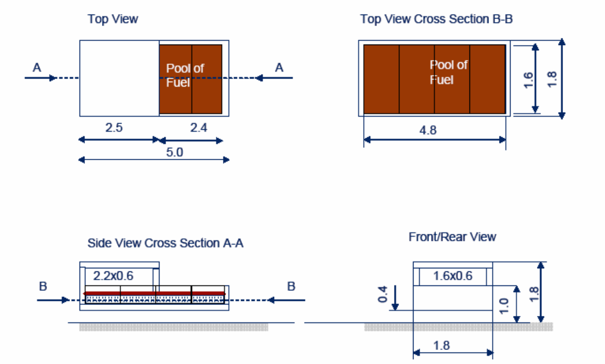

Figure 7: Fire load trough for the UPTUN tests at the DMT (2004) [UPTUN 2008a]

The cooling effect was clearly proved during the tests with the spray mist system: after activating the extinguishing system the temperatures at practically all measurement points in the test tunnel dropped almost to the temperature of the incoming fresh air. It was also confirmed that water spray systems are not capable of completely suppressing a fire. Even the smallest fire investigated involving 5 MW continued to burn at the original speed once the water spray system was deactivated. The effectiveness was not perceptibly affected by the maximal possible air speed of 3 m/s in the test tunnel, something that could be attributed to the drops produced by the water spray system.

The effect was also clearly proved during the tests with the low pressure water mist system, which required roughly 1/10th of the water consumed by the water spray system. However, the effect was less evident compared to the results of the water spray system. After activation of the water mist system, the temperatures measured in the ceiling zone still ranged from 100 to 200 °C. The temperatures in the central as well as the floor zone also remained at a higher level than during comparable tests involving the water spray system. The low pressure water mist system was also incapable of completely putting out the blaze. After deactivation the same re-ignition effect prevailed as in the case of the water spray system [UPTUN 2008a].

4.8.2 Test Series in Virgolo Tunnel (2005)

In 2005, fire loads of 10, 20 and 30 MW were produced within the scope of the UPTUN real fire tests in the Virgolo Tunnel on the Brenner motorway near Bolzano in South Tyrol. Figure 8 provides an overview of the tests carried out with a water mist system being applied in the 2nd and 3rd test [UPTUN 2005]

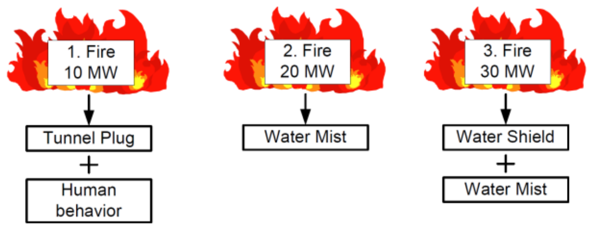

Figure 8: Test programme in the Virgolo Tunnel 2005

4.8.3 IF Oslo

Fire tests were also carried out also within the framework of the UPTUN research project in a test facility belonging to the IF Insurance Company. The test facility is located on the fringe of Oslo (Norway). The test tunnel possesses a cross-sectional area of 40 m² with a length of 100 m. The efficacy of two newly developed water mist systems for permanent installation in tunnels was tried out:

- a low pressure water mist system (< 12.5 bar) as well as
- a high pressure water mist system (> 35 bar).

The tests were executed with troughs filled with heptane with 20 MW fire loads as well as wooden pallets with 15 MW fire load. The speed of the longitudinal ventilation varied between 1.0 and 2.5 m/s [Cetu 2010], [UPTUN 2008b].

The fire tests on a 1:1 scale were directed more towards fire control than fire suppression and were tackled using the above mentioned low pressure and high pressure systems. Both liquid and solid matter fires using piled wooden pallets were applied as fire scenarios. Fire loads ranging from 10 to 20 MW were applied for the tests involving fire fighting systems under free combustion conditions.

The tests results revealed that both systems (low pressure and high pressure) were capable of reducing the heat release rates by 30 to 60 %. The effect of the systems depended on the size of fire, the applied spray nozzle, the amount of water sprayed and the fire's distance from the FFFS. The tests were not, however, able to verify that one system was more suitable than the other.

After activating the extinguishing systems, the downstream temperatures always dropped very quickly. The visual conditions downstream of the fire did not improve during the initial minutes after the fire broke out. Subsequently however, visibility increased as the spread of fire and the heat release rate were reduced by the water mist system. Activating the system caused the visibility to improve upstream resulting from backlayering of the smoke gas [Häggkvist 2009].

4.9 SOLIT (2004-2006)

The Safety of Life in Tunnels research project (SOLIT) was executed during the period from July 2004 to September 2006. It was sponsored by the German Federal Ministry of Economics and Technology (BMWi).
The goal of the SOLIT research project was to develop an economic water mist system for fighting fire in tunnels, and in the event of fire to

- improve evacuation conditions of persons,
- facilitate speedy and safe combating of fire by the fire brigade,
- reduce the spread of fire and minimise damage to the tunnel structure.

Based upon the concluded EU research project "UPTUN – cost-effective, sustainable and innovative Upgrading methods for fire safety in existing Tunnels" (please compare Chapter 4.8) it was examined how different safety systems mutually affect each other in a tunnel through theoretical studies and practical tests, e.g. water mist with fire detection or ventilation. Towards this end, an extensive programme was carried out on a 1:1 scale. In addition to this test programme, methods and recommendations were developed for integrating automatic fire fighting systems in tunnel safety systems.

A total of 53 major fire tests were undertaken within the scope of the SOLIT project with solid matter fires and liquid fires. The test results have not been published in detail but excerpts are explained in the public research report [Kratzmeir 2008].

4.10 A73 Tests (2005-2008)

The Dutch Ministry of Transport, Public Works and Water Management – Rijkswaterstaat (RWS) – undertook a compressed air foam system (Compressed Air Foam = CAF System) as a pilot project in two new tunnels (Roer Tunnel and Swalmen Tunnel) on motorway A73 in the south-east of the Netherlands in 2005 (please also see Section 3.1 – Netherlands). In this connection, fire tests on an original scale were undertaken in the Runehamar Tunnel in Norway at the end of 2005. The test results of the CAF systems executed were assessed as successful regarding their extinguishing effectiveness. [PIARC 2008].

4.11 SP Tests on Model Scale (2006)

A model study on a 1:23 scale was undertaken at SP in Sweden in order to improve basic understanding of the influence of water spray systems in tunnels with longitudinal ventilation (Fig. 9) [Ingason 2006].

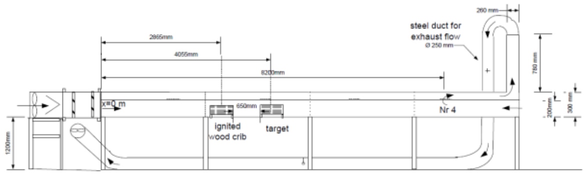

Figure 9: Schematic presentation of the test set-up

4.12 Building Research Establishment BRI (2006-2009)

The UK's Building Research Establishment carried out fire tests with cars in car parking facilities between October 2006 and March 2009 on behalf of the British government. Although the tests did not deal with tunnels, the results are notwithstanding of interest as they can at least in part be transferred. They indicate that a fire flashover in car parks from vehicle to vehicle can take place over 5 m distances. The application of sprinkler systems effectively prevented this happening and strongly suppressed the spread of fire. This action then enables the fire brigade to step in to completely extinguish the fire [Brinson 2010; Shipp 2007].

4.13 M30 Tests in Spain (2006)

In February 2006, a series of fire tests on an original scale were undertaken by the water mist system manufacturer Marioff in the test tunnel on the TST premises in San Pedro de Anos (Spain). These tests were geared especially to dimensioning fire fighting systems for the M30 motorway tunnel in Madrid, which has portions with extremely wide road cross-sections. The fire fighting system was tested combined with different tunnel ventilation systems. The results testify that under the prevailing general conditions, the three tested systems (water spray, water mist system and a combination of both in a so-called hybrid system) operate with practically the same effect thus decisively hampering fire and smoke development. The smoke was transferred into the exhaust duct through the smoke extraction flaps in the ceiling so that a semi-transverse ventilation system turned out to be the optimal solution within the scope of tests [Vuolle, Mawhinney 2007; Arvidson 2003].

In similar fashion to the above mentioned tests, the system manufacturer Fogtec carried out independent tests at TST (Spain) for the same project. These tests, also on a 1:1 scale, served FFFS dimensioning in the sections of the M30 Tunnel equipped by fogtec [fogtec 2007, Fernandez 2012].

4.14 Euro-Tunnel (2010)

Extensive tests were carried out during 2010 for the “SAFE Station” project in the Channel Tunnel described in Chapter 3.2.

The method of working of the high pressure water mist system (HDWN) for the Euro Tunnel had to be proven in accordance with the client’s specifications in keeping with the state of the art and the current standards for fire fighting systems in tunnels (e.g. UPTUN R251; NFPA 502) within the framework of fire tests on a 1:1 scale. It should be emphasised accordingly that comparable applications had never been previously safeguarded by fire fighting systems particularly in view of the ventilation conditions and the size of fire anticipated in the Channel Tunnel.

Furthermore, the manner of functioning of the fire detection and localisation system had to be verified. As a result, the Institute for Applied Fire Safety (IFAB) executed an extensive test programme in the San Pedro des Anos test tunnel in Spain. Experts from STUVA, efectis France and SETEC also participated. The Euro Tunnel cross-section and two trucks were simulated in this special test tunnel.

Mock-ups of trucks made of wooden pallets were applied as fire load over a distance of 40 m. As the effectiveness of a HDWN system given a fire of at least 150 MW had to be verified in this particular case, the truck mock-ups were ignited by diesel pool fires with an approx. initial fire load of 25 MW. Once 150 MW was reached or exceeded, the HDWN system was activated.

The ventilation flow was reversed when the HDWN system was activated so that the fire emergency ventilation’s manner of operation could be simulated at the same time.

More than 150 sensors were set up in the entire tunnel to monitor the temperatures, heat radiation, water pressure, gas concentrations and flow speed to collate the measurement values for the fire tests. A pile of wooden pallets was installed at both sides of the fire load at a distance of 1.50 m as a further target for checking how far the fire would spread.

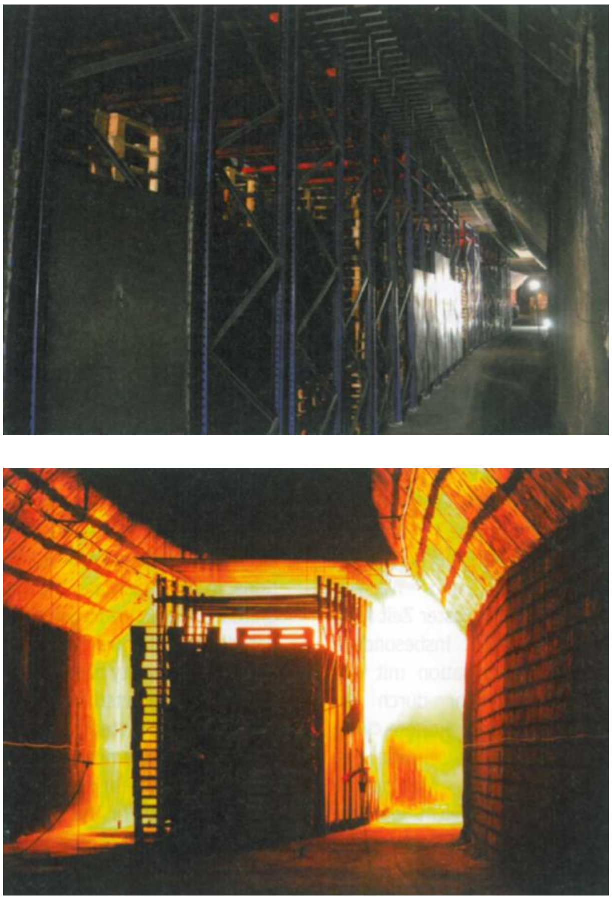

Figure 10: Test set-up and fire test [Kratzmeir 2010]

Once the fire load was ignited, the fire spread very quickly. This was due in particular to the high air speed in the tunnel’s longitudinal direction. A heat release rate of approx. 200 MW was attained within a few minutes. The temperatures and heat radiation were considerably reduced immediately after the high pressure water mist system was activated. An extremely rapid reduction of the heat release rate was achieved especially in combination with the reverse flow produced by the fire emergency ventilation. In this way, rapid activation of the HDWN system clearly reduced the effects of the fire on the tunnel infrastructure and in turn, possible damage. Furthermore it was also revealed that speedy and comparatively safe intervention by the fire brigade is possible with an activated HDWN system [Kratzmeir 2010].

Part 5 Conclusions and Research Requirements

5.1 Conclusions

The previously cited applications show in practice that in the recent past a number of different systems have been developed for fire fighting purposes and are available for use in tunnels. In addition, extensive fire tests have been carried out to try out the systems and establish their various pros and cons.

The most important conclusions obtained from pertinent literature research are collated as follows. They are based on the documents and details relating to the use of FFFS in tunnels contained in this report.

- FFFS are generally not applied with the aim of completely extinguishing the blaze. They are generally not capable of accomplishing this in the case of a fully developed fire. Instead the main goal is to control or suppress the fire in such a way until the fire brigade intervenes to provide the fire brigade the chance to fight the fire in the first place.
- The FFFS and the ventilation system must be geared to each other and provide mutual support as far as their effect on the fire and the spread of smoke are concerned.
- A smoke gas layer is destroyed within a relatively short time given the conditions prevailing in a tunnel regardless of whether a FFFS is applied.
- The most favourable activation time point for a FFFS should be established within the scope of a risk analysis. The FFFS should be controlled by the tunnel operations centre and the fire brigade should have the capacity to adjust it.
- FFFS application delays the fire development thus reducing the heat release rate in the event of fire and diminishes damage caused by heat and combustion. This results in lower costs for rectifying structural damage and shorter operational outages after fire incidents.
- FFFS prevent fire spreading to neighbouring vehicles and in this way can save the lives of people, who are unable to escape from the vicinity of the fire.
- Vehicle fires normally occur as a result of mechanical or electric malfunctions. Escaping liquids seldom form the primary cause.
- Liquid fires can be combated by applying water spray or water mist systems with smaller drops. Small drops effectively cool the fire without splashing upon contact with the incendiary substance or distributing as a result of pools being formed.

So far there have been standard rules for the installation and activation of FFFS. The pros and cons of such systems must be assessed individually for each project on the basis of a project-specific risk analysis. For this purpose, a balanced cost-benefit ratio is advisable. In addition, effective integration of the system in the tunnel's overall safety concept and equipment is essential.

5.2 Research Requirements

There is still a need for research to answer the following issues in spite of the extensive fire tests carried out so far with FFFS (as of 2010, when the primary status analysis was undertaken[4]):

- Fundamental interaction of fire smoke, ventilation and extinguishing agent
- Mathematical modelling and validation of the overall system including the FFFS by means of numerical CFD simulation
- Ascertaining and expanding the application limits of CDF models
- Determining the optimal ventilation system (longitudinal ventilation, transverse ventilation) combined with a FFFS under the specific general conditions of different types of tunnel to cater for optimal protection of persons and property.
- Influence and optimisation of nozzle formation and drop size on the effect of FFFS with respect to evacuation conditions
- Influence and potential of individual control of the release of water geared to the prevailing fire situation so that disadvantages, e.g. with regard to destroying the smoke gas layer are minimised
- Optimisation of the system design
- Minimising the maintenance costs
- Effects on saving persons (visual conditions, air quality, smoke gas washing, improving the deployment conditions for the fire brigade)
- Optimisation of the activation time point (automatic or manual) by the fire brigade or operations centre before, after or during evacuation)
- Potential interaction with hazardous goods
- Optimisation of the nozzle arrangement
- Potential for saving costs by minimising structural damage and tunnel outages.

The status analysis (AP2) was mainly produced when SOLIT2 got off the ground as the basis for all other work packages.

Answers were provided to some of the above mentioned issues by the SOLIT2 project. The results of the SOLIT2 research project have been published in the main document (Guidelines) and the corresponding appendices. However, in the case of all test results the problem exists of their limited applicability to other general conditions, such as tunnels and extinguishing systems.

[4] The main work on the status analysis was executed at the start of the project. At the end of the project and also afterwards (as of November 2012) topical information was also integrated in the final SOLIT2 reports.

Part 6 List of Sources

6.1 Illustrations

Where not otherwise specified the rights of the illustrations belong to the partners of the research consortium that were involved in producing this document.
Where other illustrations have been used a note regarding the complete source information appears in the caption. Their use is governed by the German Copyright Act §51 Nr.1.

6.2 Bibliography

The listed sources can be accessed for academic researches after request to the project coordinator, as far as they are publically available and non-confidential.

Arditi (2010), e-mail 23.08.2010. STUVA, Survey on fixed fire fighting systems.

Arghirou (2010), e-mail 25.10.2010. STUVA, ITA Survey on fixed fire fighting systems in Romania.

Arvidson, Magnus (2003), Alternative Fire Sprinkler Systems for Roadway Tunnels SP report 2004:05, SP Fire Technology.

ASTRA (2000), Bundesamt für Strassen, Schweiz, Tunnels Task Force. Schlussbericht, 13th Australien Tunneling Conference. 23.05.2000.

Aquasys (2010), High Pressure Water Mist System for Road Tunnels, Linz, 28.06.2010

Aquasys (2010b). Vortrag: Rauchgaskühlung Gleialmtunnel, Sicherheit und Belüftung von Tunnelanlagen, Graz. 04.05.2010.

Bagis (2010), e-mail 01.09.2010. STUVA, List of Australian FFFS Tunnels.

BAST (2011), oral information. 24.01.2011. STUVA, PIARC Technical Committee C4.4.

Bettelini, M. und N. Seifert (2009), ITA, Automatic fire extinction in road tunnels. State of the art and practical application. 2009, Budapest World Tunnel Congress.

Blennemann, Friedhelm (2005), Brandschutz in Fahrzeugen und Tunneln des ÖPNV. Fire protection in vehicles and tunnels for public transport, Blaue Buchreihe des VDV 11, Alba-Fachverlag, Düsseldorf.

Both (2010), e-Mail 23.08.2010. STUVA, Survey on fixed fire fighting systems.

Brinson, Alan (2010), Active Fire Protection in Tunnels, in Proceedings from the Fourth International Symposium on Tunnel Safety and Security, edited by A. Lönnermark, and H. Ingason.

CEN European Comittee for Standardization (Deutsche Fassung CEN/TS 14972:2011). TS - Technical Specification, Ortsfeste Brandbekämpfungsanlagen - Feinsprüh-Löschanlagen - Planung und Einbau(DIN CEN/TS 14972). Deutsche Fassung CEN/TS 14972:2011.

Cetu (2010), Water Mists in Road Tunnels. State of knowledge and provisional assessment elements regarding their use.

Del Rey (2010), e-mail 25.08.2010. STUVA, Survey on fixed fire fighting systems.

Eskesen (2010), e-mail 11.10.2010. STUVA, ITA Survey on fixed fire fighting systems.

EU Komission (2008). Entscheidung der Kommission, TSI Eisenbahntunnel Entscheidung über die technische Spezifikation für die Interoperabilität bezüglich „Sicherheit in Eisenbahntunneln“ im konventionellen transeuropäischen Eisenbahnsystem und im transeuropäischen Hochgeschwindigkeitsbahnsystem(Aktenzeichen K(2007) 6450). 7.3.2008.

Europäisches Parlament und Rat (1997), 97/23/EC Pressure Equipment Directive.

Femern Sund (2011), Consolidated Technical Report, Draft 2011, Online Adresse: http://www.femern.com/material-folder/documents/2011-publications/consolidated-technical-report, Zugriff am 26.04.2012

Fernandez, S.; Del Rey, Ignacio (2012), Large Scale Fire Tests for the "Calle 30 Project", in ISTSS 2012.

FM Approvals (2009), Approval Standard for Water Mist Systems(FM 5560). March 2009.

fogtec, Fogtec protection of M4 Metro Line in Budapest, Online Adresse: http://www.fogtec-international.com/news/PDF/1204_News.pdf, Zugriff am 25.07.2012.

fogtec (2007), Fogtec Fire suppression System put into operation in M30 Tunnels of Madrid.

fogtec (2009), Tunnel news Sept. 2009. Protection of New Tyne Crossing by Fogtec high-pressure water mist technology, Zugriff am 12.11.2010.

fogtec (2010), Dartfort River Crossing. Themse-Querung von Londons Ringautobahn M25, Zugriff am 27.05.2011.

FSV (2010). Merkblatt, RVS 09.02.51 - Merkblatt Tunnelausrüstung Löschsysteme, Ortsfeste Löschsysteme (09.02.51). 01.06.2010, FSV.

FSV (2011), RVS 09.02.22 – Tunnelausrüstung (09.02.22). 01. November 2011, FSV.

Georgieva (2010), e-mail 08.10.2010. STUVA, Survey on fixed fire fighting systems, Bulgarien.

Grov (2012). 10.02.2012. STUVA, Installation of fixed Fire firghting Systems in Norwegian road tunnels.

Haack, A. (2007), STUVA, Tunnel Fixed Fire Suppression Systems. Symposium Introduction and Overview. 2007, Las Vegas.

Haerter, A. (1994). Vortrag: , Fire Tests in the Ofenegg-Tunnel in 1965, Fires in Tunnels, SP Conference - Borås, Sweden, Borås, Sweden. 10-11 October 1994.

Häggkvist, A. (2009), Luleå University of Technology, Fixed Fire Fighting Systems in Road Tunnels. An overview of current research, standards and attitudes. 03.11.2009, Lund.

Haraldsson (2010), e-mail 11.10.2010. STUVA, ITA Survey on fixed fire fighting systems.

Heyn, J. (2010), Brandschutz in Schienenfahrzeugen, ZEVrail, 134(6-7).

Highway Agency (1999), Design manual for roads and bridges, Design of road tunnels (BD 78/99, Volume 2, Section 2, Part 9). August 1999.

Hjelm, E., H. Ingason, und A. Lönnermark (2010). SP (Ed.), Effective Firefighting Operations in Road Tunnels(SP Report 2010:10). 2010, Boras.

Horvath (2010), Letter. 13.09.2010. STUVA, Survey fixed fire fighting systems.

Ingason, H. (2006). SP Technical Research Institute of Sweden (Ed.), Model Scale Tunnel Fire Tests. Brandforskprojekt 406-021(56). 2006.

ITA COSUF (2011), Updated survey of existing regulations and recognised recommendations. (operation and safety of road tunnels). 21.07.2011.

Iwata, H., and Y. Ota (2001). Vortrag: , Tokyo-wan Aqualine - Experience of Traffic and Safety. Tokyo Bay Tunnel, 1st International Conference on Traffic and Safety in Road Tunnels, Hamburg. 28/29.05.2001.

Järvinen (2010), e-mail 08.09.2010. STUVA, Survey on fixed fire fighting systems.

Jonker (2010), Letter. 27.09.2010. STUVA, Answers Netherlands for state owned road tunnels.

Kokkala, M. (1990), Technical Research Centre of Finland, Espoo, Extinguishment of liquid fires with sprinklers and water sprays analysis of the test results. 1990.

Kratzmeir, S. (2008), Safety of Life in Tunnels, Forschungsbericht SOLIT - Wassernebelanlagen in Strassentunneln. 26.02.2008.

Kratzmeir, S. (2010), Brandschutz im Eurotunnel, Tunnel(7), Page 33–36.

Lemaire, A., and V. J. A. Meussen (2008), Effectis Nederland, Effects of water mist on real large tunnel fires: Experimental determination of BLEVE-risk and tenability during growth and suppression. June 2008.

Le Parisien (2011), Premier feu dans le tunnel de l'A86, Online Adresse: http://www.leparisien.fr/abo-seine-et-marne-sud/premier-feu-dans-le-tunnel-de-l-a86-23-12-2010-1201668.php, Zugriff am 20.01.2011.

Lundström (2011), e-mail 27.04.2011. STUVA, Norra Länken.

Marioff, Referenzen Wassernebel Systeme, Online Adresse: http://www.marioff.com/references/transportation/en_GB/transportation/, Zugriff am 01.06.2011.

Märkische Allgemeine Zeitung online (2012), One-Seven stattet Thueringer Poerzbergtunnel mit automatischer Brandschutzanlage aus, http://www.maerkischeallgemeine.de/cms/ziel/604050/DE?article_id=2276217, Zugriff am 20.10.2011.

Mawhinney, R. N. (2007), Hughes Associates, Computational Fluid dynamics modelling of water mist systems on large HGV fires in tunnels. 2007.

Meijer, G. J. und Meeussen, M. P., New development for a fixed fire fighting system in road tunnels, Tunnel 5/2008, S 52-54

Ministere de l´equipement (2000), Circulaire interministerielle N° 2000- 63 du 25 aout 2000 relative à la sécurité dans les tunnels du réseau routier national(EQUR001042C). 25.08.2000.

Ministry of the Interior (2000), Ministry of Establishment, Transport and Housing, France, Appendix 2 to inter-ministry circular no 2000-63 of 25 August 2000. Technical instruction relating to safety measures in new road tunnels (Design and Operation).

Ministry of Transport (2002), Directorate-General for public works and water management, Project "Safety Test". Report on fire tests. 08.2002, Netherlands.

NFPA 25, Standard for the Inspection, Testing and Maintenance of Water-Bases Fire Protection Systems.

NFPA 20, Standard for the Installation of Stationary Fire Pumps for Fire Protection.

NFPA 750, Standard on water mist fire protection systems, National Fire Protection Association, Quincy, Mass.

NFPA 13, Installation of Sprinkler Systems 2010.

Ota (2010), e-mail 17.08.2010. STUVA, ITA Survey on fixed fire fighting systems.

PIARC (1999), Technical Committee on Road Tunnel, Fire and smoke control in road tunnels(05.05 B). 04.10.1999.

PIARC (2008), Technical Comittee 3.3 Road Tunnel Operation, Road Tunnels, an assessment of fixed fire fighting systems(2008R07)

Ponticq (2010), e-mail 08.12.2010. STUVA, Survey on fixed fire-fighting systems.

Railway Gazette, Eurotunnel demonstrates €20m suppression system, Online Adresse: http://www.railwaygazette.com/nc/news/single-view/view/eurotunnel-demonstrates-EUR20m-fire-suppression-system.html, Zugriff am 16.02.2011.

Schneider, Ulrich; Horvath, Johannes (2006), Brandschutz-Praxis in Tunnelbauten. Brandverhalten, Brandschutzmaßnahmen, Sanierung, ISBN 3-89932-037-9, Bauwerk-Verlag, Berlin.

Sergui, F., und P. E. Luchian, Parsons Brinkerhoff, The Memorial Tunnel Fire Ventilation Test Programme.

Shipp, M. (2007). Vortrag: , Fires in enclosed Cap Parks. 11.01.2007.

Solit2 (2009), Safety of Life in Tunnels 2. Vorhabensbeschreibung Verbundprojekt 19S9008D. 2009.

Statens Vegvesen Norwegen (2010), Håndbok 021 Vegtunneler. März 2010, Norwegen.

Sturm (2010), e-mail 24.08.2010. STUVA, Survey on fixed fire figting systems.

Tarada, F. (2009), Emerging trends in tunnel fire suppression, Eurotransport(5), 43–49.

UPTUN (2005), "Cost effective sustainable and innovative UPgrading Methods for Fire Safety in existing TUNnels", D62 Real Scale Tunnel Fire Tests Virgolo Tunnel. 03.10.2005.

UPTUN (2006), "Cost effective sustainable and innovative UPgrading Methods for Fire Safety in existing TUNnels", D52b Fire growth models: Water-based suppression systems. 24.10.2006.

UPTUN (2008a), "Cost effective sustainable and innovative UPgrading Methods for Fire Safety in existing TUNnels", D231 Evaluation of Current

Mitigation Technologies in Existing Tunnels. 09.2008.
UPTUN (2008b), “Cost effective sustainable and innovative UPgrading Methods for Fire Safety in existing TUNnels”, D241 Development of new innovative technologies. 09.2008.
UPTUN (2008c), “Cost effective sustainable and innovative UPgrading Methods for Fire Safety in existing TUNnels”, D252 Engineering Guidance for Water Shield Mitigation System for the Protection of Tunnels and SubSurface Facilities. 09.2008.
Vägverket (2004), Vägverkets allmänna tekniska beskrivning för nybyggande och förbättring av tunnlar ATB Tunnel 2004. 25.11.2004, Schweden.
Vuolle, P., Water mist concept, effective choice for improving safety in road tunnels.
Vuorisalo, M., Marioff Corporation Oy, Water mist concept for road and rail tunnels.