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MASTER'S THESIS

Fixed Fire Fighting Systems in Road Tunnels

An overview of current research, standards and attitudes

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Preface

I would like to thank Magnus Arvidson and Haukur Ingason at SP for their guidance and for being a solid source of information. I especially direct my gratitude to my supervisor Magnus for the much appreciated time he has spent at giving me a good platform from which I was able to start my work from.

Family and friends, I thank you all for your support through hard times. It has been, in many ways, a hard and sometimes brutal year. But the aftermath has really been refreshing.

Sundsvall, Sweden in August 2009

Andreas Häggkvist

Abstract

The way of looking at the use of Fixed Fire Fighting Systems (FFFS) in road tunnels in Europe has changed during recent years due to several catastrophic tunnel fires (CTF). Tests have been conducted which have proven some statements from the past to be wrong but this is still a field that has to be studied further to gain a more accepted status in Europe.

When installing a water based FFFS in a road tunnel it is important to understand that the system's objective is to suppress or control the fire and not necessarily to extinguish it. Furthermore, the engineer must have an understanding on how the FFFS will do this. Smaller droplets will attack the flame and larger droplets will attack the fuel. This knowledge is important for example concerning hazardous goods. The FFFS should be designed so that it operates together with the ventilation system to get maximum effect on suppress or control abilities and the possibilities for self evacuation.

Standards and guidelines to be used regarding FFFS in road tunnels are the national standards combined with NFPA 502 and the guidance published by UPTUN.

Japan and Australia are two countries with experience of using FFFS in road tunnels. Especially Japan has a long experience with FFFS using it for about four decades. Europe has a lot to learn from these countries not only when it comes to the use of FFFS in road tunnels but also on how to regard its role in general.

Sammanfattning

Sättet att betrakta användningen av FFFS i vägtunnlar i Europa har förändrats under de senaste åren på grund av ett flertal katastrofala tunnelbränder, även kallade CTF (Catastrophic Tunnel Fires). Experiment har visat att några argument mot användningen av FFFS i vägtunnlar har varit felaktiga, men fler experiment måste utföras för att FFFS i vägtunnlar ska få en mer accepterad status i Europa.

Vid installationen av vattenbaserade FFFS i vägtunnlar är det viktigt att förstå att systemets mål är att undertrycka eller kontrollera branden och inte nödvändigtvis att släcka den. Vidare måste ingenjören ha en förståelse för hur systemet gör detta. Små droppar kommer att attackera flamman och stora droppar attackerar bränslet. Denna kunskap är viktig till exempel när det rör sig om farligt gods. FFFS bör vara designad så att det arbetar tillsammans med ventilationssystemet för att få maximal effekt vad gäller brandbekämpningsegenskaper och för att öka evakueringsmöjligheterna.

Standarder och anvisningar att följa vad gäller FFFS i vägtunnlar är de nationella standarderna tillsammans med NFPA 502 och anvisningen publicerad genom UPTUN.

Japan och Australien är två länder som har erfarenhet av användandet av FFFS i vägtunnlar. Speciellt Japan har lång erfarenhet efter att ha använt FFFS i omkring fyra årtionden. Från dessa länder har Europa mycket att lära inte bara när det gäller användandet av FFFS utan även dess roll som helhet.

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1 Introduction

1.1 Background

Fixed Fire Fighting Systems (FFFS) are an issue very widely discussed around the world today whenever a new road tunnel is to be built or an upgrading of an existing road tunnel is to be performed. The need for an overview of information concerning FFFS in road tunnels has therefore been requested by SP Fire Technology in Sweden.

This report is written as a thesis in Fire Protection Engineering at Luleå University of Technology in Sweden assigned by SP Fire Technology.

1.2 Aim

This report aims to give the reader an overview of current attitudes, research progress, existing standards and general ideas concerning FFFS in road tunnels.

It aims to satisfy readers with different levels of knowledge in this field. The only thing that is required is that the reader is not totally new to the concept of sprinklers or fire dynamics.

1.3 Delimitations

The focus has been on information concerning water based FFFS in operational road tunnels; not tunnels under construction or other forms of tunnels. The main focus is at traditional sprinklers, water spray and water mist systems without added agent. There are not any references available to water curtain systems. Furthermore, when it comes to standards and regulations, the author has deliberately chosen not to go to deep into the standards but instead tries to describe them in a more general way. The author’s intention is therefore to introduce the reader to these standards and encourage him or her to read them separately.

Detailed material properties as for examples nozzles, detection systems and so on will not be handled in this report. The author is for that purpose recommending the reader to read, as an example, the standards mentioned in this report.

1.4 Method

The material has been gathered from articles, reports and presentations handed out by SP Fire Technology or collected from different search databases via the Internet. The Internet has also been used to find relevant homepages of organisations related to FFFS or road tunnels. Furthermore, materials from standards have been used.

2 Fire dynamics in road tunnels

2.1 Why know about fire dynamics in road tunnels?

It is of importance to understand the basic principles of fire dynamics in tunnels, when working with FFFS, because it contributes to the understanding of for example transport of toxic smoke and fire spread. Especially, as criticisms in the past involve fire dynamics such as smoke stratification[1]. The water spray can pull down the smoke and that in turn can affect the evacuation process. Furthermore, it is of importance to know the conditions when FFFS are activated so the preferences can be evaluated in relations to the general research results presented in this report.

Also, the best performance of the FFFS is achieved if the ventilation and the FFFS are working together. See chapter 7 for more information about FFFS and ventilation in practice.

2.2 Tunnel fires vs. open fires and compartment fires[2]

A tunnel fire is not an open fire and neither is it a compartment fire. It is more confined than an open fire, and it is more open than a compartment fire.

2.2.1 The difference between tunnel fires and open fires

There are some important differences between a tunnel fire and an open fire.

- The confined enclosure in tunnels tends to make the heat feedback to the burning vehicles more effective than in open fires. Experiments show that the heat release rate (HRR) in tunnel fires increases with a factor of up to 4 compared to the same material burning in an open fire.

- The available amount of oxygen in tunnel fires is not as great as in open fires. The fire can develop to either a fuel controlled fire or a ventilation controlled fire. The fuel controlled fire makes unreacted oxygen pass by the burning vehicles and the ventilation controlled fire produces a large amount of toxic gases and products of incomplete combustion. Basically, all oxygen is consumed and fuel rich gases leave the tunnel openings.

- As a fire evolves in a tunnel it interacts with the airflow of the ventilation and creates aerodynamic disturbance in the tunnel flow. This may cause buoyancy effects like throttling of airflow and also cause backlayering in the ventilation system, which is when hot gases and smoke from the fire forces itself back ways through the system. This

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[1] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

[2] H Ingason. *Fire dynamics in tunnels. [book auth.] A Beard and R Carvel. THE HANDBOOK OF TUNNEL FIRE SAFETY.* London : Thomas Telford Publishing, 2005.

can spread toxic gases and smoke far from the original fire source and complicate fire fighting procedures

2.2.2 The difference between tunnel fires and compartment fires

Tunnel fires differ from compartment fires in the following ways:

- In tunnels the natural ventilation is govern by the fire size, the tunnel slope, the cross-sectional area, length, type of tunnel (concrete, blasted rock) and meteorological conditions at the entrance and not the opening factor as in compartment fires. The excess of air available in tunnels is also much greater than in relations to compartments. Forced ventilation in form of mechanical ventilation is often used in tunnels. These factors influence the combustion efficiency and gives significantly different HRR than compartment fires.

- Flashover cannot with current definition occur in tunnel fires but only in compartment fires. However, another phenomenon with dramatic effects may occur if the tunnel fire is under-ventilated and a ventilation system is switched on during the fire. The flames suddenly increase in length and size and the fire can easily spread forward in the direction of the preheated vehicles. This can be dangerous to fire fighters and people trapped in the tunnel.

- The formation of stratified smoke differs between tunnel fires and compartment fires. In its early stage the tunnel fire can have similar stratified smoke layers as in the early stage of a compartment fire. There are an upper buoyant smoke layer and a smoke free layer below, if there is essentially no longitudinal ventilation. Gradually this smoke layer will descend the further away from the fire it gets. Depending on the length of the tunnel this smoke will reach the tunnel floor. The distance from the fire at which this may occur depends on the fire size, height of the tunnel cross-section, the perimeter and the tunnel type. The stratified smoke layer will gradually dissolve when the longitudinal ventilation gradually is increased. On the upstream side of the fire a backlayering of smoke is created and on downstream side of the fire the degree of stratification of the smoke is governed by the heat losses to the surrounding walls and by the turbulent mixing of the moving cold layer and the opposite buoyant smoke layer.

2.3 The smoke stratification

The smoke stratification in tunnels is depending on which type of ventilation to be used. This report’s main focus is not ventilation but it is important to understand the stratification of the smoke and toxic gases and how the FFFS may have an impact on that movement. The ventilation’s contribution to the smoke stratification is here illustrated with principal sketches of two types of ventilation; longitudinal and transversal.

2.3.1 Longitudinal ventilation

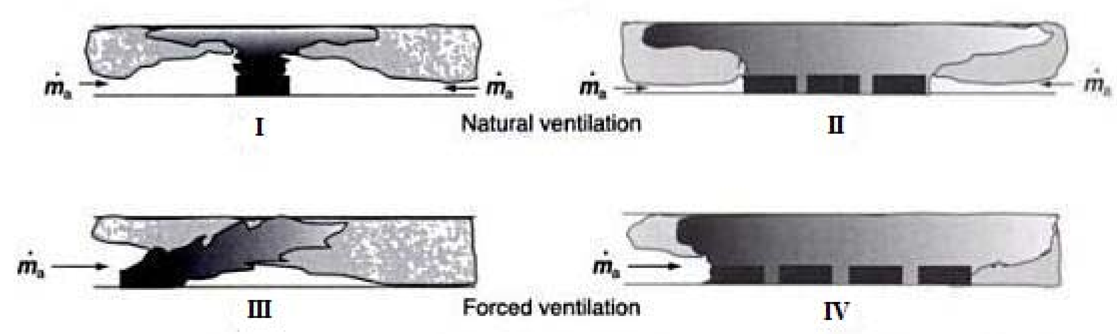

Figure 1: I and II illustrates a natural draught. III and IV are sketches of forced ventilation.[3]

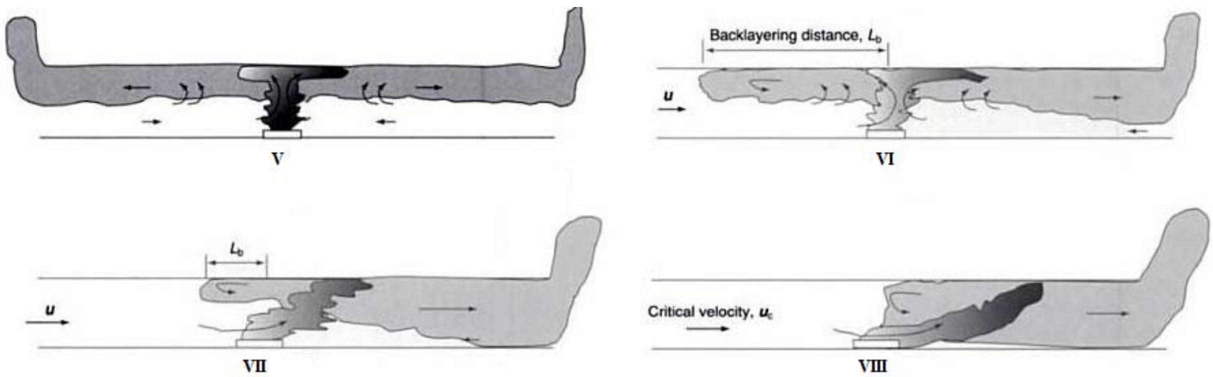

Figure 2: Illustration V is showing stratification at typically 0-0.3 m/s, VI at about 1 m/s, VII at 1-3 m/s and VIII at velocity greater than the critical velocity (>3m/s).[4]

The longitudinal ventilation is important in regards in which direction the fire spreads and the smoke stratification. Larger air velocities tend to limit the backlayering upstream the fire and downstream it tends to mix the two smoke layers earlier then at low velocities. Critical velocity is defined as the air velocity that prevents any backlayering.

2.3.2 Transversal ventilation

This type of ventilation is aiming to keep the stratified smoke near the ceiling. The smoke is ventilated from the tunnel via the tunnel ceiling or the top of the walls.[5] One other type of ventilation is semi-transversal which uses a combination of longitudinal and transversal ventilation.

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[3] H Ingason. Fire dynamics in tunnels. [book auth.] A Beard and R Carvel. *THE HANDBOOK OF TUNNEL FIRE SAFETY.* London: Thomas Telford Publishing, 2005.

[4] ibid.

[5] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

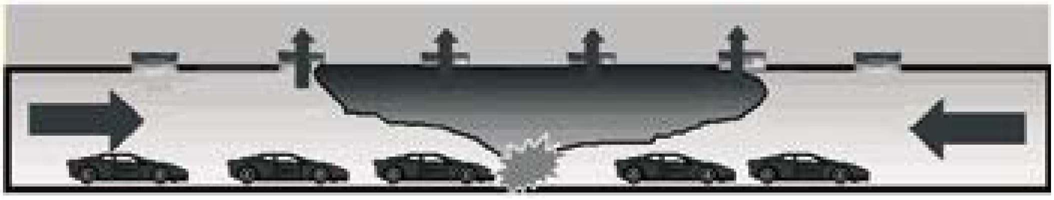

Figure 3: Transversal ventilation in road tunnels.[6]

2.4 Potential heat release rates

The potential peak heat release rate (HRR) that can develop in a road tunnel fire is difficult to estimate. It depends on the type and the amount of traffic, which in turn can depend on the time of the day. The type of traffic that is most severe and difficult to predict is the Heavy Gods Vehicles (HGV) that contain much higher fire loads than a passenger car. The amount of burning material affects the duration of the fire but tests also show that they generate a significant higher HRR. The risk for fire spread to adjacent vehicles increases as well. A large-scale test with one HGV loaded with ordinary combustible EUR wood pallets resulted in a peak HRR up to 200 MW.[7] The peak HRR in the road tunnel fire at Mt Blanc in France was estimated to have reached 380 MW and involved 14 HGVs and 9 cars.[8] The duration of the Mt Blanc fire was 3-5.5 hours during the period of intensive fire. Also, the hazardous goods that HGVs potentially can be carrying are needed to be considered (see chapter 8).

The typical design fire is a fire involving an electrical fire and/or combustible material related to ordinary traffic. Pool fires are as a following result considered more unusual.[9]

[6] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

[7] H Ingason and Lönnermark, A. *Heat Release Rates from Heavy Goods Vehicle Trailers in Tunnels.* Fire Safety Journal, 2005. **40**: p. 646-668.

[8] H Ingason.*Fire development in Catastrophic Tunnel Fires (CTF).* Borås : International symposium on Catastrophic Tunnel Fires, 2003.

[9] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations, 2008.

3 Theory and purpose

3.1 What are FFFS?

FFFS stands for Fixed Fire Fighting Systems and are defined by PIARC (see section 5.1), for road tunnels, as

> *… fire fighting equipment permanently attached to the tunnel consisting of a piping system with a fixed supply of water or extinguishing agent which when operated has the intended effect of reducing the heat release and fire growth rates by discharging the water of extinguishing agent directly on the fire. Examples of fixed fire fighting systems include sprinkler, deluge and mist systems.*[10]

3.2 The theory of water based FFFS

The most natural choice of FFFS in road tunnels is those who are water based, and for this reason, the report is focused on such systems. FFFS in road tunnels using gaseous agents has never been considered and should never be considered for obvious reasons. From now on in this report whenever FFFS are mentioned it refers to water based FFFS unless stated otherwise.

The different kinds of water based FFFS is divided into three groups in this report: traditional sprinklers/water sprays, water mist systems and FFFS with an added foam agent.

3.2.1 Traditional sprinklers/water sprays and water mist systems

Traditional sprinklers/water sprays and water mist systems rely purely on water to suppress or control the fire. The water can transport heat directly from the flame, cool the hot combustions products or cool the surface of the fuel. Even the water vapor contributes by reducing the oxygen concentration in the fire area.[11] All these characteristics combined make water a good fire suppression and control agent. Whether the droplets will cool the flames or the surface of the fuel is depending on the size of the droplets[12], as shown in Figure 4.

[10] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

[11] J Brenton, Drysdale, D and Grant, G. *Fire suppression by water sprays.* Progress in Energy and Combustion Science. 2000, **26**: pp.79-130

[12] R Wighus. *Fire growth models - Effect of water-based fire-fighting systems.* UPTUN, 2006. Project no: GRD1-2001-40739.

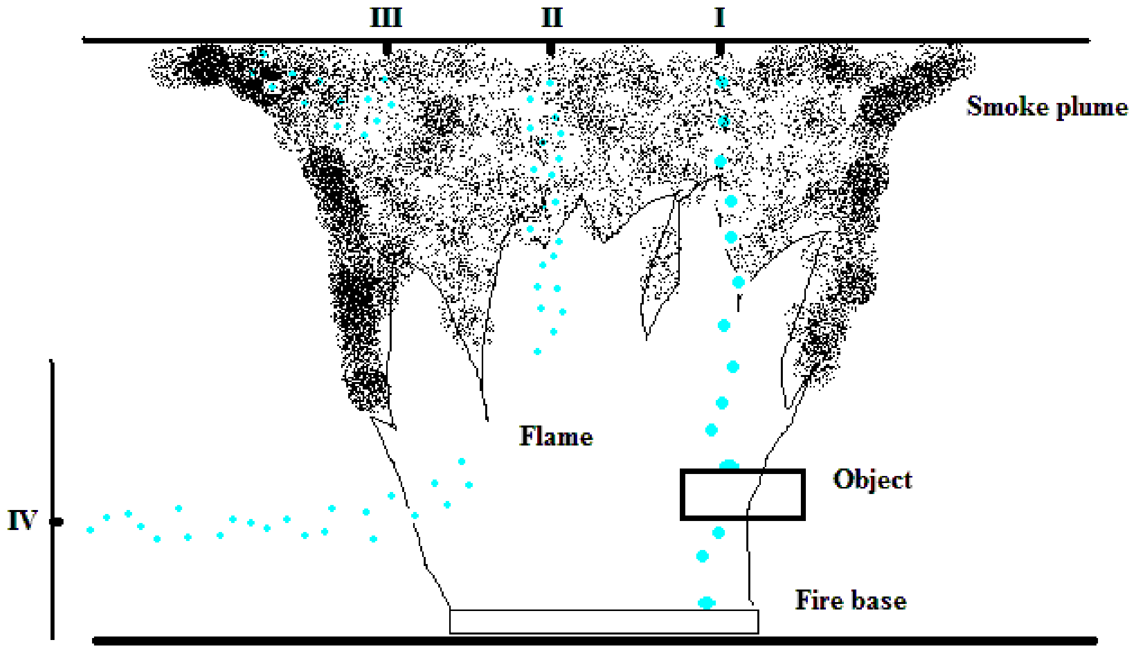

Figure 4: Destiny of droplets of different sizes when introduced into a flame and its smoke plume[13].

I. Droplets of this size are from a typical traditional sprinkler, for instance the Large-Drop Sprinkler. The droplets primarily cool objects and/or the fire base, or pre-wet un-burnt material. The products of combustion is not cooled much, relative to the mass flow of the water, because the surface area of the droplets is too small.[14] These kinds of droplets are not suitable for pool fires. Especially, when the burning liquid is not soluble in water and the relative density is smaller than 1, i.e. the liquids density is less than that of water. This can cause the fire to spread on top of the water discharge.

II. These droplets penetrate a bit into the flame and fire plume. They primarily cool and inert the combustion zone, reduce the combustion and eventually extinguish the fire. This droplet size is used in water mist systems. The large surface area of the droplets is the main reason for the superior cooling effects of water mist systems.[15]

III. The characteristics of these droplets are that they have very little penetration abilities but instead evaporates quickly, which will cool and inert the smoke. Droplets of this size are used in total flooding protections systems and with so called flashover prevention systems.[16] They have very little effect on open fires and their effects on tunnel fires are unknown.

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[13] R Wighus. *Fire growth models - Effect of wat*er-based fire-fighting systems. UPTUN, 2006. Project no: GRD1-2001-40739.

[14] ibid.

[15] ibid.

[16] ibid.

IV. The droplets evaporate in the combustion zone and do not need to penetrate an opposite directed smoke plume. The water spray has to be mounted close to the possible fire source and the location of the base of the fire needs to be predictable. This method is seldom used.[17]

Water mist systems are defined as a water spray where 99 % of the droplet volume consists of droplets with diameter less than 1 mm (also see Annex A).[18]

3.2.2 FFFS with an added foam agent

FFFS with an added foam agent creates a film of foam that covers the burning fuel. This film cools the fire surface and separates the fuel from the oxygen which suffocates the fire. Foam is especially useful when extinguishing pool fires. The foam is created by introducing air in a water solution mixed with a foam concentrate and needs a smaller water discharge density than FFFS using only water. Foam is divided into the following three groups[19]:

1. Low-expansion foam – expansion up to 20 times
2. Medium-expansion foam – expansion from 20 to 200 times
3. High expansion foam – expansion from 200 to approximately 1000 times

Further discussions concerning foam and the limitations of water as an extinguishing agent for pool fires are given in chapter 8.

3.3 The purpose of FFFS[20]

The purpose of the FFFS in a road tunnel is determined by the fire protection objectives which can be simplified to either fire suppression or fire control. The differences between the two objectives, as discussed in previous section, are the amount of water needed to be used, the possible use of a foam agent, the positioning of the sprinklers and the principle of the activation system. The more general differences between the two fire protection objectives are listed in the next page.

[17] R Wighus. *Fire growth models - Effect of wat*er-based fire-fighting systems. UPTUN, 2006. Project no: GRD1-2001-40739.

[18] National Fire Protection Association. *NFPA 750: Standard on Water Mist Fire Protection Systems 2003 Edition.* National Fire Protection Association, 2003.

[19] National Fire Protection Association. *NFPA 16: Standard for the Installation of Foam-Water Spray Systems 2007 Edition.* National Fire Protection Association, 2006.

[20] M Arvidson *Alternative fire sprinkler systems for roadway tunnels.* Borås : International Symposium on Catastrophic Tunnel Fires, 2003.

Fire suppression

- Limit the HRR from fires in vehicles.
- Suppression of flammable pool fires
- Limit the formation of toxic gases.

Fire control

- Control the HRR from fires in vehicles.
- Prevent fire from spreading from vehicle to vehicle.
- Protect the tunnel construction from heat exposure to minimize damage.
- Provide possibilities for manual fire fighting

4 The basic design

4.1 Introduction

Some fundamental requirements for water based FFFS are independent of the fire protection objectives discussed in section 3.3. Based on that, the engineer has to consider the following concepts before engineering the FFFS in the road tunnel[21, 22]:

- The water network.
- The positioning of the nozzles.
- The water consumption and the droplet size.
- Agents that may be added to the water. (See subsection 3.2.2.)
- The detection and the activation of the system.

4.2 The water network

When talking about the water network it refers to the way the water is being transported to the fire. For FFFS, that is through a network of fixed pipes and then delivered by sprinklers or nozzles in the fire area.

4.3 Sprinklers and nozzles[23]

The sprinklers or nozzles are mostly preferred to be mounted at the ceiling (over-head mounted). High level mounted sprinklers or nozzles have a better cooling effect on combustion gases but have the disadvantage that they reduce the visibility and may influence the evacuation.

The FFFS is preferable to be of the open deluge type. The reason for this, and not to be an automatic (bulb) wet-pipe or dry-pipe system, is that too many sprinklers or nozzles may be activated at the same time and overtake the water supply. Two large spill fire experiments conducted at Factory Mutual Global have shown that 178 respectively 164 automatic sprinklers activated at the same time because of the spread of the hot gases. The length of the deluge zones most be based on the tunnel width and the capacity of the water supply. It should although be mentioned here that any type of testing of automatic bulb sprinkler system has not

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[21] M Arvidson Alternative fire sprinkler systems for roadway tunnels. Borås: International Symposium on Catastrophic Tunnel Fires, 2003.

[22] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

[23] Arvidson, 2003.

been conducted in tunnels. One could consider the effects of longitudinal ventilation on the activation sequence and on the risk for losing the control of the system.

Furthermore, the droplet size may affect the choice of type of sprinkler or nozzle.

4.4 The water consumption

In tunnels where the surface can be uneven it can be more appropriate to speak of the total water consumption divided by the volume tunnel that is in the sprayed zone. The droplet size affects the water consumption in a way that smaller droplets use less water than larger droplets. The typical water consumption for larger droplets (i.e. droplet diameter around 1 000 µm) is 2-4 $l/min/m^3$ and 0.2-1 $l/min/m^3$ for water mist systems.[24]

For pool fires, the usage of a foam agent also reduces the total amount used water compared to systems relaying on only water.[25]

Also, the length of the deluge zones affects the total water consumption. Larger deluge zones needs more water but it reduces the number of control valves.[26]

The duration time of the water supply should be based on the duration times of the expected fire scenarios and added with an appropriate safety factor.[27]

4.5 Detection and activation

Smoke detectors are not suitable for road tunnels because of smog that is created in the tunnel by the vehicles. Fixed temperature or rate-of-rise heat detectors (spot detectors or linear detectors) are better suitable.[28]

The activation system should have a delay time so the operator can determine if it's a false alarm or an actual fire in the tunnel by using for an example a close-circuit television system (CCTV). This short delay of activation also increases the possibilities for evacuation of the tunnel.[29] Have in mind that the cameras often are positioned high up in the tunnel to get a good view, which means that they in case of a fire will early on be covered with smoke depending on the distance to the fire source, see section 2.3.

[24] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

[25] M Arvidson. Alternative fire sprinkler systems for roadway tunnels. Borås: International Symposium on Catastrophic Tunnel Fires, 2003.

[26] ibid.

[27] ibid.

[28] ibid.

[29] ibid.

5 *Organizations, standards and guidance*

5.1 PIARC[30]

The world road association PIARC was established 1909 and is a none-profit making and none-political association. PIARC stands for Permanent International Association of Road Congress and was granted consultative statues to the Economic and Social council of the United Nations in 1970. Members of the association are governments, regional authorities, collective members and individual members. PIARC has members in 142 countries and 117 member governments. Furthermore, it has national committees in 37 countries.

The mission of PIARC:

- *being a leading international forum for analysis and discussion of the full spectrum of transport issues, related to roads and road transport,*
- *identifying, developing and disseminating best practice and giving better access to international information,*
- *fully considering within its activities the needs of developing countries and countries in transition,*
- *developing and promoting efficient tools for decision making on matters related to roads and road transport.*

To achieve the mission the association:

- creates and coordinates Technical Committees.
- organizes the World Road Congress and as a complement to this the Winter Road Congress. These congresses are organized every fourth year in a member country. PIARC also organize technical seminars.
- publishes a number of documents including a quarterly magazine called Routes/Roads.

The Technical Committees are tasked to produce reports on best practice and recommendations in their respective field. These committees consist of engineers and experts appointed by member countries. When concerning FFFS in road tunnels the technical committee of interest is the one called Road Tunnel Operations.

The author recommends to use the PIARC homepage, http://www.piarc.org, for searching of updates related to FFFS in road tunnels. When writing this report, the next World Road Congress will be held in Mexico City, Mexico, September 26-30 2011.

[30] PIARC. *WORLD ROAD ASSOCIATION - MONDIALE DE LA ROUTE.* [Online] [Cited: 6 July 2009.] http://www.piarc.org/en/.

Furthermore, the 5th International Conference on Tunnel safety and ventilation is to be held in Austria, May 3-5 2010.

5.2 NFPA[31]

NFPA stands for National Fire Protection Association. Its main office is situated in USA but it also has international offices. The organization is an international non-profit membership organization founded in 1896. It has 81 000 members in more than 100 countries. NFPA is of good repute and accepted throughout the world when it comes to fire prevention and public safety.

The code development process is handled by more than 6 000 volunteers from diverse professional backgrounds who serve on 230 technical code and standard development committees. Through the entire process interested parties are encouraged to provide these technical committees with ideas and input. NFPA members vote on proposed and revised codes and standards.

NFPA standards are foremost used in the USA but as said earlier highly accepted throughout the world. When it comes to FFFS in road tunnels the standards to be mainly used, depending of what kind of FFFS, are NFPA 13, 15, 16, 502 and 750. These standards can be purchased from their homepage; http://nfpa.org.

Relevant to comment on the oncoming subsections is that NFPA makes a distinction between sprinkler systems and water spray systems. In this report the author has chosen to mostly incorporate the terms sprinkler systems and water spray systems in the term FFFS, and not in general make the detailed distinction as NFPA does. Water spray systems can in a simple way be described as a group of nozzles that are being triggered simultaneously (deluge system) and are designed to have a more specific water discharge distribution over the protected area or surface. Automatic sprinklers on the other hand are design to activate one by one. So when talking about FFFS in road tunnels it’s often referring to water spray.

5.2.1 NFPA 502: Standard for Road Tunnels, Bridges and Other Limited Access Highways[32]

This standard stipulates the minimum requirements for life safety and fire protection in road tunnels which are categorized by their length. Chapter 7 is the chapter concerning road tunnels and Annex E provides considerations for the incorporation of water based fixed fire fighting systems in road tunnels. NFPA 502 also standardizes tunnel safety requirements that are not directly related to FFFS.

NFPA 502 refers to more standards than mentioned earlier considering inspections and maintenance. Especially, NFPA 11: Standard for Low-, Medium-, and High-Expansion Foam,

[31] National Fire Protection Association. *National Fire Protection Association - The authority on fire, electrical, and building safety.* [Online] 2009. [Cited: 6 July 2009.] http://www.nfpa.org.

[32] National Fire Protection Association. *NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways 2008 Edition.* National Fire Protection Association, 2007.

NFPA 18: Standard on Wetting Agents and NFPA 25: Standard for Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems.

5.2.2 NFPA 13: Standard for the Installation of Sprinkler Systems[33]

The standard goes through many fundamentals concerning hardware, design and requirements. NFPA 13 works as a base for NFPA 15, 16 and 750. It shall apply to the following:

- Character and adequacy of water supplies.
- Selection of sprinklers.
- Fittings
- Piping
- Valves
- All materials and accessories, including the installation of private fire service mains.

5.2.3 NFPA 15: Standard for Water Spray Fixed Systems for Fire Protection[34]

This standard gets a bit more specialized and often refers to NFPA 13. So the best usage is to combine NFPA 13 and 15.

> *Water spray is applicable for protection of specific hazards and equipment and shall be permitted to be installed independently of, or supplementary to, other forms of fire protection systems.*

5.2.4 NFPA 16: Standard for the installation of Foam-Water Sprinkler and Foam-Water Spray System[35]

NFPA 16 only applies for systems using low expansion foam. Furthermore, it does not stipulate were foam systems are required.

5.2.5 NFPA 750: Standard on Water Mist Fire Protection Systems[36]

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.

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[33] National Fire Protection Association. *NFPA 13: Standard for the Installation of Sprinkler Systems 2007 Edition.* National Fire Protection Association, 2006.

[34] —. *NFPA 15: Standard for Water Spray Fixed Systems for Fire Protection 2007 Edition.* National Fire Protection Association, 2006.

[35] —. *NFPA 16: Standard for the Installation of Foam-Water Spray Systems 2007 Edition.* National Fire Protection Association, 2006.

[36] —. *NFPA 750: Standard on Water Mist Fire Protection Systems 2003 Edition.* National Fire Protection Association, 2003.

5.3 UPTUN guidance [37]

During the European Research Project UPTUN on behalf of the European Commission the Engineering Guidance for Water Based Fire Fighting Systems for the Protection of Tunnels and Subsurface Facilities was written. It provides information on design, installation and maintenance of Water Based Fixed Fire Fighting Systems to be used in tunnels. The guidance discusses all aspects from water supply to water drainage. The UPTUN guidance refers to NFPAs standards mentioned earlier but also refers to other related standards. These are the European standards as for example EN 12259-1 Components for sprinkler and water spray systems, which are useful to read.

5.4 National standards

There are no national standards written exclusively for FFFS in road tunnels in the European countries.[38] However, there are usually national standards/regulations concerning building and upgrading of tunnels but these are in some cases only partly related to FFFS. One example is the Swedish Tunnel 2004[39], which only states that if FFFS is to be installed the design of the system shall be evaluated. Tunnel 2004 partly also refers to NFPA 502.

When installing a FFFS in a road tunnel the author recommends to use the NFPA, European and/or UPTUN standards as a complement to national regulations/legislations and partial standards as, for an example, the Swedish Tunnel 2004.

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[37] The Research Project UPTUN. *Engineering Guidance for Water Based Fire Fighting Systems for the Protection of Tunnels and Subsurface Facilities, R251.* The European Commission, 2007.

[38] N.P Höj. *Fire Safe Design - road tunnels.* FIT. Technical Report - Part 2.

[39] Vägverket. *Vägverkets allmänna tekniska beskrivning för nybyggnad och förbättring av tunnlar. Tunnel 2004.* Borlänge : Vägverket, 2004. ISSN 1401-9612.

6 Road tunnels with FFFS

6.1 Europe

In Europe there is no country currently installing FFFS on a regular basis.[40] There are, however, an increasing number of new tunnels that are fitted with FFFS. One example in Europe is the Mona Lisa Tunnel in Austria that uses a class 1 (Annex A) deluge water mist system. An automatic fire detection system is linked to the FFFS, which detects the fire and alerts the rescue service. The fire and rescue service then decide on site if the water mist system is to be turned on. The Dutch Ministry of Transport, Public Works and Water Management has conducted a pilot application of Compressed Air Foam Systems (CAFS) in road tunnels. The idea is to investigate the possibility to install CAF FFFS in the two road tunnels near Roermond, Netherlands. In the Vielha Tunnel in Spain the system is designed to be activated manually from a control room and intended to be activated after evacuation of the tunnel.[41]

Given on next page is a short compilation of road tunnels in Europe with FFFS installed.

[40] National Fire Protection Association. *NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways 2008 Edition.* National Fire Protection Association, 2007.

[41] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

Table 1: A compilation of road tunnels with FFFS in Europe.[42, 43,44]

Country	Name of tunnel
Austria	Mona Lisa Tunnel Felbertauern Tunnel
France	A86 Tunnel
Italy	Brennero Tunnel Virgolo Tunnel
The Netherlands	Roermond Tunnel
Norway	Válreng Tunnel Fløyfjell Tunnel
Spain	M30 Tunnels Vielha Tunnel
Sweden	Tegelbacken Tunnel Klara Tunnel

6.2 North America

Currently there are six tunnels with FFFS in the USA. The decision of installing FFFS in these tunnels was based on the facts that it was originally proposed that vehicles transporting hazardous goods should be allowed unescorted trough the tunnel and to protect the structure above the tunnel.[45]

[42] National Fire Protection Association. *NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways 2008 Edition.* National Fire Protection Association, 2007.

[43] M Arvidson. Alternative fire sprinkler systems for roadway tunnels. Borås: International Symposium on Catastrophic Tunnel Fires, 2003.

[44] The Research Project UPTUN. *Workpackage 2 Fire development and mitigation measures D241 - Development of new innovative technologies.* The European Commission, 2008.

[45] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

Table 2: A compilation of road tunnels with FFFS in North America. Tunnels with FFFS that has an added foam agent are marked with an asterisk.[46]

Location	Name of tunnel
Boston, Massachusetts	CANA Northbound* CANA Southbound*
Seattle Washington	Battery Street I-90 First Hill Mercer Island* Mt. Baker Ridge* I-5 Tunnel*
Vancouver, British Columbia	George Massey Tunnel

6.3 Australia

The Australian view is that small fires, if not suppressed, easily evolves into large uncontrollable fires, particularly since this type of fire development is more typical than the occurrence of instantaneously large fires. Furthermore, it is desirable to use the capacity of the FFFS during the first few minutes of an incident to minimize rate of fire growth and to reduce the probability of large fires. These positive factors outweigh the perceived disadvantages of smoke destratification, increased heat flux from humidified air and steam generation.[47]

In a number of road tunnels the FFFS are used as follows:[48]

- There are only urban tunnels with significant length that has FFFS installed.
- The use of FFFS has changed from just intended to protect the tunnel structure to include emergency response for human life protection. The change of use is restricted to tunnels with:
  - control rooms with operators responsible for tunnel safety and not merely traffic management.
  - video cameras and/or automated incident detection system that allows the operators to make a rapid and precise event localization and event assessment.

[46] National Fire Protection Association. *NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways 2008 Edition.* National Fire Protection Association, 2007.

[47] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

[48] ibid.

Table 3: A compilation of road tunnels with FFFS in Australia.[49, 50]

City	Name of tunnel
Adelaide	Adelaide Hills Tunnel
Brisbane	North/South Busway Tunnel
Melbourne	City Link Tunnel Mitcham/Frankston Tunnel
N/A	North/South Tunnel
Perth	Graham Farmer Tunnel
Sydney	Sydney Harbour Tunnel M5 East Tunnel Lane cove Tunnel Eastern Distributor M4 Tunnel

6.4 Japan

Japan is a country where about 70 % of its land consists of steep mountains with great geological variations. Today more and more tunnels are built and they also get longer. Japan has suffered from serious accidents involving tunnel fires[51] and this has resulted in a unique experience using FFFS for a period that has extended over more than four decades[52]. They have approximately 80[53] road tunnels equipped with FFFS and in April 2001 Japan had road tunnels at 8 331[54] locations.

Activation of the FFFS was in the past decided by the owner/operator. The activation was made directly when the fire was detected or after the tunnel had been evacuated. Today, the proper activation time is evaluated by a risk analysis.

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[49] National Fire Protection Association. *NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways 2008 Edition.* National Fire Protection Association, 2007.

[50] Wikimedia Foundation, Inc. *Wikipedia The Free Encyclopedia.* [Online] [Cited: 7 July 2009.] http://en.wikipedia.org/wiki/Freeways_in_Australia.

[51] H Mashimo and Mizutani, T. *CURRENT STATE OF ROAD TUNNEL SAFETY IN JAPAN.* Japan : Public Works Research Institute and Advanced Construction Technology Center, 2003.

[52] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

[53] M Arvidson Alternative fire sprinkler systems for roadway tunnels. Borås: International Symposium on Catastrophic Tunnel Fires, 2003.

[54] Mashimo and Mizutani, 2003.

The safety design in Japan follows its National Safety Standard of Emergency Facilities on Road Tunnel.[55] For Japanese classification of road tunnels see Annex B.

[55] H Mashimo and Mizutani, T. *CURRENT STATE OF ROAD TUNNEL SAFETY IN JAPAN*. Japan : Public Works Research Institute and Advanced Construction Technology Center, 2003.

7 A series of selected fire tests

7.1 Large-scale tunnel fire tests

In this section some large-scale tunnel fire tests are discussed. Large-scale tunnel fire tests require a lot of planning, a great deal of funding and a proper test facility. The test tunnel needs to have a relative proper length and width to simulate an operational road tunnel, and that and the rest of the infrastructure surrounding such a facility is hard to come by.

7.1.1 Water mist systems

In this subsection experiments from two different projects, SOLIT and UPTUN, are handled.

7.1.1.1 SOLIT[56]

During the SOLIT (Safety of Life in Tunnels) project over 50 large-scale tests were conducted. The aim of the project was to study the performance of water mist systems regarding:

I. Fire control and fire spread

II. Self-rescuing conditions for people inside the tunnels

III. Fire fighters approach to the fire

IV. Protection of the building structure.

Also, the interaction between other safety systems as ventilation and fire detection were studied.

The following fire scenarios were established:

- Pool fires – with a partly covered surface and generating 35 MW.
- Solid truck fire load – a test mock up of a common truck load made out of idle pallets generating potentially 180 MW.

The tests were conducted in the test tunnel San Pedro des Anes in Spain which is 600 m long. The tunnel represents a common two-lane road tunnel and has the possibility to study fires with both longitudinal and semi-transversal ventilation.

[56] M Lakkonen and Kratzmeir, S. *Road Tunnel Protection by water mist systems - Implementation of full scale fire test results into a real project.* Stockholm, Sweden : FOGTEC – Fire Protection, 2008. Third International Symposium on Tunnel Safety and Security.

The following results were observed:

I. Fire control and fire spread

The water mist system was activated as early as possible by an external fire detection system. The development of the fire was reduced significantly and the maximum fire size was much smaller compared to a free burning fire.

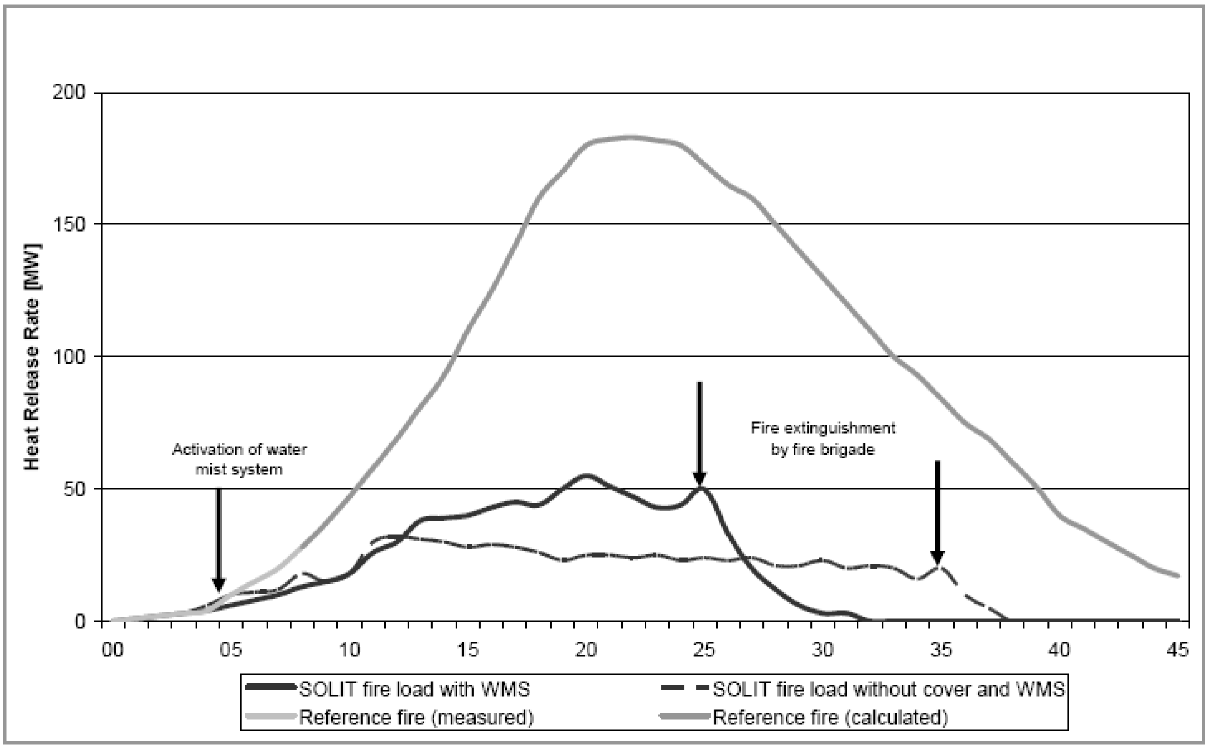

Figure 5: A comparison of HRR between the fire load with the water mist system activated and a free burning fire.

The fire was still growing at the beginning of the activation of the water mist system (WMS) because of the canvas covering the fire load.

Fire spread was controlled with targets and with the water mist system activated no spread could be observed 5 m downstream of the fire load. In the St. Gotthard tunnel fire and the Runehamar fire tests a fire spread of distances more than 50 m were reported.

II. Self-rescuing conditions for people inside the tunnels

Toxic gases are typically spreading fast throughout a tunnel during a road tunnel fire. But, the production of smoke was reduced due to an early activation of the water mist system. In contradiction to opinions in the past it was shown that the smoke stratification was not completely destroyed. A layer of the toxic gases could still be observed even after the activation of the system due to a still existing temperature difference in the tunnel cross section.

Also, because of the cooling effect and the limitation of the HRR the effectiveness of the ventilation system was increased.

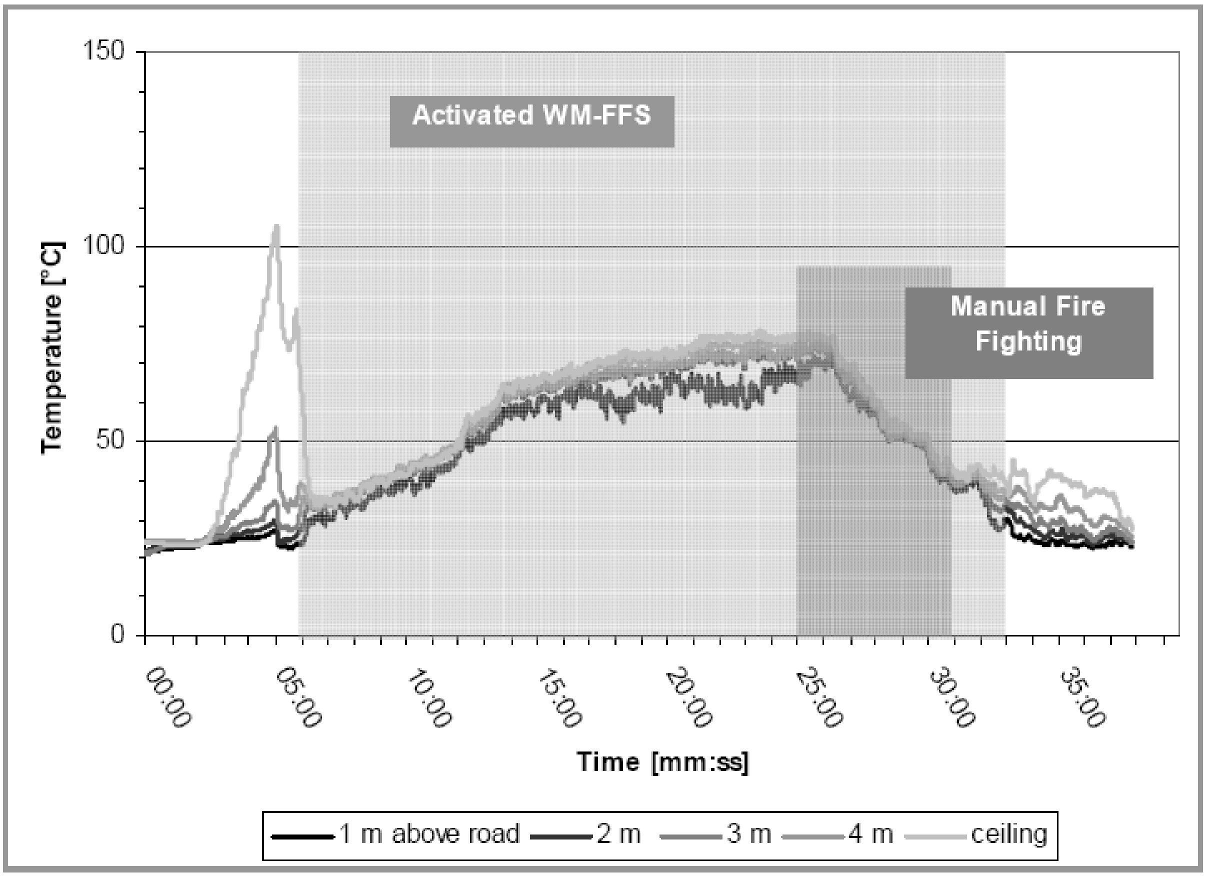

Figure 6: Temperatures at 20 m downstream from the covered fire load.

III. Fire fighters approach to the fire

Due to high temperatures and radiation, experience has shown that it is extremely difficult to approach tunnel fires. In the St. Gotthard fire the fire services arrived a few minutes after the fire had started but it was impossible to fight the fire because of the intense heat and radiation.

In the tests the cooling and the shielding effect of water mist made it possible for the fire fighters to approach the fire scenarios at the most intense phase of fire development and to extinguish the fires within minutes without problems. No evidence of exposure to hot water vapor was reported. During additional two weeks training and tests with the Madrid fire brigade using real fire loads like cars, tires etc. no reports on exposure to hot water vapors were reported.

IV. Protection of the tunnel structure.

Large tunnel fires cause huge damages on the tunnel structure and the facilities inside. Early activation of a water mist system can reduced damages greatly and limits it to a few meters. Thereby, reducing cost for repairs and the closing time of the road tunnel.

7.1.1.2 UPTUN[57]

The main objective of the UPTUN project was to find new upgrading methods for fire safety in existing tunnels and large-scale tests with water mist systems were then carried out. The large-scale fire tests were focused on fire control rather than fire suppression and conducted with low pressure and a high pressure water mist systems. Two different fire scenarios were used in the tests; pool fires and solid fuel fires in the forms of a stack with idle wood pallets. The fires had a potential severity in the order of 10 MW to 20 MW under free burning conditions. The tests showed that both types of systems were able to reduce the heat release rates of the fires in the range of 40% to 70%. The efficiency of the systems was dependent on the fire size, nozzle type, water discharge density and the location of the fire. It was not possible to determine whether or not one type of system performed better than the other. After the activation of the systems, gas temperatures were reduced rapidly downstream the fire. The visibility downstream the fire was not improved during the first minutes, however, when the fire size and the HRR were reduced by the water mist system the visibility also increased. Backlayering was reduced after the activation of the system which rendered in better visibility upstream the fire.

During UPTUN’s mission to demonstrate the performance of water mist systems in large scale, a section of the Virgolo tunnel in Italy was fitted with a high pressure water mist system. Because of the successful demonstration a complete high pressure water mist system was installed as a part of the upgrading of the tunnel.

Conclusions from the project as a whole were that every system is unique and that testing and documentation are important in order to ensure its quality. The system needs to be able to work together with other mitigation measures such as the ventilation system. Installation of these kinds of systems is associated with high investment cost and costs due to maintenance. These cost has to be regarded and under control. FFFS will improve ventilation conditions and eventually improve the ability to evacuate the tunnel and reduce the thermal exposure to the tunnel construction. Thereby reducing costs after a tunnel fire.

7.1.2 Foam[58]

In 2005 a series of tests were conducted in the Runahamar Tunnel in Norway to evaluate the effectiveness of FFFS using compressed air foam (CAF). Two types of simulated tunnel fires were arranged in the tunnel which is 6 m high, 9 m wide and 1600 m long. Test fire one consisted of solid fuel in form of idle wood pallets with a volume of 100 m^3 and with a HRR up to 300 MW. The second test fire was a diesel pool fire with an area of 100 m^2 and a HRR of 200 MW. The FFFS in the test used a water density of 5.6 $L/m^2/min$ that was activated 2-3 minutes after ignition for the pool fire and 5-10 minutes after ignition for the idle wood pallet fire. During the test a ventilation system was running to maintain the longitudinal ventilation air flow at 2-3 m/s.

[57] The Research Project UPTUN. *Workpackage 2 Fire development and mitigation measures D241 - Development of new innovative technologies.* The European Commission, 2008.

[58] Liu, Z.G et al. *Challenges for Use of Fixed Fire Suppression Systems in Road Tunnel Fire Protection.* Ottawa : Institute for Research in Construction and National Research Council of Canada.

The FFFS successfully extinguished the large pool fire and controlled the solid fire, but did not extinguish it. Upstream of the fire the air temperature was cooled down to 50˚C and downstream the temperature it was cooled to below 100˚C. Thus, preventing fire spread and generating an acceptable working environment for fire fighters. The visibility in the tunnel was completely lost before the discharge of the FFFS. No significant formation of steam and no deflagration were experienced during the suppression of the fires

7.1.3 Sprinklers/Water Sprays[59]

During 2000 and 2001 fourteen large-scale fire tests were conducted in the Second Benelux Tunnel near Rotterdam in the Netherlands. The objective of the tests was to investigate:

I. the spread of heat and smoke, and its effect on means of escape.

II. the longitudinal ventilation's contribution to the development of the fire when it comes to HRR and the tenability conditions (does not include the effects of toxic gases) in the tunnel.

III. the effect of large drop deluge sprinklers on the fire development, the formation and spread of steam and smoke, the temperature in different parts of the tunnel and the cooling effect on vehicles near the fire that are not burning.

IV. the efficiency of linear fire detection systems with regard to their accuracy of locating the source of the fire and the detection time.

V. the qualitative visibility of several types of escape route signage.

VI. CFD methods accurateness in predicting fires in tunnels.

The test tunnel had a rectangular cross section with the width 9.8 m, the height 5.1 m and a length of 980 m. The intended traffic direction was unidirectional. The slope of the tunnel was maximum 4.4 % and its lowest point was in the middle of the tunnel. The tube had two traffic lanes. Six fans were installed in the upstream tunnel opening to be able to create longitudinal ventilation air flow up to 6 m/s. The test area was located 265 m from the downstream portal. Measurements were taken in an area ranging from 50 m upstream to 200 m downstream of the fire.

The tests conducted within category III, tests 11-14, are summarized in this report. Test 11 consisted of one van loaded with 18 wood pallets having a total weight of 400 kg. Tests 12 and 13 had a covered truck load and test 14 had an open truck load. The open truck load consisted of 72 wood pallets and six tires having a total weight of 1 600 kg. The covered truck loads consisted of 36 wood pallets with 4 tires on top and had a total weight of 800 kg stacked under an aluminum cover with the rear side open.

The open deluge system was designed for a water discharge density of 12 l/m^2/min and consisted of two sections. Section 1 that was directly above the fire and section 2 that was

[59] Y Kenyon and Lemaire, T. *Large Scale Fire Tests in the Second Benelux Tunnel.* Fire Technology 2006., 42: pp. 329–350.

downstream of the fire right beside section 1. Both sections consisted of two rows of nozzles. The sections were activated immediately or delayed depending on purpose of the test (see Annex E).

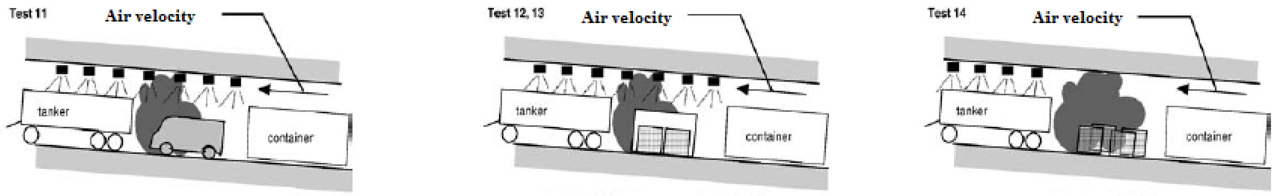

Figure 7: Illustrations of test 11 (left), tests 12 and 13 (middle) and test 14 (right).

The conclusions made from the use of the sprinklers were:

- No increased thermal exposure could be observed at these HRR. Instead the use of the sprinklers considerably reduces the temperature of the smoke/air and the vehicles adjacent to the fire. This reduces the probability of fire spread significantly. Smoke temperatures downstream do not attain the lethal tenability limit and steam production was insignificant.
- Visibility was reduced such that escape routes will become hard to find.
- For all the tests conducted in the Second Benelux Tunnel none of the tenability limits for heat were exceeded at a distance of 50 m or more downstream from the fire.
- For small truck fires, fatal conditions because of radiation can be expected within a radius of 10 m from the fire.
- Fire spread from a small truck to a nearby car at a distance of 10 m may occur if sprinklers are not used.

7.2 Model scale tunnel fire tests

It is much easier and less expensive to do model scale test than large-scale tests of the magnitude that is required. In this section results and conclusions from one selected model scale tunnel fire test are presented. No explanation to the scaling theory will be presented in this report.

7.2.1 Water spray[60]

This experiment was performed in a scale of 1:23 and the water spray system consisted of 12 nozzles mounted at the ceiling. An electrical axial fan with a maximum capacity of 2000 m^3/h created the longitudinal ventilation air flow inside the tunnel. The speed of the fan could be controlled via an electrical device coupled to the motor. Between the tunnel entrance and the fan a plywood box was mounted to create a uniform flow at the entrance of the tunnel. The swirls created by the fan were damped by filling the plywood box with straw fibers. The

[60] H Ingason. *Model Scale Tunnel Fire Tests - Sprinkler.* Borås : SP Swedish National Testing and Research Institute, 2006. SP Report 2006:56, ISBN 91-85533-49-1.

nominal longitudinal ventilation velocities used in the tests were 0.42 m/s and 0.62 m/s which correspond to the large-scale velocities of 2 m/s respectively 3 m/s.

The model tunnel was 10 m long, 0.4 m wide and 0.2 m high which correspond to large scale dimensions 230 m long, 9.2 m wide and 4.6 m high. The exhaust system consisted of steel and had a nominal flow rate of 0.12 m^3/s which in large scale is 304 m^3/s. The model tunnel itself consisted of non combustible 15 mm thick boards (Promatect H).

The fire load simulating HGVs were wood cribs consisting of pine, see Figure 8. The distance from the top of the wood crib and the ceiling was about 0.045 m.

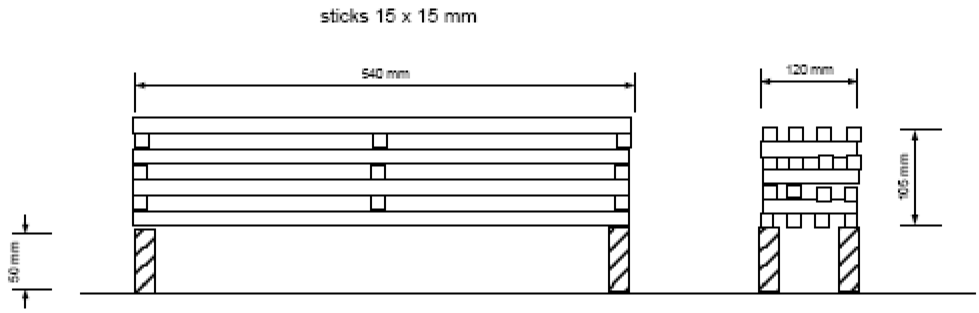

Figure 8: Wood cribs used in the model scale tunnel tests.

The water spray system consisted of two parallel 1600 mm long steel pipes with an outer diameter of 12 mm running horizontally above the main ceiling of the tunnel. The nozzles used were Lechler Hollow Cone Spray 212.085.11.CC.00.0 and creates a fine uniform hollow spray cone. The flow rates were adjusted to correspond to the water discharge densities 3.5 mm/min, 5 mm/min and 6.7 mm/min in large scale. The nominal flow rates of the water spray system were 0.35 l/min, 0.5 l/min and 0.67 l/min. These flow rates correspond to 888 l/min, 1268 l/min and 1700 l/min in large scale.

Every crib used in the tests was dried over night in a furnace. The ignition source consisted of a fiberboard cube soaked in heptane. A total of 13 tests were carried out. Two of these were free burn tests and eleven tests were conducted with either the water spray system or a water curtain system (this report only refer to the water spray tests). The system was activated one minute after ignition which corresponds to 4.8 minutes in large scale. The HRR were 50-75 MW in large scale. Downstream the fire source a wood crib was placed as a target with a distance of 0.65 m which is 15 m in large scale. This target was used to determine if fire spread would occur.

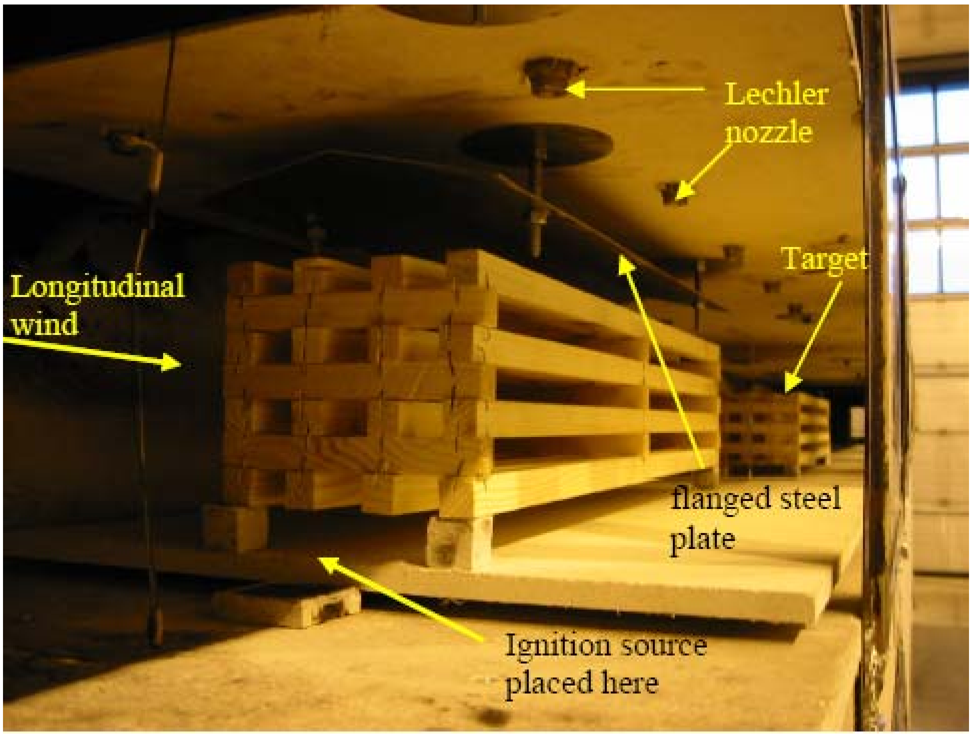

Figure 9: A photo of the test setup.

The tests showed that no fire spread to the target occurred when the flow rate was equal or higher than 0.35 l/min (888 l/min). Charring of the target happened when the water flow were 0.35 l/min and 0.5 l/min (1268 l/min) but not with 0.67 l/min (1700 l/min). The critical water flow for extinguishment, i.e. the amount water needed to extinguish the burning crib, was estimated to be 0.86 l/min.

7.3 Other interesting fire tests

In this section results and conclusions from some selected fire tests and computerized simulations are discussed which are related to FFFS and its usage in road tunnels.

7.3.1 Water discharge densities[61]

The Technical Research Centre of Finland (VTT) has done tests using ten different flammable liquids and seven different sprinklers and nozzles. The tests were conducted without using any foam agent with the water.

The pool fires varied in sizes from 0.4 m^2 to 12 m^2 and consisted of liquids with flashpoint ranging from -6˚C to 234˚C. The nozzle to pool height varied from 3 m to 8 m.

Conclusions from the tests:

- The water extinguished the fire in most cases by cooling the fuel below its flashpoint. Liquids with a lower flashpoint could only be extinguished by blowing off the flame from the surrounding area of the fuel surface. Liquids with greater flashpoint than 60˚C

[61] M Arvidson *Alternative fire sprinkler systems for roadway tunnels.* Borås : International Symposium on Catastrophic Tunnel Fires, 2003.

could be extinguished easier. At lower flashpoints the cooling of the fuel surface and the production of water vapor are not as effective.

- Large pool fires need greater water discharge densities than smaller pools.
- Sprinklers and nozzles situated high above the pool fires caused sputtering due to the largest water drops which can be unfavorable. In this case the fire may only be extinguished after the water is turned off.
- It was observed that not only the delivered water density was a good measurement of capacity of extinguishment. A fire was controlled with 7 mm/min with one type of nozzle and with another nozzle type the same fire was not even controlled with 34 mm/min. Also, medium and high velocity spray nozzles worked less effectively than sprinklers of the same nominal orifice size.

Despite this the following can be said. Sufficient protection can be assumed when it comes to immiscible hydrocarbon liquids with a flashpoint higher than 60˚C if sprinklers with water density discharges higher than 25 mm/min are used and for liquids with flashpoints higher than 120˚C, 10 mm/min are probably sufficient. This refers to exposed fires.

7.3.2 CFD-simulations

Computer simulations that replaces large-scale test should not be expected to be available in the near future. If computer simulations are to be used it should only be to evaluate data that has been gather from such large-scale tests.[62] Having this in mind the author has excluded CFD-simulations in the report. The results are not reliable in most cases and therefore of no interest for this report.

[62] The Research Project UPTUN. *Engineering Guidance for Water Based Fire Fighting Systems for the Protection of Tunnels and Subsurface Facilities,* R251. The European Commission, 2007.

8 Hazardous goods

Transport of Hazardous goods trough road tunnels increases the risk-scenario and that must be considered. The sizes of the risks depends on the tunnel characteristics as example the length and the location. Will an explosion risk a cave in or water entering the tunnel? Also, the toxicity of the goods when subjected to heat or fire must be kept in mind because of the restricted settings in a tunnel. Furthermore, when it comes to the FFFS, will it be able to suppress or control a fire caused by the hazardous goods in question? FFFS in road tunnels combined with hazardous goods has not been studied in such a great extent. Following are plausible scenarios that might occur.

Closed vessels which are in use when transporting pressurized liquids exposed to fires or being punctured may turn into a BLEVE (Boiling Liquid Expanding Vapor Explosion) resulting in a catastrophic outcome to a tunnel structure and human lives. The FFFS system may in such a case be rendered useless relative the intense heat or by the blast itself. The fire characteristics of the goods perhaps will give such a HRR that will overtax the FFFS design. An extremely fast spread of the fire may activate too many sections and drain the water supply. Also, the use of medium in the FFFS must be discussed thoroughly before transport of hazardous goods is to be allowed. If water is to be used in the system a smaller droplet size (see subsection 3.2) is to be preferred in relation to the supposed chemical/liquids relative density and miscibility. If the liquid has a low density, i.e. relative density less than 1, and is immiscible the liquid may float on top of the discharged water and spread the fire. Furthermore, the use of water on for example carbides and some metals produces combustible gases, i.e. acetylene and hydrogen gas, which in turn may be ignited by the heat.

Because of these limitations of purely water as a suppression or controlling agent when fire occur in some chemicals and/or liquids it may be preferred to use a FFFS with a foam agent added. When installing FFFS in some tunnels in North America the engineers have chosen to use a system with a foam agent added. These are marked in subsection 6.2.

Restrictions of transporting hazardous goods in road tunnels in relation to the FFFS design are therefore advised.

9 Reservations against the usage of FFFS in road tunnels today and in the past

9.1 Introduction

This chapter lists common reservations against the usage of FFFS in road tunnels. Reservations made in the past and today. Every reservation is marked with an R and is followed by a comment marked C. The comments are based on facts from this report and other studies.

9.2 Reservations and comments

R: Steam will be generated by evaporating water which can injure evacuating tunnel users[63]

C: FFFS lowers temperatures in the tunnel considerably even close to the fire (see chapter 7). A free burning fire can reach 1000˚C at relatively long distances from the fire source. Steam can in some cases be found in the close proximity of the fire but the cooling effect of a FFFS outweighs any danger that might be caused by this.[64]

R: The cooling effect will cause a destratification of the smoke or destabilize the smoke layer and this will worsen conditions for the evacuees.[65]

C: It is true that the smoke will reach the tunnel floor when using FFFS. But tests conducted within the UPTUN project has shown that the smoke keeps stratified only relative short distances even when FFFS are not used due to thermal effects and ventilation (see subsection 2.3). The FFFS also reduce the production of smoke and the water droplet itself has to some extent the ability to bind particles and thereby reducing the toxic effects and increase visibility conditions.[66]

R: Most fires starts in the engine or in the compartment and the FFFS will only be effective if it is an open fire.

C: True is that the fire perhaps will not be extinguished while it is in the engine or the compartment. However, the vehicle may be overtaken by the fire in a very short time and start spreading the fire to other vehicles nearby (see subsection 10.1.1). The general view today on FFFS is that they are used to suppress or control the fire, stopping it from spreading and to reduce temperatures in the tunnel. The main reason for installing a FFFS is therefore not to extinguish a fire.

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[63] The Research Project UPTUN. *Engineering Guidance for Water Based Fire Fighting Systems for the Protection of Tunnels and Subsurface Facilities*, R251. The European Commission, 2007.

[64] ibid.

[65] ibid.

[66] ibid.

R: Maintenance of a FFFS in a road tunnel can be very costly.[67]

C: If maintenance costs are costly or not are subjective. The costs have to be weighed against potential costs due to a fire. Will the FFFS save lives and/or reduce repair costs? It is hard to see benefits that may or may not lie in the future; especially economical benefits have these tendencies. Examples of maintenance costs from two manufactures are given in Annex C.

R: A FFFS is difficult to handle manually.[68]

C: The author has not found any reference that confirms or rejects this. Of course the operator needs some training and ordinary cameras may be shielded by the smoke.

R: The use of water can spread burning gasoline.[69]

C: Using smaller droplets which only attack the flames and the hot combustion gases or using a FFFS with an added foam agent will not generate this problem. See the discussion in subsection 3.2 and chapter 8.

R: Water contact with reactive materials may cause dangerous products.[70]

C: Should these kinds of vehicles be allowed to have unrestrictive use of a tunnel. See the discussion in chapter 8.

R: Petroleum fires may continue to produce combustible gases after they have been extinguished. This will create an explosive environment.[71]

C: First of all, the main aim of a FFFS is not to extinguish the fire. The FFFS is to be expected to suppress or control. The fire is later on extinguished by the rescue service. Second, if the fire will be allowed to grow it has been shown that they very quickly generate high HRRs and temperatures. This will cause the fire to spread rapidly to adjacent vehicles. See section 7 and subsection 10.1.1. Furthermore, it is more vital to protect the evacuees from the high temperatures than a potential explosive environment after the fire has been extinguished and, in the most cases, people who can escape have done so.

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[67] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

[68] ibid.

[69]M Arvidson. Sprinkler i vägtunnlar. *Stockholm : SBF Sprinklerdagen 2008, 2008.*

[70] ibid.

[71] ibid.

10 Conclusions and lessons to be learned

10.1 Lessons to be learned

There have been many major tunnel fires in the past. A selection of them is listed in Annex D. Some are referred to as Catastrophic Tunnel Fires (CTF) as for example the St. Gotthard Tunnel fire in 2001.[72] In fact, there are the CTFs during recent years that have for real initiated the discussion in Europe about using FFFS in road tunnels. It is logical to assume that the future increasing number of vehicles and tunnels will increase the number of fires in tunnels. Furthermore, it is also logical to assume that the increasing complexity of the tunnels themselves, regarding for example the length, the location and number of lanes may worsen fire scenarios.

10.1.1 Learning about tunnel fires by studying a real accident investigation [73]

The St. Gotthard Tunnel is situated in the Swiss Alps and consists of one roadway with two lanes running along a north-south axis. On the morning of October 24, 2001 a Belgian heavy goods vehicle (HGV) travelling north ran up against the wall on its right hand side causing the HGV to fling over to the southbound lane where it collided with the left hand wall. After that the HGV swerved back and finally stopped in the middle of the road. Another Italian HGV travelling in the northbound lane tried to avoid colliding with the Belgian HGV and steered onto the wrong side of the road. The two HGVs collided with each other 1.2 km from the south portal. Within a minute after the collision a fire broke out on one of the HGVs and soon the two HGVs were under intense fire. The driver of the Italian HGV raised the alarm and instructed oncoming traffic from the south to turn back. To the north of the fire there was a line of HGVs that had stopped when the collision occurred. The ventilation in the tunnel caused smoke and considerable heat to travel north which in turn spread the fire to these HGVs one by one. Because of the drivers action the fire brigade coming from the south was on scene within seven minutes but the heat was so intense that they could not get within 15-20 meters of the burning vehicles. Fire fighting was also obstructed due to an explosion, which shook the fire truck, about half an hour after the fire fighting began. The fire brigade at the north part of the tunnel was seriously obstructed in their work because of the spread of the fire in their direction and the oncoming toxic gases and smoke.

After the fire had burned out 11 bodies were found north of the accident scene. The fire burned for about 24 hours.

The following conclusions were made during the fire investigation:

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[72]H Ingason. *Fire development in Catastrophic Tunnel Fires (CTF).* Borås : International symposium on Catastrophic Tunnel Fires, 2003.

[73] C Calisti et al. *Tunnel fire investigation II: The St Gotthard Tunnel fire, 24 October 2001.* [book auth.] A Beard and R Carvel. THE HANDBOOK OF TUNNEL FIRE SAFTEY. London : Thomas Telford Publishing, 2005, pp. 53-75.

- The fire source was fuel on the roadway coming from one of the HGVs involved in the collision and its ruptured fuel tank. This fuel was vaporized due to the heat of various hot parts on the engine and was ignited by electrical sparks due to a short circuit caused by the collision.
- In approximately one minute the spread of the fire involved both HGVs and caused a high HRR which in spite of the fast intervention from the fire brigade spread to additional five HGVs and was then stopped by the fire brigade in the north.
- Small explosions were caused by tires bursting during the fire due to the high HRR. The larger explosion occurred after about 30 minutes from the start of the fire fighting and was caused by the rupture of the virtually empty fuel tank of one of the HGVs causing the fire.

10.2 Conclusions

The following conclusions are based on the material presented in this report and are representing the usage of FFFS in road tunnels in general. They are not intended to be a complete list of conclusions but more an inspiration and a starting point for the reader. The conclusions are made by the author of this report or given by other authors.

- A FFFS is not to be assumed to extinguish a tunnel fire. It assists the fire fighters to get access to the fire source by suppressing or controlling the HRR (see chapter 7).
- The FFFS and the tunnel ventilation system should be designed to complement each other concerning the fire spread direction, the spread of the fire in general and the spread of smoke and toxic gases (see chapter 7 and section 2.3).
- The smoke layer is to be expected to reach the tunnel floor at a relative short distance from the fire source (see section 9.2). This applies even if the FFFS is in use or not.
- The activation time for the FFFS should be based on a risk analysis and the FFFS should be managed from a control room by an operator (see sections 4.5 and 6.3).
- The usage of FFFS may keep repairing cost down due to the FFFS ability to keep HRR down which in turn renders in smaller damages caused by heat and combustion. This will in turn lower the closing time of the tunnel due to repairs and the traffic situation will not be affected as hard as if the tunnel is closed for a longer period of time (see subsection 7.1.1.1).
- FFFS stops the spread of the fire which can save people trapped near the accident.
- Fires often occur in vehicles due to mechanical or electrical problems. Fires due to fuel spills are quite rare. [74]

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[74] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

- The transport of hazardous goods in road tunnels should be evaluated and restricted concerning especially BLEVEs, its toxicity and its fire characteristics. Also the location of the tunnel must be considered (see chapter 8).
- When using sprinkler or water spray systems, smaller droplet sizes are preferred in case of a pool fire. This will cool the fire without risking sputtering in the liquid fuel or spreading the burning fuel to other areas (see subsections 7.3.1 and 3.2.1).

10.3 Further studies

Resent year's interest in FFFS in road tunnels, especially in Europe due to CTF in some of its major tunnels, has increased the number of studies in this field. Countries like Japan and Australia which have implemented the use of FFFS in road tunnels for a much longer time than the rest of the world can contribute a lot to help the implementation in Europe and in other nations. They can be really helpful contributing with their experience, what they have learned by real situations and what to expect from a FFFS. Despite the fact that these countries have a good head start relative the rest of the world there are some subjects to be studied further and questions to be answered better.

The combined use of the ventilation system and FFFS should be studied further. Especially concerning which ventilation type that would be the best to use together with a FFFS; longitudinal, transversal or semi-transversal ventilation. Most studies that the author has come across deals with longitudinal ventilation. Perhaps it will solve some issues about increased smoke destratification due to the use of FFFS which can be observed in some tests and relative insignificant in others. The author finds semi-transversal ventilation interesting because of its ability to direct the smoke in the longitudinal direction and its plausible ability to decrease the smoke destratification by extracting smoke transversally through the tunnel ceiling or the top of its walls.

Tests should be undertaken to evaluate if water mist or water spray, i.e. which size of the droplets, is to prefer when it comes to hazardous gods (see chapter 8) and self-escaping possibilities.

CFD-simulations and their limitations have to be better evaluated. Software must be more independent from modifications during simulations to be more reliable. When these become more reliable it will be a good and inexpensive tool for the engineer helping him to implement FFFS in road tunnels.

Further, more as a creative idea, if the water discharge densities could be regulated for an example in the control room by the fire brigade it may be helpful. Finding a way to do this could result in smaller water discharge densities creating less smoke and destratification and when the situation's priorities changes from control and evacuation to extinguishment of the fire the water discharge density could be increased. It is at least an interesting idea to be able to change the water discharge density after what the situation require.

Finally the author looks for a way to minimize maintenance costs. Further studies should be conducted to try to satisfy the tunnel owners' concerns about high maintenance costs. However, lower installation costs and general installation improvements will likely follow as a result if installations of FFFS in road tunnels become more common.

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Annex A

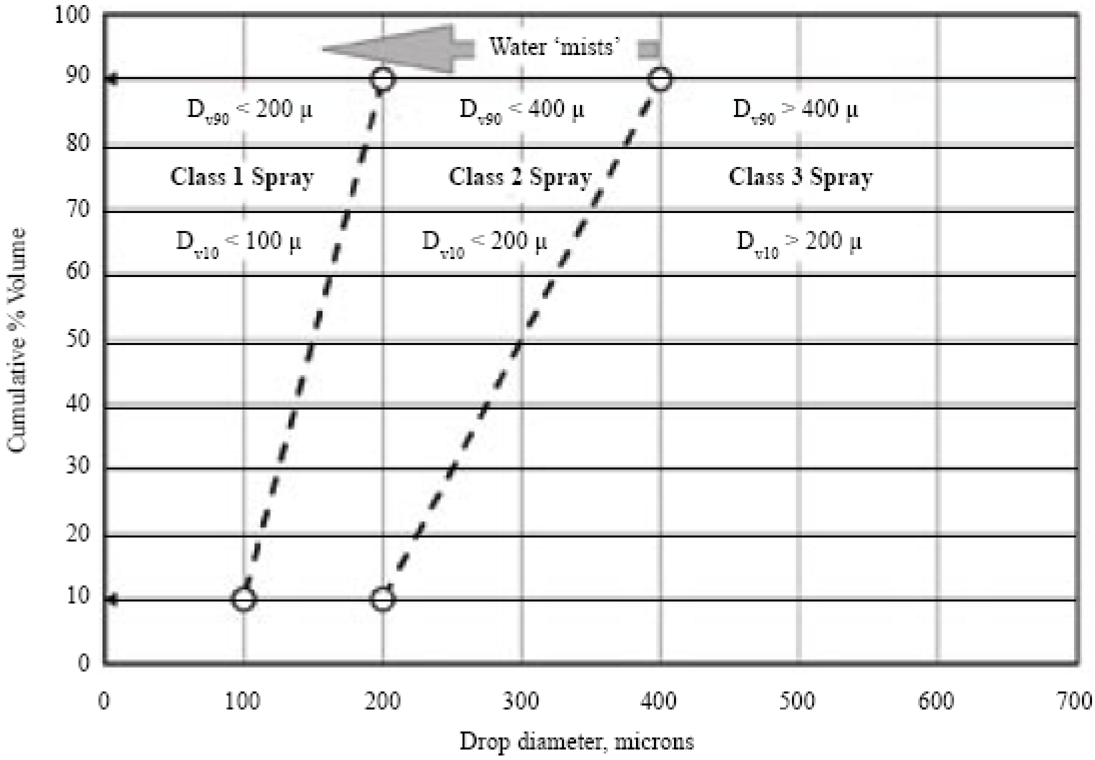

Figure 10: Water mist classification.[75]

[75] Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. *ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS.* France: PIARC, 2008. ISBN 2-84060-208-3.

Annex B[76]

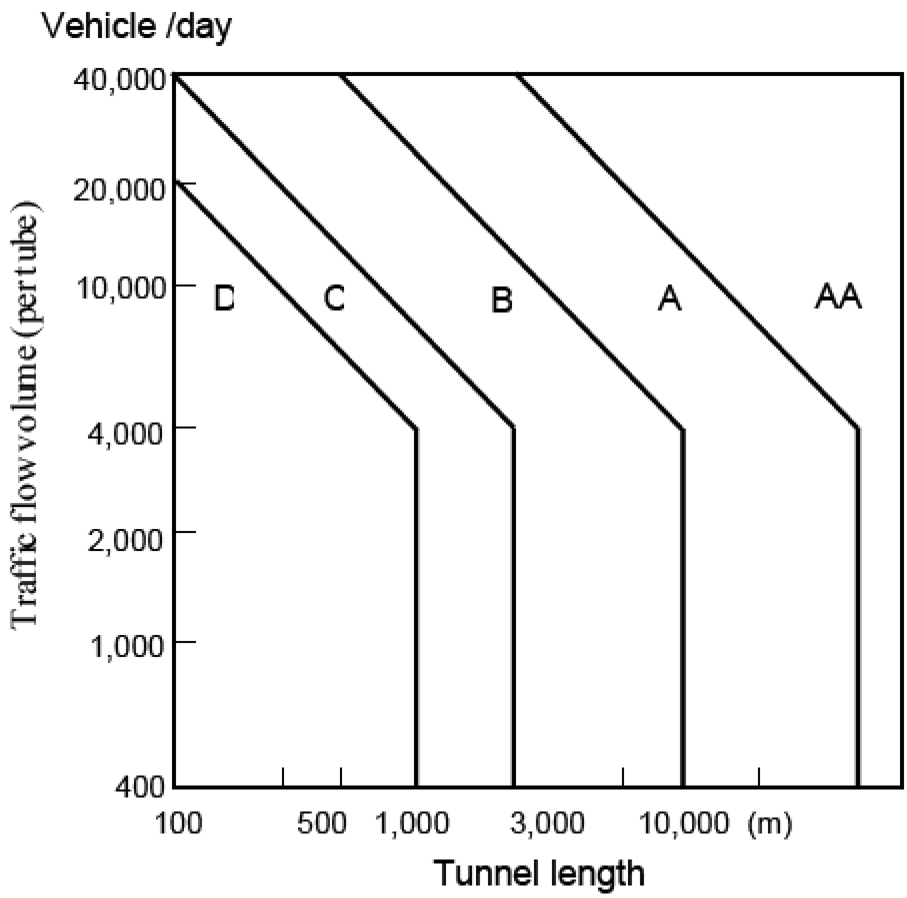

Figure 11: Classification of road tunnels in Japan.

[76] H Mashimo and T Mizutani. *CURRENT STATE OF ROAD TUNNEL SAFETY IN JAPAN.* Japan : Public Works Research Institute and Advanced Construction Technology Center, 2003.

Table 4: Standard of emergency facilities of road tunnels in Japan.

Emergency facilities	Tunnel classification	AA	A	B	C	D
Information and alarm equipment	Emergency telephone	●	●	●	●	
	Pushbutton type information equipment	●	●	●	●	
	Fire detector	●	••			
	Emergency alarm equipment	●	●	●	●	
Fire extinguishing equipment	Fire extinguisher	●	●	●		
	Fire plug	●	●			
Escape and guidance equipment	Guide board	●	●	●		
	Smoke exhaust equipment or escape passage	●	••			
Other equipment	Hydrant	●	••			
	Radio communication auxiliary equipment	●	••			
	Radio re-broadcasting equipment or loudspeaker equipment	●	••			
	Water sprinkler system	●	••			
	Observation equipment	●	••			

Note: In the table, ● indicates that the equipment should be installed as a rule, and •• indicates that the equipment should be installed as required.

Annex C

Table 5: Typical maintenance and cost suggested by manufactures.[77]

MANUFACTURER 1	MANUFACTURER 2
Every month : pump start control, visual checking of the pumps room equipment	Every month : pump start control, visual checking of the pumps room equipments
Periodic test every 6 months: Pump checking (flow rate, pressure), alarm test, visual monitoring of the pipes. Work to be done in 1 night by 3 to 4 persons.	Annual test: Pump checking (flow rate, pressure), alarm test, visual monitoring of the pipes and the nozzles. Operation control of the deluge valves. Work to be done in 4 nights
Annual test: Periodic test + activation of all spraying zones for spray structure visual control, filters checking. Work to be done in 2 nights by 3 to 4 persons.	Global monitoring (every 5 years): Annual test + renewal of all the joints, synthetic tubes and filters. Work to be done in 5 to 6 nights.
Annual maintenance cost: 0.5% to 3% of the installation cost. (1.75% on average)	Annual maintenance cost: 1% of the installation cost.

[77] *Working Group 6 - Ventilation and Fire Control of the Technical Committee C3.3 - Road Tunnel Operations. ROAD TUNNELS: AN ASSESSMENT OF FIXED FIRE FIGHTING SYSTEMS. France : PIARC, 2008. ISBN 2-84060-208-3.*

Annex D

Table 6: A number of major tunnel fires since 1949.[78,79]

Year	Location/ Country	Tunnel/ Length	Number of vehicles involved where the fire originated	Presumed cause of fire	Reported duration of fire	Consequences to people	Damage to vehicles	Damage to tunnel
1949	New York USA	Holland 2 550 m	1 lorry loaded with 11 tons of carbon sulphide	Cargo falling of truck	4 h	66 (smoke poisoning)	10 lorries 13 cars	200 m with severe damages
1968	Hamburg Germany	Moorfleet 343 m	1 lorry with a trailer	Problems with the breaks	1 h 30 min	None	1 trailer	34 m with severe damages
1974	USA	Chesapeake Bay	N/A	N/A	4 h	1 injured	Tank lorry	N/A
1975	Guadarrama Spain	Guadarrama 3 330 m	1 tank lorry loaded with resin	Unknown	2 h 45 min	None	1 lorry	210 m with severe damages
1976	Paris France	B6 430 m	1 lorry loaded with 16 tons of polyester	Unknown	1 h	12 injured	1 lorry	150 m with damages

[78] A Bergqvist et al., *Räddningsinsatser i vägtunnlar*. Karlstad: Swedish Civil Contingencies Agency, 2005.

[79] R Carvel and Marlair,G. *A history of fire incidents in tunnels. [book auth.] A Beard and R Carvel. THE HANDBOOK OF TUNNEL FIRE SAFETY.* London : Thomas Telford Publishing, 2005, pp. 3-37.

1978	Haarlem Holland	Velsen 770 m	2 lorries 4 cars	Head on collision	1 h 20 min	5 dead 5 injured	2 lorries 4 cars	30 m with severe damages
1979	Shizuoka Japan	Nihonzaka 2 045 m	4 lorries 2 cars	Head on collision	4 days	7 dead 2 injured	127 vehicles	1 110 m with severe damages
1980	Japan	Sakai	10 vehicles	unknown	3 h	N/A	10 vehicles	N/A
1980	Japan	Kajiwara	1 lorry (4 tons) loaded with 3 600 l of paint and 1 lorry (10 tons)	Collision with wall and overturned	Unknown	1 dead	2 lorries	280 m with severe damages
1982	Oakland USA	Caldecott 1 083 m	1 lorry 1 car 33 000 L of gasoline	Front – back collision	2 h 40 min	7 dead 2 injured	3 lorries 1 minivan 4 cars	580 m with severe damages
1983	Modane France - Italy	Fréjus 12 868 m	1 lorry loaded with plastic material	Gearbox malfunction	1 h 50 min	None	1 lorry	200 m with severe damages
1984	Austria	Felbertauern 5 130 m	1 bus	Breaks	1 h 30 min	None	1 bus	Damaged roof and equipment (100 m)
1984	Goeschenen Switzerland	Gotthard 16 321 m	1 lorry with plastic rolls	Fire in engine	24 min	None	1 lorry	30 m with severe damages

1986	France	L'Arme 1 100 m	N/A	Collision	N/A	3 dead 5 injured	N/A	N/A
1987	Bern Switzerland	Gumefens 340 m	1 lorry	Mass collision on slippery road	2 h	2 dead	2 lorries 1 van	Little damage
1993	Bologne Italy	Serra Ripoli 442 m	1 lorry loaded with paper rolls 1 car (reckless driving)	Collision	2 h 30 min	4 dead + injured	4 lorries 11 cars	Severe damages on lining
1993	France	Frejus 12 870 m	1 lorry	Engine fire	2 h	None	1 lorry	N/A
1993	Norway	Hovden 1 283 m	Lorry	Collision	2 h	5 injured	Lorry with polyeten	N/A
1994	Goeschenen Switzerland	Gotthard 16 321 m	1 lorry and trailer loaded with bicycles packaged in cardboard and plastic	Friction in tires	2 h	None	1 lorry and trailer	Severe damages in roof, equipment damaged for 50 m, tunnel closed 2.5 days
1994	South-Africa	Huguenot 4 000 m	N/A	N/A	1 h	1 dead 28 injured	Bus	N/A

1995	Austria	Pfänder 6 719 m	1 lorry 1 minibus 1 car	Collision	1 h	3 dead at collision	1 lorry 1 minibus 1 car	Severe damages in roof and to equipment. Tunnel closed 2.5 days.
1996	Sicily Italy	Isola delle Femmine 150 m	1 tank lorry with liquefied gas and a minibus	Slippery road, collision	unknown	5 dead due to fire 20 injured	1 tank lorry 1 bus 18 cars	Damaged lining and lighting
1996	England - France	Eurotunnel 50 000 m	1 lorry	Presumed arson	2 h 30 min	30 smoke poising	10 lorries	Severe damages to roof
1996	Norway	Ekebergs-tunnel	1 bus	Engine failure	1 h	None	1 bus	Localized damages
1997	Switzerland	St.Gotthard 16 321 m	1 lorry loaded with cars	Engine fire	1 h 20 min	None	1 lorry	100 m with severe damages, 1000 m of smoke in tunnel.
1999	France - Italy	Mont Blanc 11 600 m	The fire starts in a lorry	Unknown	50 h	39 dead	23 lorries 1 smaller lorry 9 cars 1 motorcycle	900 m with severe damages. Tunnel closed several years.

1999	Austria	Tauern 6 400 m	Multiple collision caused by maintenance	Fire caused by leakage of paints and varnishes	15 h	12 dead	16 lorries 24 cars	N/A
2000	Norway	Seljestads-tunnel 1 279 m	Multiple collision	N/A	1-2 h	4 smoke poising	1 truck 5 cars	N/A
2001	Switzerland	St. Gotthard 16 321 m	Collision between two lorries	Fire caused by the collision	4 h	11 dead	13 lorries 10 cars	N/A
2002	Milford Sound New Zealand	Homer Tunnel	1 coach	Engine fire	N/A	3 smoke inhalation	1 coach	N/A
2003	Bergen Norway	Fløfjell Tunnel 3.1 km	1 car	Collision with tunnel wall	Fire brigade arrived in 6 min and quickly extinguished the fire	1 dead	1 car	Damages to the lining due to fire put out by FFFS.
2004	Liège Belgium	Kinkempois Tunnel 0.6 km	1 HGV	N/A	N/A Extinguished by safety system	None	1 HGV	Closed a few days due to cleaning and repairs.
2004	France - Italy	Frejus tunnel 12.9 km	1 HGV	Overheated breaking system	N/A	None	1 HGV	N/A
2009[80]	Norway	Eikesund tunnel 7 765 m	Head on collision between two cars	Fire caused by the collision	N/A	5 dead	N/A	N/A

[80] *The Norway Post. Doorway to Norway. [Online] [Cited: 9 July 2009.] http://www.norwaypost.no.*

Annex E

Table 7: Measurements during the large-scale tests in the Second Benelux Tunnel.[81]

Test NR		Rate of heat release			Ventilation			Sprinkler	
Nr	Type of fire	Controlled	Time (min)	RHR (MW)	Time (min)	Velocity upstream. (ms)	Mechanical ventilation	Time (min)	Sections
11	Loaded van, delayed sprinkler activation	no	0–8		0–15	~ 1	almost none	14–36	1 + 2
			8–10	~ 2.5	15–35	~ 1.6	almost none		
			10–13	2.5/7					
				~ 7					
12	Aluminium covered truck load, direct sprinkler activation	no	0–3	0/6	0–35	~ 3	Low	4–14	1 + 2
13	Aluminium covered truck load, delayed sprinkler activation	no	0–5	~ 0	0–5	~ 1.5	low	10–19	1 + 2
			5–10	0/14	5–6	1/5\0	low		
					6–12	0/3	low		
					12–20	3–0.2	almost none		
					20–22	0.2/1	almost none		
					22–30	1–1.5	almost none		
					30–40	~ 1.5	almost none		
14	Open truck load, delayed sprinkler activation	no	0–6	~ 0	0–4	~ 1	low	21–39	2
			6–12	0/25	4–7	1\0	low	31–39	1 + 2
			12–22	25\13	7–12	0/2.5	low		
			22–29	13\0	12–26	2.5\1.8	low		
					26–29	1.8\0	low		

[81] Y Kenyon and Lemaire, T, *Large Scale Fire Tests in the Second Benelux Tunnel.* Fire Technology, 2006. 42, pp. 329–350.