Ventilation strategies for road tunnels in different countries and consequences using Fixed Fire Fighting System (FFFS)

Rohan John Baptiste

Fire Safety Engineering
Lund University
Sweden

Report 5548, Lund 2017

Master Thesis in Fire Safety Engineering

Ventilation Strategies for road tunnels in different countries and consequences using Fixed Fire Fighting System (FFFS)

Rohan John Baptiste

Report 5548
ISRN: LUTVDG/TVBB—5548--SE
Number of pages: 58
Illustrations: 31
Keywords
Longitudinal ventilation, fixed fire fighting system (FFFS), fractional effective dose (FED).

Abstract

A study is carried out on the ventilation strategies for road tunnels in different countries and consequences using fixed fire fighting systems (FFFS). The type of ventilation strategy for road tunnels can ensure the safety of people during the evacuation stages and protection of the rescue services during their intervention of the fire. Ventilation strategies vary from country to country and therefore it is important to get a suitable strategy which can be applied in these countries [1]. FFFS in road tunnels are defined as fire fighting equipment, which is permanently installed in the tunnel with a pipe system that water or other extinguishing agents. Usually FFFS are water spray systems and can be either high pressure or low pressure systems. Such systems will be able to fight fires that are relatively large and thereby potentially prevent a major disaster. In a tunnel without a fire suppression system, a slightly lower ventilation velocity is preferred to slow down the fire growth at the initial stage of evacuation. At the fire fighting stage the ventilation velocity can be adjusted up to critical velocity. In order to explore the effects of FFFS during different ventilation conditions, an analysis will be conducted on a large scale Runehamar and model scale tunnel fire experiments conducted at SP. The analysis show that the longitudinal ventilation system and FFFS will provide a tenable environment for safe evacuation.

Fire Safety Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden
http://www.brand.lth.se
Telephone: +46 46 222 73 60

HOST UNIVERSITY: Lund University

FACULTY: Faculty of Engineering

DEPARTMENT: Department of Fire Safety Engineering

Academic Year 2016-2017

Ventilation strategies for road tunnels in different countries and consequences using Fixed Fire Fighting System (FFFS)

Rohan John Baptiste

Promoter(s): Prof. Haukur Ingason

Master thesis submitted in the Erasmus Mundus Study Programme

International Master of Science in Fire Safety Engineering

DISCLAIMER

This thesis is submitted in partial fulfilment of the requirements for the degree of *The International Master of Science in Fire Safety Engineering (IMFSE)*. This thesis has never been submitted for any degree or examination to any other University/programme. The author declare that this thesis is original work except where stated. This declaration constitutes an assertion that full and accurate references and citations have been included for all material, directly included and indirectly contributing to the thesis. The author gives permission to make this master thesis available for consultation and to copy parts of this master thesis for personal use. In the case of any other use, the limitations of the copyright have to be respected, in particular with regard to the obligation to state expressly the source when quoting results from this master thesis. The thesis supervisor must be informed when data or results are used.

Read and approved

Baptiste

Rohan John Baptiste
April 30th, 2017

Abstract

A study is carried out on the ventilation strategies for road tunnels in different countries and consequences using fixed fire fighting systems (FFFS). The type of ventilation strategy for road tunnels can ensure the safety of people during the evacuation stages and protection of the rescue services during their intervention of the fire. Ventilation strategies vary from country to country and therefore it is important to get a suitable strategy which can be applied in these countries [1]. FFFS in road tunnels are defined as fire fighting equipment, which is permanently installed in the tunnel with a pipe system that water or other extinguishing agents. Usually FFFS are water spray systems and can be either high pressure or low pressure systems. Such systems will be able to fight fires that are relatively large and thereby potentially prevent a major disaster. In a tunnel without a fire suppression system, a slightly lower ventilation velocity is preferred to slow down the fire growth at the initial stage of evacuation. At the fire fighting stage the ventilation velocity can be adjusted up to critical velocity. In order to explore the effects of FFFS during different ventilation conditions, an analysis will be conducted on a large scale Runehamar and model scale tunnel fire experiments conducted at SP. The analysis show that the longitudinal ventilation system and FFFS will provide a tenable environment for safe evacuation.

Keywords: Longitudinal ventilation, fixed fire fighting system (FFFS), fractional effective dose (FED).

Acknowledgements

I would like to thank Professor Haukur Ingason (Promoter) for his immense help with this thesis. His invaluable input and guidance was crucial for me during the development of my thesis.

I would like to thank the IMFSE Management Board for giving me this opportunity to participate in the programme. The exposure and knowledge I have obtained will go a long way in helping me shape the future of fire safety engineering.

I would like to thank my wife Sergin John Baptiste for her loving support, patience and guidance along this journey.

I would like to thank my mother Placides Pierre Louis and aunt Charitiana Pierre Louis for all their prays, love, support and guidance.

Last but not least my IMFSE family and friends for all the memories through this epic journey.

List of abbreviations

CO - Carbon Monoxide

CO_2 - Carbon Dioxide

O_2 – Oxygen

CCTV - Close-Circuit Television System

ECOH - Extended Coverage Ordinary Hazard

FFFS - Fixed Fire Fighting System

FED - Fractional Effective Dose

FID - Fractional Incapacitating Dose

FGR - Fire Growth Rate

HRR - Heat Release Rate

HGV - Heavy Good Vehicles

HCN - Hydrogen Cyanide

NFPA - National Fire Protection Association

PPM - Part per Millions

RMV – Respiratory Minute Volume

UPTUN - Upgrading of Existing Tunnels

List of Tables

LIST OF FIGURES

Table of Contents

1 Introduction

The type of ventilation strategy for road tunnels can ensure the protection of people during the evacuation stages of a fire emergency and ensure the protection of the rescue services during their intervention of the fire. Different ventilation strategies are found from country to country and therefore it is important to get a suitable strategy which can be applied in these countries. When the word tunnel is used it refers to road tunnels and when ventilation is used it refers to longitudinal ventilation velocity [1]. The longitudinal velocity selected is important to prevent the smoke back flow (backlayering) and can affect the fire in the tunnel in a positive or negative way depending on the stages of the fire.

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 that water or other extinguishing agents. Usually FFFS are water spray systems and can be either high pressure or low pressure systems. Systems with small water droplets are called water mist. If the system operates in zones it is called deluge. Such systems will be able to fight fires that are relatively large and thereby potentially prevent a major disaster. In the case of congestion and specifically when a queue is formed, the system will increase safety by minimizing the risk of propagation of a fire as it could occur [2].

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 [3]. Some countries have introduced FFFS into road tunnels namely: the 1,140 m Pörzberg Tunnel in Thuringia is Germany’s longest tunnel on a highway, two tunnels in Norway:1) Fløffjell Tunnel (3.2 km long, average daily traffic frequency (DTV) 26,000 vehicles two tunnel bores), 2)Vālreng Tunnel (800 m long, DTV 37,000 vehicles, two tunnel bores); four in Sweden:1) Tegelbacken Tunnel,2) Klara Tunnel [3] , 3) Gnistängs Tunnel and 4) Northern Link tunnel.

The introduction of such a system may affect the type of ventilation strategy selected. The FFFS not only limit the growth of fire but also affect the buoyancy of the smoke layer within the tunnel. In a tunnel without a FFFS, a slightly lower ventilation velocity is preferred to slow down the fire growth at the initial stage of evacuation. At the fire fighting stage the ventilation velocity can be adjusted up to critical velocity of 3 m/s. In a road tunnel with a FFFS, a slightly higher velocity is recommended to reduce the toxic gas concentration and increase the visibility downstream [1]. This thesis will combine the effects of the strategy both with and without the use of FFFS in road tunnels with longitudinal ventilation and explain its consequences in the downstream of the road tunnel. In order to investigate the effects an analysis of tests data from large scale and model scale tests that has not been applied earlier is carried out.

Objectives

- Explore the effects of the conditions inside the road tunnel with and without FFFS on evacuees form experimental data found from scale models and fullscale SP data.
- Recommend a realistic longitudinal ventilation strategy with and without FFFS.
- Calculation of the fractional effective dose or fractional incapacitating dose (FED/FID) for a free burn test and a test with a deluge system in a tunnel.
- Analyze the effects of FED/FID on people at a particular distance from the fire.
- Propose a ventilation strategy to use in conjunction with FFFS.

Limitations

This study would have been more appropriate with an experimental study but because of time limitation an analytical study is more convenient. The information that will be analyzed are obtained from already existing experiments from SP.

Method

The methodology that will be followed in this project as indicated below:

- Literature Review: The publications and papers regarding longitudinal ventilation strategies, large scale fire tests with FFFS and other similar experiments will be reviewed to gather information to guide the project.
- Documentation/Report Writing: Collected results/data will be analyzed to obtain fundamental conclusion and compared with literature and previous experiments conducted at SP. The information will be used to develop a strategy for the usage of a longitudinal ventilation velocity to work with the FFFS.

2 Principles of Fire Dynamics in Tunnels

Understanding the basic principles of fire dynamics in tunnels when working with ventilation systems and FFFS is important, because it assists in understanding the smoke spread in tunnels with low ceiling heights and on fire development in a single burning vehicle [4]. The influence of ventilation and FFFS on the heat release rates (HRRs) in vehicle fires and how the smoke, toxic gases and heat spread in tunnel is very important to understand since it may affect the evacuation of people in the tunnel. It is also important to know what will be an appropriate distance away from a fire which may be considered to be a safe zone for people in a tunnel.

2.1 Tunnel Fires

The ignition and burning of a combustible material in an open area has a different fire behavior than burning of the combustible material in an enclosed space, such as a tunnel. After ignition, the fuel in an open area maintains the burning process with radiation feedback from its own flame. With the fuel in an enclosed area, radiation feedback is increased because of the confined area thus making the burning process more vigorous. This therefore results in a greater flame size and higher heat release rate than in an open area.

The developed fire can either be fuel controlled or ventilation controlled. The fuel controlled fire can cause unreacted oxygen to pass by the burning vehicles, whereas, ventilation controlled fire may produce large amounts of toxic gases and products of incomplete combustion [5].

Tunnel fires and compartment fires have something in common, they both are confined. The difference is mainly found in the nature of ventilation through the openings. Compartment fires have in and outflow through the same openings while in tunnel it is through separated portals. The burning process can be increased depending on the geometry of the confined area, but can be affected by the geometry if there isn't sufficient ventilation. The availability of oxygen supplied through an opening can enhance fire growth, and the burning process is dependent on the fuel characteristics and radiation feedback. This fuel controlled burning will continue until the air to fuel ratio drops below the ideal fuel mixture or stoichiometric air to fuel ratio.

Compartment fires and tunnel fires are similar in that the fire is affected by its confinement. The burning can be enhanced depending on the degree of confinement, but it can also be restricted by the confinement if there is not sufficient ventilation [6]. If oxygen is readily available or oxygen supplied through an opening in the enclosure is enough, the fire grows, and the burning mechanisms depend mainly on the characteristics of the fuel and the radiation feedback. This 'fuel-controlled' burning is sustained until the air to fuel ratio drops below the stoichiometric air to fuel ratio. If the fire is influenced by a continuous airflow supplied by a forced ventilation system which might be present in the tunnel, then the tunnel fire is likely to be a fuel controlled.

Fires in compartments can easily grow to flashover within a few minutes. Flashover is not expected to take place outside a confined space such as a compartment. The volume of the compartment is very important as is the composition of the materials found in the compartment together with the opening sizes. Tunnel fires, in that sense meaning in a long space with two large portal openings, are therefore not likely to grow to a conventional flashover. The main reason is due to large heat losses from the fire to the surrounding walls, lack of fuel in relation to the volume size and containment of hot fire gases [5].

During a compartment fire, buoyant smoke creates a hot upper layer, which can be called stratification. All combustible material found in the compartment can be ignited by this hot smoke layer which can increase the burning process of the fire. In tunnel fires a buoyant hot smoke can also be observed during the early stages of fire growth if no forced ventilation system is activated. The smoke layer will move along the ceiling of the tunnel since there are no restrictions. As the smoke layer travels along the length of the tunnel it will lose heat and buoyancy and at a certain distance will begin to descend down to the tunnel floor. This distance is dependent on the distance from the fire and the geometry of the tunnel. Backlayering can be created on the upstream side of the fire whilst the degree of stratification of the smoke governed by heat losses to the surrounding environment and the turbulent mixing of cold air layer and an opposing buoyant smoke layer can affect the downstream side [6]. When FFFS are used these conditions may be changed considerably. This will be discussed further in chapter 4.

3 Ventilation

3.1 Tunnel Ventilation Systems

The ultimate goals of tunnel ventilation systems are to provide an environment sufficiently clear of smoke and hot gases to permit safe evacuation and to allow relatively safe access for rescue services as a function of actual fire scenario. The system must also prevent the spread of smoke into uninvolved areas. If a tunnel is filled with smoke, the system must be able to replace it with clean or smoke-free air, which can be removed through portals or supplied mechanically. The dilution of the smoke can improve tenability by reducing the concentrations of the toxic gases. The ventilation system must be available and capable of handling combinations of worst-case fire conditions: fire size, location, traffic pattern, etc. Establishing airflow requirements in the tunnel, and consequently the capacity of the ventilation system, are challenging due to the difficulty of controlling many variables [7].

Although the focus in this study is on longitudinal flow, a brief introduction to different types of ventilation systems, including longitudinal ventilation, is given.

3.2 Longitudinal Ventilation

In case of a fire, a longitudinal ventilation system is designed to produce a longitudinal flow to create a smoke-free path upstream of the fire. This can be achieved by using injection, using central fans, using jet fans mounted within the tunnel, or a combination of injection and extraction at intermediate points [8]. Therefore at least upstream of the fire, the tunnel users can escape. However, tunnel users located downstream of the fire are exposed to heat and smoke flow.

The two most important parameters for a tunnel with longitudinal ventilation are critical velocity and the back-layering length.

Critical velocity is defined as a minimum longitudinal ventilation velocity to prevent reverse flow of smoke from a fire in the tunnel.

The backlayering length is defined as the length of the smoke backlayering upstream of the fire when ventilation velocity is lower than the critical velocity [2].

In a longitudinally ventilated tunnel, a fresh air flow with a velocity not lower than the critical velocity at the designed HRR is created to prevent smoke backlayering, which means that the tunnel is free of smoke upstream of the fire site. However, smoke stratification downstream of the fire may not persist as the ventilation velocity is too high [2].

3.3 Transverse Ventilation

Transverse ventilation systems feature the uniform collection and/ or distribution of air throughout the length of the tunnel roadway and can be of the full transverse or semi- transverse type. The systems also experiences some longitudinal airflow, the quantity depends on the system.

3.4 Natural Ventilation

In road tunnels where there are high traffic flows, the piston effect is the result of natural induced draft caused by free-flowing traffic in uni-directional tunnel thus providing natural ventilation. This reduces the concentration of contaminants and dust, and also remove the heat.

3.5 The effects of ventilation on fires

The ventilation rate plays an important role in the fire development. It mainly affects how initial flames are tilted and consequently how the flame spreads further within the fuel. High ventilation rates can potentially prevent continuous fire spread; example of such an ignition delay is on the running vehicles which come to a stop. The flames may suddenly burst out after the stop, and the fire starts to develop rapidly [1].

It is difficult to predict a potential fire growth from the incipient period to the continuous FGR period, where the heat release rate (HRR) continue to increase rapidly, and will lead to a fully developed fire if not intervened [1].

Although the ventilation velocity may result in an increase of the HRR and the FGR, the forced longitudinal ventilation is important and necessary to prevent the smoke back flow (backlayering) in most tunnel fires. It constitutes the basis for the design of critical velocity and therefore gets such high focus among tunnel engineers [1].

4 Fixed firefighting systems (FFFS)

FFFS have become a common fire safety method in tunnels over the last 10 years. One of the main drivers behind this development are the European research projects, which have shown on hand that fires with heavy good vehicles (HGV) can lead to much higher heat release rates (HRR) than previously used as design fires. Also the test carried out by SP in 2003 in Runehamar tunnel showed that the HRR potentially could be very high and the temperature exposure as well [9]. The design fires for over 25-50 tons HGVs are typically considered between 70-100MW nowadays [10]. Some standards e.g. NFPA502 specifies 150MW design HRR for HGV's [11]. FFFS have been noticed to be very effective in limiting and suppressing fires resulting in a safer environment for users to be evacuated, improved safety for rescue services and protecting the tunnel structure [12].

4.1 Description of FFFS

Typical FFFS use a system of pipes and valves to bring water to discharge nozzles. Most systems fall into one of two categories. Deluge Systems generate larger droplets, control the fire principally /by surface cooling, and generally operate at lower pressures. Water Mist Systems, on the other hand, operate at higher pressure, generate smaller droplets and promote more effective gas cooling [7]. Conventional deluge nozzles in zones that can be activated either automatically or by the operator from the tunnel operation control room. Water mist systems are also designed with zones, although the zone length may differ from that used in deluge systems. Both of these systems have been applied to tunnels, although deluge systems without additives represent the vast majority of the installed systems.

The benefits of FFFS are primarily that they can be used to increase safety in tunnels. Such systems will be able to fight fires that are relatively large and thereby potentially prevent a major disaster. In the case of congestion and specifically when a queue is formed, the system will increase safety by minimizing the risk of propagation of a fire as it could occur [4]. FFFS can enhance asset protection by reducing the risk of collapse of a tunnel, e.g. for underwater tunnels or where important infrastructures are located above the tunnel [7]. FFFS can also support asset protection by reducing the duration of tunnel closures after a fire. FFFS will, in most circumstances retard fire growth but not extinguish it. Extinguishment of the fire requires human intervention, typically by the fire brigade. FFFS are also advantageous when the fire-fighter response could be delayed.

4.2 Classifying FFFS

On an international scale there is a very wide range of manufacturers with very diverse philosophies regarding the design and technique behind firefighting systems as shown in

Table 1. The following classification may help to understand the main differences between the systems:

Table 1 Classifying FFFS redrawn from [13]

System	Extinguishing agent	Water requirement	Nozzle pressure
Water deluge	Water	8-15 mm/ m^2 per min	1-5 bar
Water mist	Water	4-7 mm/m^2 per min	Low pressure P< 12.1 bar
			Medium pressure P>12.1 bar and <34.5 bar
			High pressure P> 34.5 bar

Classifying the water mist systems into low, medium, and high pressure corresponds with classification in accordance with NFPA 750 [14].

A differentiation is made between water deluge systems and water mist systems in accordance with DIN CEN/TS 14972 [15] and NFPA 750 [14].

According to NFPA 750 [14], the DV0.99 characteristic diameter describes the diameter of the drops that fall below the size of 99% of the released volume of water. The CEN is defined in accordance with the DV0.9 diameter with a proportion of 90%. Water mist systems are associated with cases where DV0.9 < 1mm; where DV0.9 > 1mm, it is a sprinkler- and/or water spray system. NFPA 750 [14] differentiates between three classes of water mist systems based on the DV0.99 characteristic diameter as shown in Table 2.

Table 2 Differentiation between water mist- and sprinkler/water spray systems redrawn from [13]

Class I	**Class II**	**Class III**
DV0.99 ≤ 200µm	200µm ≤ DV0.99 ≤ 400µm	400µm ≤ DV0.99 ≤ 1000µm

4.3 Deluge system

4.3.1 General description

Deluge FFFS consist of open sprinklers or water spray nozzles attached to pipework at the tunnel ceiling. The pipe work consists of mains pipes, manifold pipes, feed mains, and branch pipes. The sprinklers or nozzles are attached to the branch pipes, which are typically arranged in a uniform pattern at the ceiling to distribute spray to all the sections of the roadway [5]. The branch pipes are connected to a feed main which is connected to a deluge valve. The deluge valve is mounted on the manifold attached to the mains pipe that is supplied to one or more water reservoirs or fire pump stations.

Mains pipes are normally water-filled up to the point of connection to the deluge valve. Therefore, the mains pipe and the deluge valves must be protected against freezing. The deluge valve separates the water-filled mains from the empty (dry) feed main and branch pipes supplying the sprinklers of spray nozzles [16]. When the deluge valve is opened, water flows into the feed main and branch pipes and discharges from the open sprinklers as shown in Figure 1.

Figure 1 FFFS after activation of the system. With permission of SP [2]

The branch piping is divided into deluge zones, typically 25 – 50 m in length, each served by its own deluge valve. Standard water spray nozzles, which typically require a minimum operating pressure of 1.5 -5 bar are used and they discharge a uniform pattern of water droplets over the protected area with a droplet sizes less than 2 mm in diameter [5]. The water discharge density over the length of the deluge zone or predefined are commonly in tunnel fires is in the range of 6-12 mm/min (l / min m^2).

An independent fire detection system that is capable of locating a fire accurately is required, so that the deluge valve serving the zone where the fire is located can be released. The deluge valve can be opened either automatically by the detection system, or manually by a signal from the tunnel operator. If an accident occurs on the boundary between two deluge zones, both zones may need to be activated [16]. When the deluge valves opens, water flows into the main and branch piping and discharges from all sprinklers or nozzles in the deluge zone. As the water spray nozzle (or sprinkler head) orifices are open, the branch piping is at atmospheric pressure until water is introduced. A FFFS has a time delay between detection of a fire and the discharge or water from the sprinklers or nozzles due to the time required to operate the valve and to fill the branch piping network with water and reach the desired operating pressure.

4.4 Water Mist Systems

4.4.1 General description

Water mist FFFS are fundamentally similar to deluge FFFS, that is, the pipework consists of a water-filled mains pipe, manifold, deluge valves, dry feed main, and branch pipes to which the nozzles are attached. The mains pipe is connected to a water supply and the pressure is generated by pumps. Water mist FFFS may vary with respect to their working pressures, that is, low and high pressure mist systems [5]. The piping or tubing utilized in the system must be designed for the corresponding operating pressure. To protect against plugging of small orifice nozzles, water mist system utilize corrosion resistant materials such as stainless steel pipe or tubing [16]. The primary difference between the systems is the percentage of smaller droplet sizes and the momentum of the spray ejected from the nozzles.

According to the definition given in UPTUN guidelines [12] the general principle of the low pressure water mist FFFS is to produce a fog (or mist) of small water droplets at a nozzle pressure of 3-10 bar. The high pressure water mist FFFS produces a fog (or mist) with a mix of different sizes of water droplets at a nozzle pressure of 60 – 120 bar.

The droplets produced by water mist FFFS are much smaller than those for a conventional sprinkler system and a large part of their cooling action is thought to be via the evaporation of these droplets. Most of the experimental tests on these systems have been conducted by the companies which manufacture and promote them. As such, the results released have been very selective and it is to be assumed that very few, if any, negative results would be placed in the public domain [17].

Tests carried out by commercial companies sometimes claim that a fire has been ‘suppressed’ when this has not actually been the case [18]; taking ‘suppression’ to mean a non-trivial reduction in heat release rate which is permanent and not resurgent. Fire ‘control’ may be taken to imply that the heat release rate has, at least, been held steady and not increased to any non-trivial degree. Very few experimental tests on water-mist FFFS have been carried out by independent organizations and there need to be many more. The manufacturers of water mist FFFS have access to many experimental data but the data are generally not available. Table 3 shows theoretical comparison of the two systems.

*Table 3 Theoretical comparison of deluge and water mist systems*redrawn from [13]*

		Low-pressure deluge FFFS	High-pressure water mist FFFS
Fire Fighting principle	Cooling – flames/gases	Minor	Major
	Cooling - fuel	Major	Minor
	Displacement of oxygen (locally)	Minor	Major
	Isolating fuel from oxygen	No	No
	Interrupting chemical combustion process	Minor	Minor
Main mitigation measures	Mitigation of effects of covered class A fires	No (limited)	Minor
	Suppression of uncovered class A fires	Major	Major
	Suppression of class B fires	Minor (with AFFF major)	Major (with AFFF major)
	Blocking heat radiation	Minor	Major
	Smoke washing/sooth binding	Minor	Minor
	Prevention on reigniting by wetting surfaces	Major	Minor

*Notice! This table highlights the differences between the system types in a much generalized, way. The actual performances are however related to a specific nozzle characteristic (droplet distribution/spray momentum/lay-outs) and flow rates of a specific system. [13]

4.4.2 Fire detection and activation

4.4.2.1 Detection

Fire detection systems are an essential part of the FFFS in road tunnels. Their role is to identify an emergency, provide a timely warning of a fire incident, determine its exact location and monitor the development of the fire in the tunnel [19]. As a result, the detection system is capable of aiding in indicating the proper evacuation route and guiding the firefighting operations [20]. Nevertheless, the most significant "duty" of a fire detection system in a tunnel is to coordinate the activation of the smoke extraction system in an optimal way [21]. This way, the smoke stratification is maintained and the possibility to survive is significantly increased.

During a fire, several material and energy conversions take place and result in end-products referred to as fire phenomena. Automatic fire detection, in principle, converts certain fire phenomena into electrical signals. As a result, the parameters of the fire that define the detection principles are the following [22]:

- Smoke

Smoke is usually detected by optical systems based on the principle of reflection. Light emitters and light receivers are used and the loss of light intensity caused by smoke is what triggers the alarm.

- Heat

In this case, the ambient temperature is measured by the detector. The alarm threshold is a maximum temperature value. When this is exceeded, the alarm is activated by the system.

- Flames (radiation)

Flame is a fire phenomenon that results in the emission of radiation. Flame detection uses light-sensitive sensors that trigger an alarm when a certain radiation is received.

As a result, the fire detection technologies are developed based on these basic principles. Specifically in road tunnels, the methods that are basically used for fire detection are:

- Linear heat detection: a continuous heat detection cable able to detect fires across the whole tunnel length
- Closed-circuit television: using cameras to monitor the environment and detect fire incidents
- Video image smoke detection
- Flame detection
- Smoke and heat detectors
- Spot-type heat and smoke detection

4.4.2.2 Activation

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. 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 [6].

5 FFFS used worldwide

Currently there is no European country with national regulations, basically promoting the use of FFFS. Regardless of this situation, there is a growing recognizable tendency to equip tunnels, especially new ones with such systems [3]. According to references [23], [24], [25] and [26] the following are countries which contain FFFS in tunnels:

1) 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 [3]

2) Denmark

Currently there are no road tunnels in Denmark fitted with a FFFS although retrofitting the Øresund Tunnel is being contemplated [3]. This passageway is already equipped with a water mist system to protect it against cable fires, in contrast to the running tunnels.

3) Finland [3]

The first road tunnel was provided with a FFFS on a water mist basis at the end of 2009. It was installed in the 2 km long “Keskustan huoitotunnell, KEHU” – Helsinki Service Tunnel.

4) France

The A86 tunnel in Paris is still the sole project, involving a FFFS (water mist system).

5) Great Britain

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

- Tyne Tunnel (Fogtec 2009)
- Dartford Tunnel

6) Sweden
    - Tegelbacken Tunnel
    - Klara Tunnel
    - Northern Link Tunnel
    - Gnistängs Tunnel

7) 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 FFFS.

8) Netherlands

Two projects involving FFFS in road tunnels have been pursued in the Netherlands. Both these tunnels possess twin bores with one-way traffic, equipped with a longitudinal ventilation system:

- Roermond Tunnel
- Swalmen Tunnel

9) Norway

Two tunnels are equipped with FFFS in Norway:

- Fløffjell Tunnel
- Vālreng Tunnel

10) Germany

The Pörzberg Tunnel in Thuringia

11) Austria

Two FFFS are operating in Austria (as of 2011):

- Felbertauern Tunnel
- Mona Lisa Tunnel in Linz

12) Spain

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

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

13) USA

Currently six tunnels in the USA are equipped with FFFS. 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 (*FFFS without foam-forming additives):

- Boston Massachusetts
    - CANA Northbound
    - CANA Southbound*),
- Settle Washington
    - Battery Street,
    - I90 First Hill Mercer Island*),
    - Mt. Baker Ridge*),
    - I-5 Tunnel*).
- Vancouver, British Columbia
    - George Massey tunnel

14) Australia

Road Tunnels in Australia with FFFS, [6]

- Lane Cove Tunnel
- M5 East
- Cross City Tunnel
- Sydney Harbour Tunnel
- Eastern Distributor
- Burnley Tunnel
- Kemp Place Tunnel
- Inner City Bypass (Tunnel A)
- Inner City Bypass (Tunnel B)
- Inner Northern Busway
- Southern Crossing Tunnel Adelaide Hills
- North/South Busway Tunnel

- Melbourne
- Graham Farmer Tunnel
- M5 East Tunnel
- M4 Tunnel
- M7 Clem Jones Tunnel
- Airport link

15) Japan

FFFS, usually water spray systems, are applied in Japanese road tunnel according to national standards. Since the late-1970s more than 80 tunnels have been fitted with firefighting systems [7].

16) Abu Dhabi

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

6 Tenable Environment

The goals of the longitudinal ventilation system, in addition to addressing fire and smoke emergencies, are to assist in the containment and purging of hazardous gases. The purpose of using FFFS is to reduce the fire size, fire growth rate and reduce the risk for fire spread between vehicles. A consequence of using FFFS is also to improve the tenable conditions for the evacuees.

Fire produces high temperatures, heat radiation, low concentration of oxygen, low visibility, and different lethal toxic and/or corrosive gases. All of these physical phenomena, some of which can be calculated with some accuracy, can be dangerous to people, construction, equipment, and vehicles. The tenable environment is an environment that supports human life for a specific period of time [6]. In the following a description of each of these parameters are given in order to put it into the context of using either ventilation, or FFFS or both.

6.1 Gas concentrations

The reason for fatalities in fires is most often due to inhalation of toxic gases. Increased temperature can, however, affect both the physical health and the capacity to escape. The toxic gases produced form a fire are normally categorized into one of two groups based on the effects on humans. These two groups are asphyxiant gases and irritant gases. The irritant gases cause sensory irritation to the eyes, nose and upper respiratory system with also some hypoxia due to breathing difficulties and can thus impede escape significantly. Inhalation of higher doses can cause lung inflammation and oedema, which might result in death sometime after exposure. For sensory irritation the effects does not depend on the dose but occur immediately upon exposure [27]. The effects of irritant gases will not be discussed further since it is not in the scope of this thesis.

The asphyxiant gases also called narcotic gases, may cause confusion and loss of consciousness followed by death from asphyxia when a sufficient dose has been inhaled [27]. Some of the gases found in this group are carbon monoxide (CO) and hydrogen cyanide (HCN), however; also carbon dioxide (CO_2) and oxygen (O_2) are included in this group. Among these gases, carbon monoxide (CO) is seen to be an important component responsible for causing fatalities, even the effect of hydrogen cyanide (HCN) has been considered to be one of the most toxic gas, which is extremely dangerous for humans to inhale as shown in Table 4. Carbon dioxide (CO_2) has an important affect, both by being at high levels, but mostly by the increasing the uptake of other toxic gases. Although not all toxic gases don't led to fatalities, sub lethal effects, e.g. incapacitation, decreased walking speed, lowered motor capability, and visual obscuration are also important. Many gases can cause long term or chronic effects, which is relevant for the fire fighters and rescue personal.

Table 4 Tenability limits for asphyxiant gases as in ISO/TR 9122 -1 redrawn from [27]

Species	5 min		30 min	
	Incapacitation	Death	Incapacitation	Death
CO	6000-8000 ppm	12000-16000 ppm	1400-1700 ppm	2500-4000 ppm
HCN	150-200 ppm	250-400 ppm	90-120 ppm	170-230 ppm
Low O_2	10-13 %	< 5%	<12 %	6-7 %
CO_2	7-8 %	>10%	6-7 %	>9 %

6.2 Carbon monoxide content

Carbon monoxide is produced from all incomplete and is always present among the products from a fire. Depending on the condition the concentration of CO may be very high and reach several thousand part per millions (ppm). It is produced from pyrolysis and during flaming combustion with vitiated oxygen concentration conditions. It may also be formed in the hot gas layers depending on the temperature and chemical composition of the material [27].

6.2.1 Toxicity of CO

The toxicity of fire smoke is determined primarily by a small number of gases, which may act additively, synergically, or antagonistically [6]. The toxic effect of CO is due to a combination with haemoglobin in the blood to form carboxyhaemoglobin (COHb) [28].

Carbon monoxide combines readily with haemoglobin to form COHb and the CO is not readily released. Thus the amount of COHb increases steadily as CO is inhaled up to well defined saturation levels that depend on the concentration in the inspired air [27]. The toxicity CO is, however, dependent on the accumulated dose of COHb, usually expressed as the percentage of the total haemoglobin present as COHb as shown in Table 5.

Table 5 Summary of health effects at different COHb levels redrawn from [28].

COHb level [%]	Effect
10	Asymptomatic or headache
20	Dizziness, nausea, and dyspnea
30	Visual disturbance
40	Confusion and syncope
50	Seizures and coma
≥ 60	Cardiopulmonary dysfunction and death

The lethal level of CO has a strong dependence on the characteristics of the victim. The most important factors, however, seem to be the age and the physical condition of the victim, although such factors as blood-alcohol levels also have an influence.

6.3 Low Oxygen Content

Oxygen is consumed from the atmosphere when the combustibles are being burned during fires. Hypoxia can be caused by exposure to low oxygen concentrations in fire atmospheres. Incapacitation due to hypoxia occurs when the oxygen supply to the brain falls below a certain value [29].Table 6 details the effects on human beings exposed to different oxygen concentrations in the respired air.

Table 6 Effects on human beings exposed to different oxygen concentrations redrawn from [27].

Concentration (%)	**Effect on human**
20.9-14.4	No significant effects, slight loss of exercise tolerance.
14.4-11.8	Slight effects on memory and mental task performance, reduced exercise tolerance.
11.8-9.6	Severe incapacitation, lethargy, euphoria, loss of consciousness.
9.6-7.8	Loss of consciousness, death.

In humans there is a little effect down to 15% oxygen beyond a slightly reduced exercise tolerance, however at around 10% oxygen the effects become severe. Due to physiological compensatory mechanisms there is a very little effect until a certain point is reached when the tissue hypoxia becomes critical. This endpoint marks the sudden change from a condition of near normality, to a condition in which escape would not be possible [27].

6.4 Carbon Dioxide Content

Carbon dioxide is not a particularly toxic at levels observed in fires, although moderate concentrations can stimulate the rate if breathing. This condition may add to the fire situation by causing an increase in the uptake of other toxicants. However, at very high concentrations of carbon dioxide (greater than 5%) can also have toxic effects. At these concentrations they may be considered as an asphyxiant or narcotic gas. In Table 7 indicates the human responses of higher carbon dioxide exposures. To threaten an exposed person’s ability to escape on his own the carbon dioxide content in air must exceed 10%. Concentrations of this order of magnitude are usually encountered in enclosed fire atmospheres [27].

Table 7 Carbon dioxide (CO_2) responses redrawn from [27]

Concentration (%)	**Effect on human**
2	The rate and depth of breathing is increased with 50 %.
3	The rate and depth of breathing is doubled.
5	The rate and depth of breathing is tripled.
3-6	Carbon dioxide there is a gradually increasing degree of respiratory distress, which becomes severe at 5-6 %.
7-10	Dizziness, drowsiness and unconsciousness is superimposed on the severe respiratory effects.

10	Approaches threshold of human unconsciousness in 30 minutes.
12	Threshold of unconsciousness reached in five minutes
15	Exposure limit of one minute.
20	Unconsciousness occurs in less than one minute.

6.5 Heat Effects

Another threat from fires that may incapacitate people and hinder evacuation is heat, which perhaps is quite obvious. The exposure of evacuees to heat may can threaten life in three basic ways:

- Hyperthermia,
- Body surface burns, and
- Respiratory tract burns.

For prolonged exposure to a hot environment there is a risk for incapacitation and even death from hyperthermia. The risk increases for a fully clothed person and is further increased by a high activity and high moisture content of air. Even at lower temperatures where no burns are caused, prolonged exposure can result in an increased body temperature, i.e. hyperthermia [27].

Thermal tolerance data for unprotected skin suggest a limit of 120 °C for convective heat. Above this limit considerable pain occurs along with burns within few minutes [29]. Depending on the length of exposure, convective heat below 120 °C may still result in incapacitation due to heat stroke or hyperthermia [27]. Examples of tolerance times to different air temperatures are shown in Table 8.

Table 8 Limiting conditions for tenability caused by heat redrawn from [27]

Mode of heat transfer	**Intensity**	**Content of water**	**Tolerance time**
Convection	<60 °C	100 % (saturated)	>30 min.
	100 °C	<10 %	12 min.
	120 °C	<10 %	7 min.
	140 °C	<10 %	4 min.
	160 °C	<10 %	2 min.
	180 °C	<10 %	1 min.

Note that thermal burns to the respiratory tract from the inhalation of air containing less than 10% water vapor by volume do not occur in the absence of burns to the skin (the face); therefore, tenability limits with regard to skin burns normally are lower than for burns to the respiratory tract [6]. However, thermal burns to the respiratory tract can occur upon inhalation of air with a temperature above 60°C (140°F) that is saturated with water vapor.

6.6 Visibility

In a tunnel environment, visibility tends to be the most restrictive criterion for tenability. Evacuation can be significantly hindered by poor visibility. For acceptable visibility and, therefore, safe evacuation, reliable and robust control of airflow velocity is essential at all times [30]. The acceptance criteria for visibility within a tunnel is visibility ≥ 10 m [5].

7 Fire test

In order to obtain a better understanding of the effects of different parameters on the survivability of evacuees using ventilation or FFFS, or both, analysis of performed fire test is necessary. In order to do this, information from already performed tests that had not been analyzed in accordance to the aim of this study, was provided in order to be carried out within the frame of the thesis. In the following a short description of different tests using FFFS are shown. After that an analysis of two test series will be carried out. The results are presented in chapter 8.

Fire tests are of vital importance in the understanding of the physics of tunnel fires, understanding the impacts of fires, and for verifying calculations, assumptions, computer models, and tunnel design. They are also important for tunnel operators and emergency responders in their efforts to coordinate and verify in practice the emergency response plans [8]. These test can be expensive to carry out in large or full scale scenarios, however, the information gathered can help clear doubts with reference to HRR, protection of lining material and installations in tunnels. Measurements obtained in these test require advanced data analysis and instrumentation.

7.1 A series of selected FFFS test in tunnels

Most of the studies adopted scenarios where the fire was shielded by the vehicle body. Pool fires and wood crib fires which were shielded or half shielded were used as fire sources. Real vehicle fires as well as simulated HGV fires were also tested, and in some tests, some obstructions were placed to simulate possible traffic conditions. Many of the tests were conducted under longitudinal ventilation and FFFS. This section gives a summary of each study, and the overall results found from these studies are discussed below.

7.1.1 UPTUN If tunnel tests

The purpose of the UPTUN If tunnel tests was to evaluate the efficiency of a water mist FFFS. A total of 19 tests using a low pressure water mist FFFS and a total of 56 tests using a high pressure water mist FFFS were run in the "If-sikkerhetssenter" tunnel which is arched, 8.07 m wide, 5.05 m high, and 100 m long. The fire scenarios used in the tests were similar to the ones used in the UPTUN DMT tunnel tests. They used a pool fire divided with four vessels. The half of the pool area was covered. Each pool vessel could generate a HRR of 4-5 MW; however, the fire sizes were affected by the ventilation conditions as well as by the pool cover. In addition to the pool fires, wood pallet fires generating 20-25 MW and real vehicle fires were also tested [26].

The layout of the water mist FFFS was designed to cover the pool fire area as well as 14 m downstream of the fire. Parameters tested in the study were the droplet distribution and droplet sizes as well as the discharge rates. For the low pressure water mist system, a total of 30-40 nozzles covering an area of 140 -210 m^2 was distributed at the ceiling of the tunnel. Total water flow rates ranged from 221 to 683 1/min. For the high pressure water mist FFFS, a total of 7 to 14 nozzles were used covering an area of 230 ~ 290 m^2 and the total water flow rates ranged from 140 1/min to 550 1/min. HRR, gas concentrations, and smoke density were measured [31]. The temperatures in the fire area and 25 m downstream of the fire were also measured. Results showed satisfactory mitigation of the fires with a fraction of water discharge rates of traditional sprinklers systems.

7.1.2 The San Pedro de Anes tests [32]

High pressure water mist tests were carried out in the San Pedro de Anes test facility in Asturias, Spain, in 2006. The tunnel facility was 9.5 m wide and 600 m long, and the ceiling height was 5.2 m. Stacks of wood pallets with potential maximum HRRs from 30 MW and up to 100 MW were tested with longitudinal air velocities between 1.9 and 3.4 m/s. The water mist FFFS was installed directly over the fire, and the application density of the water mist system was in the range between 3.69 and 4.26 $1/min/m^2$. The HRR and temperature along the tunnel were measured. The study showed that the water mist system greatly reduced the HRR of the fire and temperature in the tunnel.

7.1.3 A86 tunnel tests [33]

A high pressure water mist FFFS was tested for passenger vehicle fires in tests conducted in the Hagerbach tunnel research facility in Sargans, Switzerland, which was recreated to simulate an 'A86' tunnel of 9 m wide and 2.5 m high. A realistic fire scenario was tested in the test program. In the scenario, a fire involving three vehicles was arranged, and, to examine fire spread, many other passenger vehicles were placed close to 3 m/s. Tenability conditions in the tunnel were examined using data for temperatures and gas concentrations. Results showed that the water mist FFFS prevented fire propagation and reduced the radiative heat flux. It was also observed that the visibility downstream of the fire improved with the water mist FFFS.

7.1.4 Benelux Tunnel Tests [8]

In the Benelux Tunnel, 14 fire tests were used to determine the benefits of fitting large drop sprinklers. These sprinklers were selected so that the large droplets would penetrate the powerful fire plumes and not be swept away by the tunnel ventilation. In the tests, with ventilation at up to 5 m/s (984 fpm), sprinklers reduced temperatures to safe levels upstream and downstream of the fire. They also reduced the probability of fire spread between vehicles.

8 Tunnel fire test with ventilation and FFFS experiments conducted at SP

8.1 Large-scale fire tests with different types of FFFS in the Runehamar tunnel [4].

Six large-scale tests with FFFS were carried out in the Runehamar tunnel in June 2016. The fire load consisted of 420 standardized wooden pallets and a target of 21 wooden pallets. The test setup was the same as for the tests carried out in Runehamar in 2013 [4]. Five of the tests were carried out with a 30 m long deluge zone delivering varying water densities using three different types of side-wall nozzle and an interval distance of 5 m. One test with 93°C glass-bulb nozzles (sprinkler head) in the same zone was also conducted (automatic sprinkler system). In the five deluge tests, the detection system was simulated using thermocouples in the tunnel ceiling. The alarm was registered when the ceiling gas temperature reached 141°C, and the system was activated manually after a delay of 4 minutes. The protection goal of the system was to prevent fire spread to a target positioned 5 m from the rear of the main fuel area, and to ensure that the fire did not exceed 30 MW in size [4]. The results of this test will be compared to a model scale test on the influence of fire suppression on combustion products in tunnel fires [34]. With reference to one of the objectives in this thesis, the effect of FED/FID will be determined using the results of this large scale will be discussed here.

8.1.1 Description of experimental setup [4]

The same FFFS setup was used as in the 2013 tests. The pipe was placed at the ceiling on one side of the tunnel, with nozzles discharging water towards the opposite wall and the fuel (see Figure 2). The water density in the deluge zone of the FFFS was the same as if the pipe had been located at the centre of a full-sized tunnel, where the system would be placed centrally and use a T-coupling to throw water symmetrically in both directions. The deluge zone was 30 m long, and the total water flow rate varied depending on the nozzle type used. In a full-sized tunnel, the deluge zone would be at least 50 m in length. A 600 m-long ground pipe (on the surface of the road) with a diameter of 140 mm (inside diameter of 127 mm) delivered the water from the water tank, located outside the tunnel portal. The ground pipe was connected to the ceiling pipe as shown in Figure 2. The water tank had a volume of 230 m^3, and was refilled between tests with groundwater from the nearby mountain. The total tank water was sufficient to maintain a 120 minute continuous delivery of water for each test, using a 55 kW electrical pump with a maximum flow capacity of 2300 lpm at 7 bar.

Figure 2 Test setup and FFFS *after activation. With permission of SP* [4]

The TN-25 is a horizontal spray nozzle with a K-factor of 362.9 l/min/bar$^{1/2}$ (25.2 gpm/psi$^{1/2}$), and is a specialized open-deluge nozzle for use in tunnel fire protection systems. Its minimum and maximum working pressures are 0.7 and 2.1 bar, respectively, according to the data sheet 5. The TN-17 is a prototype, and not currently available on the market. Its K-factor is 240 l/min/bar$^{1/2}$ (17 gpm/psi$^{1/2}$). The third nozzle was a SW-24, with a K-factor of 161.3 l/min/bar$^{1/2}$ (11.2 gpm/psi$^{1/2}$) and maximum working pressure of 12.1 bar. The SW-24 is an ECOH (Extended Coverage Ordinary Hazard) horizontal sidewall nozzle that uses a standard-response glass bulb, originally designed for use in ordinary hazard occupancies. The SW-24 sprinkler head used had a 3 mm-thick 93°C (green) glass bulb. In one deluge test with the SW-24 nozzles, the glass bulbs were removed prior to testing.

8.1.2 Fire source [4]

The fire source consisted of 420 wooden pallets placed in the centre of the tunnel, 600 m from the west portal. This type of test fuel mock-up is often used to simulate the payload of a Heavy Goods Vehicle (HGV) trailer. A target, consisting of a pile of 21 wooden pallets, was positioned 5 m from the rear of the fuel mock-up in order to evaluate the risk of fire spread.

The wooden pallets were placed on lightweight concrete slabs (Siporex), with 12 mm-thick plywood boards mounted on top of the slabs. Ten rows, each consisting of 2 piles of 21 pallets, were placed on the slabs, as was the target, which constituted one additional row. In Figure 3 , the main fuel load is shown in detail from the side. In order to maintain the correct distance between the sprinkler nozzles and the top of the fuel load, the concrete platform was 0.2 m high.

In total, the fuel load weighed just over 10 tonnes (441 x 24 kg). This meant that the potential energy content was approximately 180 GJ. The target consisted of 21 pallets, giving an additional energy of approximately 9 GJ, bringing the total to 189 GJ. The moisture content in the wooden pallets varied between 15 and 20%.

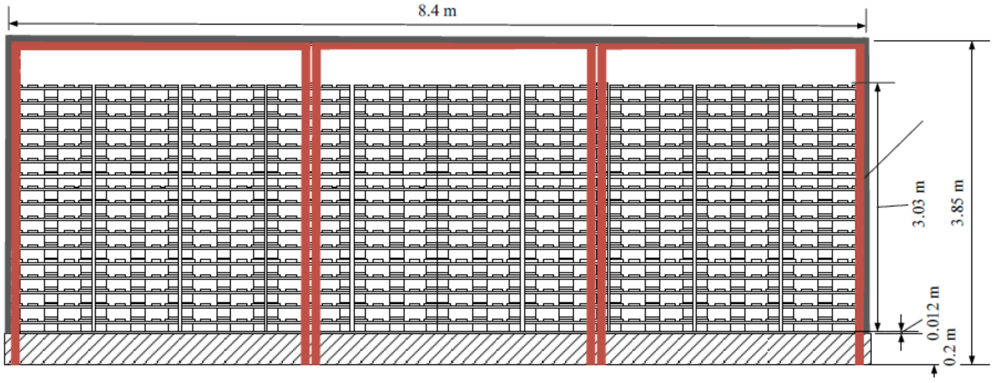

Figure 3 A side view of the fuel load, which consisted of 420 standard EUR wooden pallets. A steel frame was mounted to support the steel sheets that covered the wooden pallets at the ends and the top. With permission of SP [4].

8.1.3 Instrumentation [4]

Gas temperature, gas concentration, visibility, radiation, water flow rate, and water pressure were measured every second. The heat release rate in MW was determined by measuring the gas and air flows approximately 1000 m from the fire, where a measurement station was located at the point marked as ‘Pile A’, at x= c. 1000 m, in Figure 4 . In total, 22 thermocouples, 6 bi-directional pressure probes, 3 gas analysers (O2, CO2, and CO), 5 plate thermometers (PT), 2 photocells, 1 water pressure monitor, and 1water flow gauge were used in these tests. The location of each instrument is shown in Figure 4.

All of the ceiling thermocouples (Type K, 0.5 mm) were placed 0.4 m below the ceiling, except at pile A. PTs were mounted at the ceiling at x= -18, 0, 9, and 150 m in order to estimate the incident heat flux towards this position. There was also a PT 1.5 m above the road surface, at x= -18 m. All of the PTs were placed so that their plates always faced the fire source.

One of the two photocell visibility instruments was placed at the measurement station (x= c. 1000 m), with the other at x= 150 m. Smoke density was presented as a reduction (%) of air transparency over a given length (1.1 m), and was measured 1.5 m above the road surface. Air transparency was used to calculate visibility in m.

The thermocouples (Type K, 0.5 mm) were located close (50 mm away) to the nozzle positions N2, N4, and N6. The nozzles were positioned at the ceiling, 3.2 m from the centre line of the fuel load, and at a distance corresponding to x= -12.5 (N1), -7.5 (N2), -2.5 (N3), 2.5 (N4), 7.5 (N5), and 12.5 m (N6). The bidirectional probe and the thermocouple upstream at x= -50 m were placed at the centre line of the tunnel cross-section (see Figure 4)

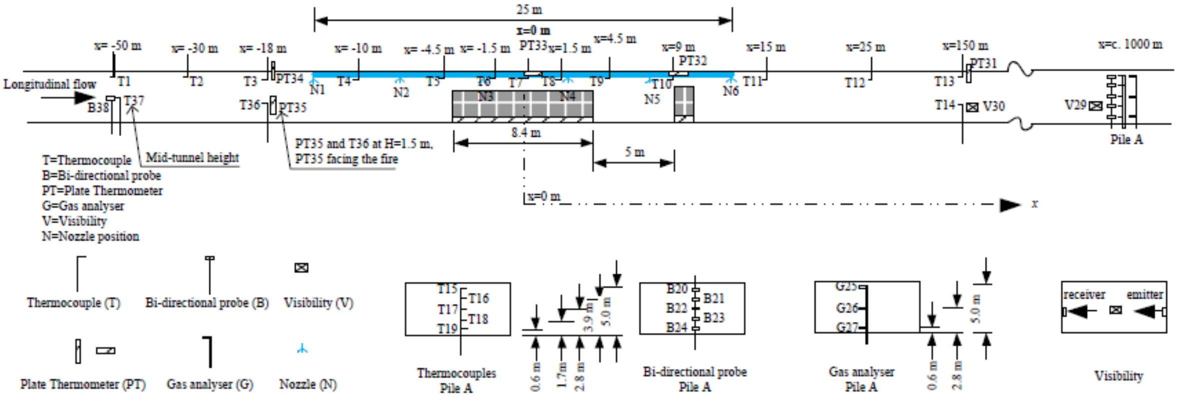

Figure 4 Layout of the instruments used in the test series. With permission of SP [4]

8.1.4 Test procedure [4]

For the tests that used the deluge system, a similar test procedure was used as in the 2013 tests, and the 2016 test programme is shown in Table 9 and Table 10 present the test sequence, test dates, and physical parameters that were varied. Five tests were performed with a deluge system (Tests 1-5), and one with sprinkler heads that used glass bulbs (Test 6).

To mimic a real detection scenario for the deluge system, the detection temperature was set at 141°C, and the first ceiling thermocouple to register this temperature was used as starting time (alarm) for the delay period. In all five tests the thermocouple at x= 4.5 m (7.3 m from the centre of the first row of piles, where the fire was ignited) reached the 'detection' temperature first. A four-minute 'delay' between detection (alarm) and activation was implemented for Tests 1-5 in order to simulate the manual operation time that a traffic control centre takes to initialize activation. In this thesis only test 1 and 6 will be analyzed and discussed.

Table 9 Test programme of the 2016 large-scale test in the Runehamar tunnel redrawn from [4]

Test number	Test date	Nozzle type	K-factor	Flow rate per nozzle	Total flow rate	Nozzle Pressure	Ventilation velocity
	June 2016		l/(min·bar$^{1/2}$)	l/min	l/min	bar	m/s
1	13	TN-25	360	300	1800	0.69	3
2	14	TN-17	240	268	1608	1.25	3
3	15	TN-17	240	233	1400	0.95	3
4	16	TN-25	360	268	1608	0.55	3
5	17	SW-24	160	233	1400	2.13	3
6	20	SW-24 bulb	160	298	-	-	2

Table 10 Activation times recorded during the tests redrawn from [4].

Test number	Time of detection at 141°C (min:s)	Time of water at nozzles (min:s)	Time of fully developed flow in nozzles (min:s)
1	3:55	7:53	8:16
2	3:42	7:52	8:15
3	3:27	7:44	8:12
4	4:17	8:22	8:47
5	4:06	8:10	8:33
6	-	N4; 5:22 N5; 5:456 N3; 6:47 N6; 30:56	-

The longitudinal velocity during all of the deluge tests was set at 3 m/s, corresponding to a critical velocity for this type of tunnel and no backlayering of smoke. The velocity in Test 6, which used sprinkler heads, was set at 2 m/s, as it is known that, in the real tunnel in which these sprinkler heads are to be installed, the longitudinal velocity is lower than 2 m/s. An additional reason for this relates to safety, in that the decision was made in order to prevent long backlayering.

As previously mentioned the above test setup was a replica of a Runehamar test conducted in September 2013 [2]. In Table 11, the test sequence and parameters varied are given. From the table stated above, test 6 contained a special condition which relevant for this thesis and will be discussed in part 8.4.

Table 11 Test series for the STA large scale tests in Runehamar tunnel in September 2013 redrawn from [2].

Test number	Special conditions	Delay time after 141$_{o}$C in ceiling (min)	Time of detection at 141$_{o}$C	Time of activation after ignition (min:sec)
1		2	4:04	6:04
2		4	4:20	8:20
3		8	5:18	13:18
4	tarpaulin	4	14:25	18:25
5	no steel blockage	4	3:17	7:17
6	**”free burn”** (due to failure in one of the bolt in a coupling, very little water was delivered on the fire. Most of it bypassed the fire as the main pipe was off just behind the fire source)	12	3:48	15:48

In the last test (test 6), the water supply was originally planned to activate 16 minutes after detection, but already after 12 minutes it was realized that the situation might be too challenging for the tunnel structure. Therefore it was decided to activate the system after 12 minutes from detection. Unfortunately, nearly no water reached the fire since a bolt in one of the couplings to the main supply pipe in the ceiling broke due to the repeated mechanical loads and heating from the previous tests [2].

8.2 Model scale influence of fire suppression on combustion products in tunnel fires

A series of pre-tests and a series of model scale tunnel fire tests with and without FFFS were carried out to investigate the effect of water sprays on production of key combustion products. The key parameters accounted for in the tests include fuel type, ventilation velocity and activation time [34].

The focus of the study was on production of CO, visibility and soot production and put it into the context of corresponding free burning fire load without any interaction of FFFS. The main concern is whether the FFFS can cause adverse effects on the conditions inside the tunnel [34].

8.2.1 Description of model scale tunnel fire test experiment setup

8.2.1.1 Tunnel fire tests [34]

For the fires of all the three types of fuel, i.e. wood pallet, PE crib and PUR crib, the effect of ventilation velocity on the maximum heat release rate is insignificant. The fire appears to grow more rapidly at a higher ventilation velocity. After activation of the FFFS with a water density of 5 mm/min (10 mm/min at full scale), the fires were effectively suppressed under all the velocities tested, with or without coverage.

The CO yields in the free burn tests tend to decrease slightly with the ventilation velocity and the time. In the test with fire suppression, the CO yields generally increase with the decreasing heat release rates. In tests with later activation after the heat release rate was decrease to around 100 kW to 200 kW (3MW to 6 MW at full scale), significant increase in CO yield could be observed, especially for wood pallet fires. The production of the CO production mainly occurs when the fire is close to the extinguishment. Given that the maximum CO concentration at mid tunnel height in the free burn test is still the highest for all the fuels and velocities tested, the free burn test could still represent the worst scenario from the point of view of CO concentration and evacuation. Further, early activation reduces the CO concentration significantly.

8.2.1.2 Scaling theory

The Froude scaling technique was applied. Although it is impossible and in most cases not necessary to preserve all the terms obtained by scaling theory simultaneously, the terms that are most important and most related to the study are preserved [34].

The thermal inertia of the involved material, turbulence intensity and radiation are not explicitly scaled, and the uncertainty due to the scaling is difficult to estimate. However, the Froude scaling has been used widely in enclosure fires. Our experience of model tunnel fire tests shows there is a good agreement between model scale and large scale test results on many focused issues [34].

The model tunnel was built in a scale of 1:4, which means that the size of the tunnel is scaled geometrically according to this ratio. The scaling of other variables such as the time and temperature can be seen in Table 12. L is the length scale (m). Index M is related to the model scale and index F to full scale.

Table 12 A list of scaling correlations for the model tunnel

Type of unit	Scaling model
Time *t* (s)	$\frac{t_F}{t_M} = \left(\frac{L_F}{L_M}\right)^{1/2}$
Velocity u (m/s)	$\frac{u_F}{u_M} = \left(\frac{u_F}{u_M}\right)^{1/2}$
Temperature *T* (K)	$T_F = T_M$

8.2.1.3 Model scale tunnel

The model scale tunnel was 15 m long, 2.8 m wide and 1.4 m high. The scaling ratio is 1:4 compared to a normal sized road tunnel. This suggests that the corresponding full scale dimensions were 60 m long, 11.2 m wide and 5.6 m high, respectively [34].

The model tunnel, including the floor, ceiling and one of the side walls, was constructed using non-combustible, 15 mm thick Promatect H boards. Several windows (300 mm x 300 mm) are placed on one side of the tunnel. The model tunnel was built on a platform and the tunnel floor was 0.8 m above the floor level of the lab. An axial fan was used to produce the flows inside the tunnel. The end of the tunnel was set below a smoke hood through which the smoke was exhausted to the central system [34].

8.2.1.4 FFFS

In most of the tests, the FFFS was designed to cover a region of 7.5 m, corresponding to 30 m in full scale. In the tunnel fire tests, the T-Rex nozzles were used. The T-Rex nozzles in model scale have a K factor of 22.5, corresponding to 360 in full scale [34]. A total of 6 couples of T-Rex nozzles, were placed along the centre line of the tunnel, see Figure 6. All the T-Rex nozzles were placed approximately 100 mm below the ceiling. Note that at each position, one couple of T-Rex nozzles was placed.

The FFFS with the scaled T-Rex nozzles is shown in Figure 6. The pipes have a diameter of 30 mm. The interval between the nozzles are 1.25 m, corresponding to 5 m in full scale. The FFFS delivers a water flow rate of 5 mm/min on the floor level.

8.2.1.5 Ventilation system

Two axial fans were attached to the upstream end of the tunnels to produce a longitudinal flow in the tunnel. The fans were BRV 710 with a diameter of approx.

0.71 m. Together they can produce a maximum longitudinal flow of over 3 m/s in the model tunnel, corresponding to 6 m/s in full scale. In the model scale tunnel tests, the longitudinal ventilation velocity in the tunnel was set to be 0.75 m/s, 1.5 m/s, or 3 m/s [34].

8.2.1.6 Fire load

The Heavy Goods Vehicle (HGV) mock-up was simulated using three different types of fuels. The fuels were placed in a 1 m diameter steel pan with approximately 80 mm high rims. The steel pan was placed on a weighing platform for measurement of the fuel mass loss rate [34].

In some test, two piles of wood pallets were used as the fire source, as shown in Figure 5 Fuel arrangement. 1/2 standard Europe wood pallets (pine) were used as fuels. In some tests the front, the back side and top of the fire load were covered by steel plates.

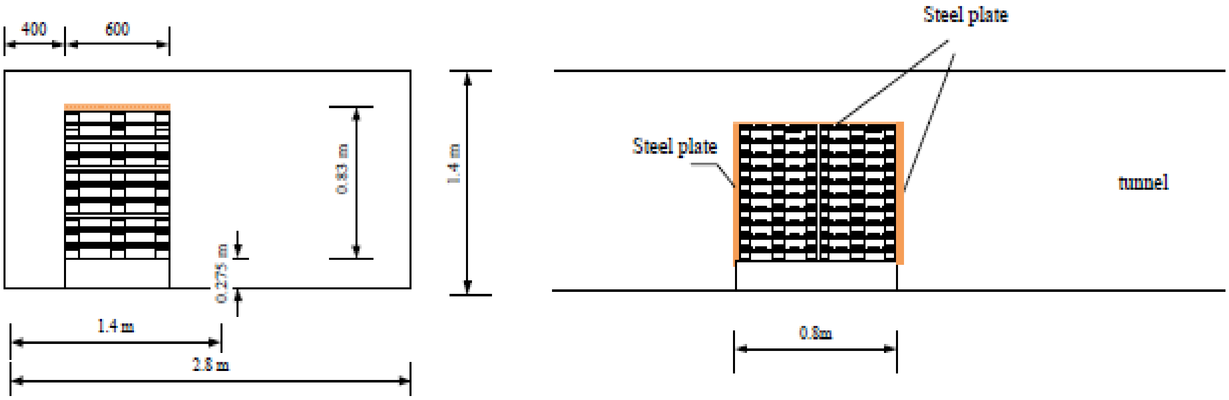

Figure 5 Fuel arrangement. With permission of SP [34]

8.2.1.7 Measurement [34]

In total, 12 thermocouples, 1 plate thermometers, 6 bi-directional pressure tubes, and 3 gas analyses were placed in the tunnel, see Figure 6. All ceiling thermocouples were placed 100 mm below the ceiling, except at Pile A. One plate thermometer was attached to the ceiling right above the fire source. At pile A, the bidirectional tubes were placed at the center, and the gas analysis and thermocouples were placed horizontally 50 mm from the gas analysis. Two laser/photocells were installed at pile A. The distance between the emitter and receiver is 0.4 m.

Measurements at pile A are used to estimate the flow rate, heat release rate, CO production and soot production. In the tunnel tests, superposition of individual horizontal cross sections are applied for all the parameters.

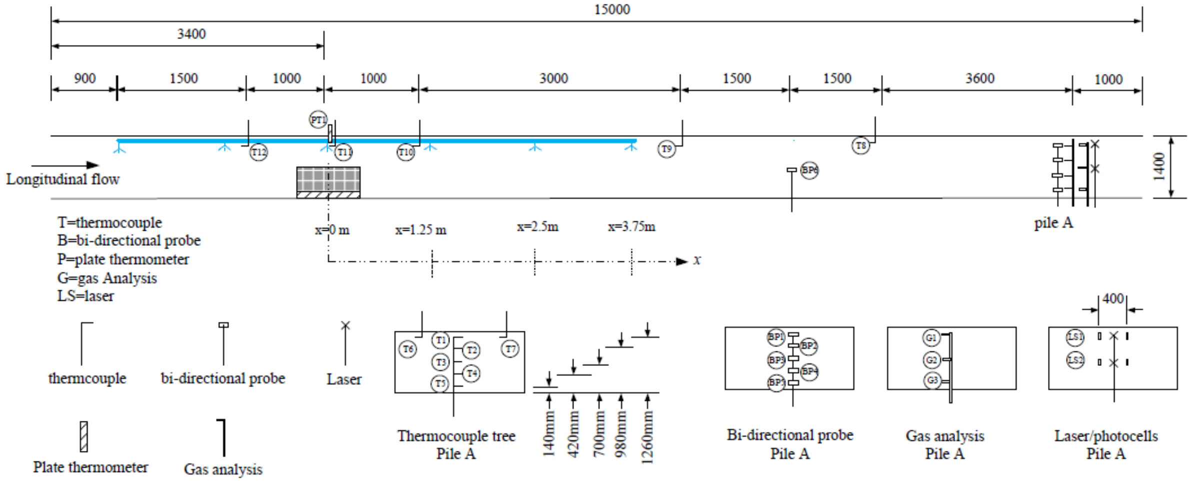

Figure 6 Layout and identification of instruments in the series of tunnel fire tests (dimensions in mm). With permission of SP [34]

8.2.1.8 Tunnel fire tests

A series of tunnel fire tests with and without FFFS was carried out. A summary of these tests is presented in Table 13. By default there was no coverage of the fuel used in the test. At a given velocity, the free-burn test was carried out followed by FFFS tests with different activation time (after ignition) [34].

In all the wood pallet fire tests, the measured humidity was approximately 10 %.

Table 13 Summary of tunnel fire tests [34]

Test no.	Fuel type	Type	Ventilation velocity (m/s)	Activation time (after ignition) (min)
1	Wood	Free-burn	1.5	-
5	Wood	FFFS	1.5	04:24
7	Wood	FFFS	1.5	05:27
14	Wood	Free-burn	3	-
17	Wood	FFFS	3	01:12
19	Wood	FFFS	3	03:18

8.3 Calculation of FED/FID

In order to evaluate the results from experimental data found from scale models and full scale SP data, a FED analysis of the smoke layer at human level height is appropriate. A general method when estimating the toxicity of a smoke composition is to assume that the effects of the individual toxicants are additive, and in this sum for each toxicant express the concentration as its fraction of the lethal concentration (LC_{50} value), the latter estimated to be lethal for 50% of the population for a 30 min exposure [5]. The focus will be the time it will take for a person to be affected by fractional effective dosage or the fractional incapacitation (or partial incapacitation), which will prevent evacuation and in turn may increase the risk for lethality in the end. The FED for incapacitation (or fraction of an incapacitating dose) are calculated based on equations given by Purser and Stewart [29].

The Stewart equation can be rewritten in the form of COHb ratios, requiring only a knowledge of the CO concentration and the exposure time, as follows:

$$F_{I_{CO}} = \frac{k(ppmCO^{1.036})(t)}{D} \qquad (1)$$

Where:

$F_{I_{CO}}$ = fraction of incapacitating dose

t = exposure time (min)

K = 8.2925 x 10^{-4} for 25 L/min RMV (light activity)

D = COHb concentration at incapacitation (30 percent for light activity)

This concept of Ct product fractional dose is also useful for predicting incapacitation and death from other fire products, and combinations of products [29].

Carbon dioxide (CO_2), like carbon monoxide, is universally present in fires. Although carbon dioxide is not toxic at concentrations of up to 5 percent it stimulates breathing, so that at 3 percent the RMV is approximately doubled, and at 5 percent tripled 25. This hyperventilation, apart from being stressful, can increase the rate at which other toxic fire products (such as CO) are taken up.

For asphyxiant gases such as CO it is likely that the increased uptake resulting from carbon dioxide induced hyperventilation will significantly reduce time to incapacitation and death.

$$F_{I_{O2,n}} = \frac{t_n - t_{n-1}}{exp\left(8.13-0.54\left(20.9-C_{O2,n}\right)\right)} \qquad (2)$$

Where $C_{O2,n}$ is the concentration of O_2 (in %) during the time step.

The fraction of incapacitating dose for all asphyxiant gases (excluding effects of irritants), $F_{IN,}$ can be written (for a certain time step):

$$F_{IN,n} = F_{I_{CO},n}.V_{CO_2,n} + F_{I_{O_2},n} \qquad (3)$$

Where,

$$V_{CO_2,n} = \frac{exp\left(0.1903C_{O2,n}+2.0004\right)}{RMV_r} \qquad (4)$$

Is the multiplying factor for the enhanced uptake of asphyxiant gases (other than CO_2) due to induced hyperventilation, $V_{CO_2,n}$ is the concentration of CO_2 (in %) during the time step, and RMV_r

Is the resting RMV (7.1 L/min is used).

This has been simplified to

$$VCO_2 = exp\left(\frac{[CO_2]}{5}\right) \tag{5}$$

At concentrations of approximately 5 percent and above carbon dioxide is itself an asphyxiant, but for elevated CO_2 concentrations (hypercapnia) the change in the degree of incapacitation with exposure concentration is more gradual than with hypoxia [29]. The total fraction of an incapacitating dose is calculated as the sum:

$$FI(t = t_N) = \sum_{n=2}^{N} F_{IN,n} \tag{6}$$

Since the asphyxiant effect of CO_2 is not additative to the effects of the other gases it is not included in equation 3.

The temperature also affects the evacuation of people and the operation of the firefighters. To make evacuation possible, the radiation level must be under the limit that causes severe pain on bare skin for an exposure time of several minutes: the threshold value is roughly 2 to 2.5 kW/m^2. Firefighters can normally withstand a radiation level of 5 kW/m^2 for at least seven minutes because of protective clothing. These levels were never reached at the measurement station in pile A.

The amount of time to incapacitation, when exposed to convective heat from air containing less than 10% water vapor by volume was calculated by using either equation 8. The FED of convective heat accumulated per minute is the reciprocal of t_{Iconv}.

Convective heat accumulated per minute depends on the extent to which an exposed occupant is clothed and the nature of the clothing. For fully clothed subjects, equation 8 was used:

$$t_{Iconv} = (4.1 \ x \ 10^8)T^{-3.61} \tag{8}$$

Where:

t_{Iconv} = time (minutes); and

T = temperature (°C).

A methodology based on additive FEDs, similar to that used with toxic gases, was applied. Since the temperature in the fire was increasing, the total fractional effective dose of heat acquired during an exposure can be calculated using equation 9.

$$FED = \sum \left(\frac{1}{t_{Irad}} + \frac{1}{t_{Iconv}} \right) \Delta t_{t_1}^{t_2} \qquad (9)$$

Note 1: in areas within occupancy where the radiant flux to the skin is under 2.5 kW/m^2 the first term in equation 9 is set to be zero [8].

The criteria for asphyxiant gases must be based on doses rather than on concentration. Thus, if the concept of fractional effective dose (FED) is used. The following accept criteria for heat exposure, toxic gases and reduced visibility are proposed [27]:

- Visibility ≥ 10 m
- Convection (temperature) ≤ 60 °C
- Radiation ≤ 2.5 kW/m^2
- Toxic gases: The model of Purser [29]: $FI_{tot} < 1$ (or FED)

Note that, the criteria FI = 1 relates to a limit at which 50 % of the population would be expected to experience tenable conditions, while 50 % would be expected to experience compromised tenability [35].

The computer program Hazard I (NIST, USA) for prediction of fire growth and smoke transport define the tenability limits shown in Table 14.

Table 14 Tenability limits used in Hazard I redrawn from [36]

Cause	Incapacitation level	Lethal level
Temperature (°C):	65	100
Toxic gases*	0.5	1

* FED due to CO, CO_2 and O_2 [36].

Here incapacitation of some human is assumed to be achieved at a dose equal to half of the lethal dose, i.e. FED = 0.5. ISO/TS 13571 [37] proposes that incapacitation occurs even smaller dose in relation to the lethal dose, i.e. incapacitation occurs at FED = 0.3 [27].

8.4 Discussion of Results

The tenability limits for asphyxiants, concentrations at which there would be danger of incapacitation (loss of consciousness) and death after approximately 5 and 30 minutes exposure in a person engaged in light activity [29] shown in Table 4, is used as reference for exposure time.

Table 15 and Table 16 shows the results from the large scale Runehamar test and a model scale tunnel fire using the equations stated above to calculate the fractions of effective dose.

Some of the measurements were not available at the height of 1.7 m above the road surface and for the carbon dioxide concentration at a height of 2.8 m, therefore Newman correlation [38] was used to calculate the gas concentrations at that height. This correlation assumes that the local gas temperature and the local gas concentration correlate through the average values. The fundamentals of this correlation were given by Heskestad in 1980, for fire plumes impacting on horizontal ceilings. Newman tested the correlation for different types of fuels placed in a test gallery representing a duct or a mine [38]. These correlations have been validated by Ingason [38] for tunnels.

A great extent of uncertainties affects the derived results. Worth mentioning is the model uncertainties, and the experimental uncertainties. However, as a relative comparison is made between two more or less identical tests (with several experimental variable being changed), it is deemed valid to compare the results.

The correlation given by Newman [38] is as follows:

$$\frac{X_{i,h}}{X_{i,avg}} = \frac{\Delta T_h}{\Delta T_{avg}} \tag{7}$$

where $X_{i,h}$ is the concentration of species i at height h, $X_{i,avg}$ is the average concentration of species i, ΔT_h is the difference between the temperature at height h and the ambient temperature, and ΔT_{avg} is the average temperature rise relative to ambient temperature, T_a.

Other heights of 0.6 m and 2.8 m are also evaluated to compare the FED effects from asphyxiant and heat convection to the height of 1.7m from the road surface, there results are shown in appendix 1. In appendix 2, the individual contributions of CO, O_2 and temperature with and without FFFS in a large scale test and a model scale tunnel fire under different ventilation velocities and an exposure time of 30 mins full scale (15 mins model scale) are shown.

Table 15 Results of FED concentration after 30 minutes for a large scale Runehamar and model scale test at 1.7m

Test		Type	Ventilation Velocity (m/s)	Distance (m)	Temperature (^{o}C)	Time 30 min	
						FED $_{\text{asphyxia}}$	FED $_{\text{heat conv.}}$
Runehamar 2016	1	FFFS	3	1000	15	0.4780	0.0013
	6	FFFS	2	1000	20	0.5141	0.0008
Runehamar 2013	6	Free burn	3	1000	24	0.1382	0.0020
Model scale	1	Free burn	3	42	72	0.0107	0.1400
	5	FFFS	3	42	18	0.0086	0.0041
	7	FFFS	3	42	28	0.0126	0.0109
	14	Free burn	6	42	68.4	0.0116	0.3741
	17	FFFS	6	42	18	0.0044	0.0027
	19	FFFS	6	42	21	0.0065	0.0091

In Table 15 details the results of the large scale Runehamar tests and model scale test at distances 42 m and 1000m away from the fire. Due to the difference in the length of the observations one can anticipate that there should be some differences. It can for example be stated that the temperature at a distance of 1000m away is not sufficient for the FED $_{\text{heat conv}}$ to affect someone in a tunnel fire with a proper clothing at stated in the equation 8 since the extent of time exposure is lengthy. However, there is clearly a chance of being affected by the FED $_{\text{asphyxiant}}$. Test 6 of 2013 was used for comparison. The low FED $_{\text{asphyxiant}}$ is due to the complete combustion of wood (low CO production) and by the low temperatures from the fire (30 – 40 ^{0}C). As stated in [2] the FFFS failed to activate in test 6 because of a failed coupling which caused a loss of water supply in the system. The raw data collected from the test detailed high concentration levels of CO and CO_2, the temperature measured above the flame in the vicinity of the fire reached a temperature of 1366^{o}C. The longitudinal ventilation velocity was 3 m/s which could have assisted in spreading the buoyant smoke layer downstream thus causing smoke stratification to occur. Due to the length of the tunnel and mixing with cooler air further downstream, the temperature measured at the 1000 m will not affect people or hamper evacuation however as shown in Table 16. In the model scale test, free burn test 1 has the highest temperature which may be due to the type of wood burning or the feedback from the type of wall structure as stated in section 8.2.1.3 and 8.2.1.6, however due to the ventilation velocity people will not be affected by the fire at 42 m away. In the model scale test 14 the temperature is also high, however it doesn't seem to make a difference in the concentration for FED $_{\text{asphyxia}}$ but contains the highest concentration for FED $_{\text{heat conv.}}$ Although the temperatures are higher at 42 m away, the FFFS system has shown to be very effective in reducing the temperatures and making the environment safe for people to evacuate. The ventilation systems at the different velocities limit the amount of FED $_{\text{asphyxiant}}$ when compared to the FFFS for all the test except large scale Runehamar 2013 test 6. Although in test 14 there is the highest concentration of FED $_{\text{heat conv}}$ it doesn't affect people at that distance. In Table 16 details are shown of the exposure time it will take for someone to be affected by the smoke. In the large scale Runehamar 2016 test 1 it will take 73.97 minutes for someone to be affected by a FI = 1.0 whereas in a test 2 it will take 44.72 minutes. In the free burn test 2013, someone will not be affected by a FI = 1.0, however, they can be affected by FI = 0.3 after 44.95 minutes. We can see that the FFFS for lower concentrations the time is lower than the free burn test 6 of Runehamar 2013. This may be due to the incomplete combustion of the wood particles due to the activation of the system. There will be no exposure of someone to FED $_{\text{heat conv}}$ in the large scale test, however in the model scale test at a velocity of 6 m/s in the free burn test people may be affected downstream by the smoke since velocity is so high smoke stratification may occur. The FFFS is effective in all tests thus providing a safe environment.

Table 16 Full scale time in min for test to reach different levels of FED concentrations at a height of 1.7m

Test									
Large scale Runehamar 2016			Large scale Runehamar 2013	Model scale					
	v = 3 m/s	v= 2 m/s	V = 3 m/s	v = 1.5 m/s (3m/s full scale)		v = 3 m/s(6 m/s full scale)			
	1	6	6	1	5	7	14	17	19
	FFFS	FFFS	Free burn	Free burn	FFFS	FFFS	Free burn	FFFS	FFFS
Time when FED asph. = 1.0	73.97	44.72	-	-	-	-	-	-	-
Timewhen FED asph. = 0.3	21.79	24.25	44.95	-	-	-	-	-	-
Time when FED asph. = 0.1	10.48	18.98	24.46	-	-	-	-	-	-
Time [min] when FED conv. = 1.0	-	-	-	-	-	-	-	-	-
Time [min] when FED conv. = 0.3	-	-	-	-	-	-	21.94	-	-
Time [min] when FED conv. = 0.1	-	-	-	25.32	-	-	18.12	-	-

In Figure 7, Figure 8 and Figure 9 shows the time at which the time for people to be affected by the fire at a distance of 1000 m away as shown in Table 16 for a large scale Runehamar 2016 test and free burn test large scale test Runehamar 2013. In the test the convective curve is not as effective as the asphyxiant curve. There is a difference in the growth rate of the $\text{FED}_{\text{asphyxia}}$ between the tests. The FFFS test 1(3 m/s) has a linear increase whilst the FFFS test 6 (2 m/s) system there is a steady increase the concentration for approximately 80 minutes then it begins to level out. In the free burn test of Runehamar test 2013 there is a liner growth for the asphyxiant curve however it doesn't reach the concentration value of FI =1. In the case of a fully clothed person the incapacitating dose was never reached in all cases presented.

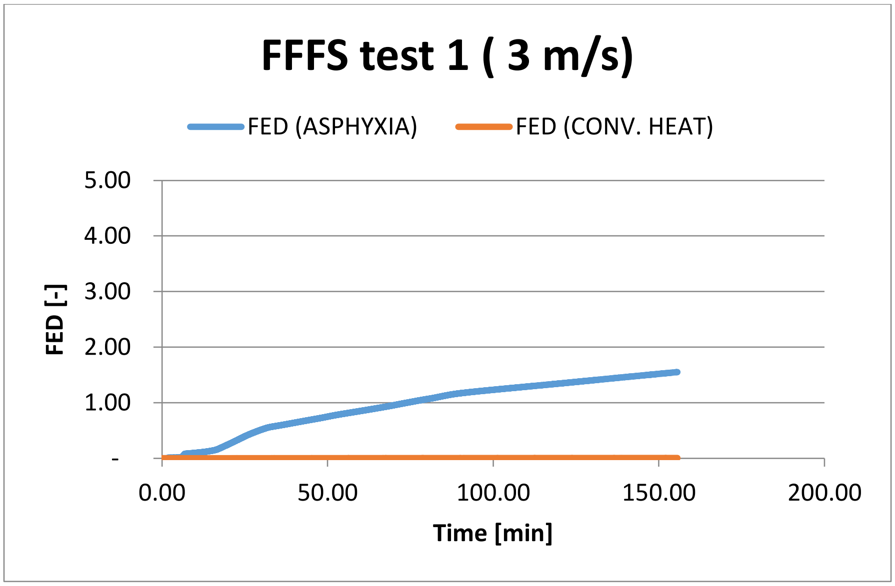

Figure 7 FED (asphyxia) and FED (convective heat) analysis with a FFFS from test 1 (3 m/s) in Runehamar tunnel at 1.7 m

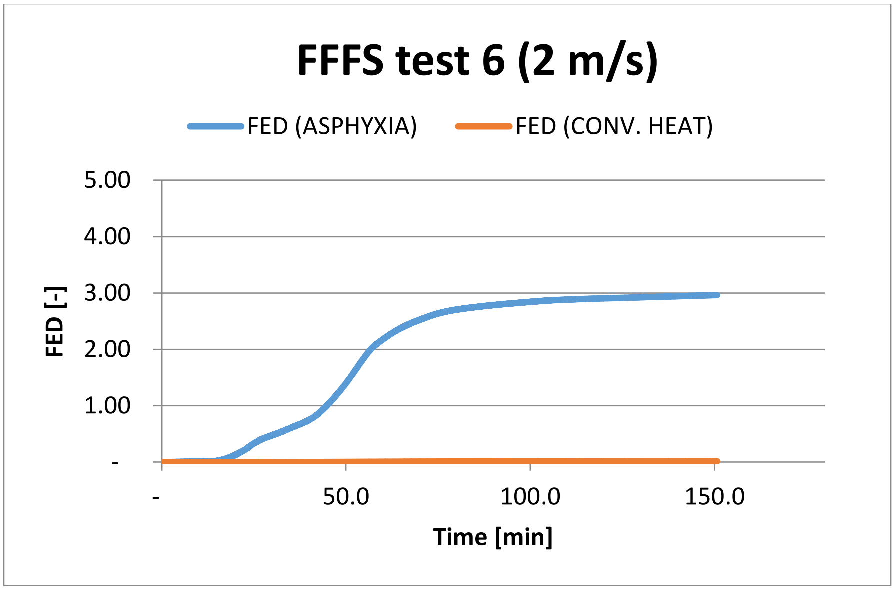

Figure 8 FED (asphyxia) and FED (convective heat) analysis in FFFS from test 6 (2 m/s) in Runehamar tunnel at 1.7 m

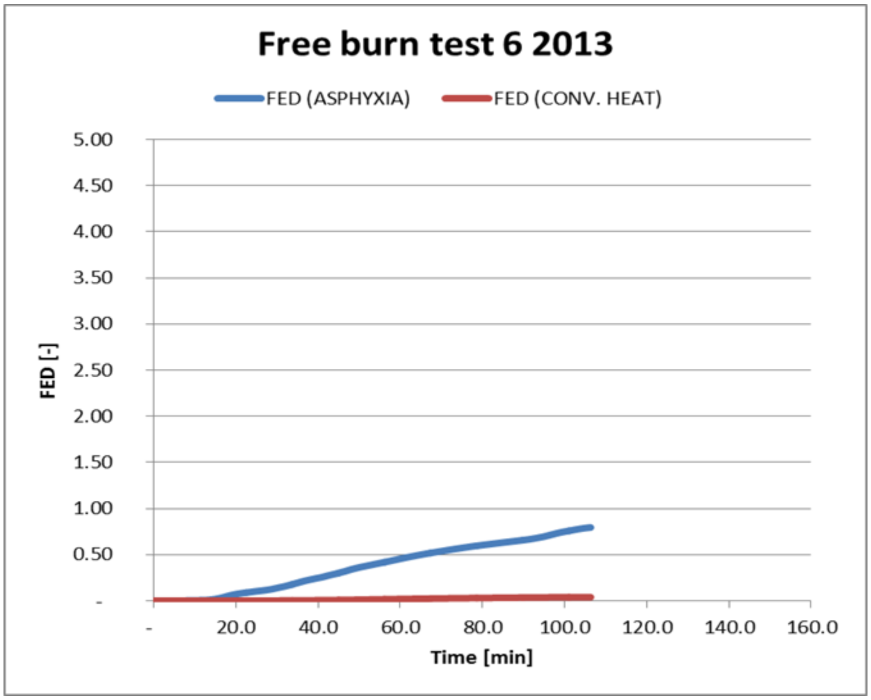

Figure 9 FED (asphyxia) and FED (convective heat) analysis in FFFS from free burn test 6 2013 in Runehamar tunnel at 1.7 m

9 Conclusion

The analysis of the test data show that the use of FFFS in test 1 of Runehamar 2016 when compared to the free burn test 6 of Runehamar 2013 were able to lower the temperature of the smoke layer by approximately 37.5 % with v = 3m/s and approximately 16.7 % with v = 2 m/s. The FFFS decreased the temperatures and will increase safety environment for people in the tunnel. In the Runehamar test 1 of 2016 and test 6 of 2013 the longitudinal ventilation velocity was set at 3 m/s, which corresponds to a critical velocity for this type of tunnels. This means that no backlayering of smoke should be expected during the test [4], thus proving effective during mitigation and the evacuation process. The ventilation velocity of 2 m/s used in test 6 of the Runehamar 2016 test can be used to prevent long backlayering in the tunnel. It can be suggested that at the initial stages of the fire that a velocity of 2 m/s be used and after the FFFS is initiated the velocity can be increased to 3 m/s. The FFFS, using TN-25 nozzle is more effective than the SW-24 bulb nozzle, it may be considered with longitudinal velocities since it is proven that it provides a better level of safety. The model scale test show that at the distance closer to the fire the ventilation velocities can increase the temperature in the free burn test however $FED_{heat\ conv}$ will not affect the people. Although using the ventilation system at the different velocities will provide a tenable environment, it is recommended that a ventilation velocity of 3 m/s working in conjunction with the FFFS will be ideal to provide a safe environment for the evacuation of people in a tunnel at both distances since it lowered the temperatures and FED concentrations as obtained in the results.

The analysis of the test show in the cases of the Runehamar test it can be concluded that people at a distance of 1000 m away from the fire will be safe with and without FFFS for test conducted 2016, however in the full scale test of 2013 due to failure of the FFFS people are affected by the concentration of $FED_{asphyxia}$ of 0.3 is obtained after 44.95 minutes. This will although be dependent on the type of material burning. The results also show that test 1 is more effective than test 6 in Runehamar 2016 in reducing the $FED_{asphyxia}$ after 30 mins of exposure. The calculated concentration for FED$_{\text{heat conv}}$. of 0.3741 was obtained after 30 minutes of exposure time was found in test 14 of the model scale. The free burn model scale test had the highest temperature values and velocities. It was represented as the worst case scenarios from the FED$_{\text{heat conv.}}$ The early activation of the FFFS reduces the concentration significantly. The other calculated concentrations for FED$_{\text{heat conv}}$. test will not affect people at the stated distances thus showing the effectiveness of the FFFS and ventilation systems. The different ventilation velocities didn't affect the suppression system performance. The different longitudinal ventilation velocities used in the test namely: 2 m/s, 3 m/s and 6 m/s has shown to be effective in controlling the fire at both distances and providing a safe environment for people. It has been shown that the most effective of the three velocities was 3m/s when FFFS is operating. The early activation of the FFFS made a difference in controlling the fire thus it's recommended for use in road tunnels. The results can confirm that although people will be safe in the road tunnels, the first few minutes are important during a tunnel fire for the ability of people in the tunnel to escape.

10 References

[1] Y. Z. Li and H. Ingason., "Influence of ventilation on road tunnel fires with and without a water based suppression systems," SP Report 2016:36, SP Technical Research Institute of Sweden, Borås, Sweden, 2016.

[2] H. Ingason, G. Appel and Y. Z. Li, "Large scale fire tests with fixed fire fighting system in Runehamar tunnel," SP Report 2014:32, SP Technical Research Institute of Sweden, Boras, Sweden, 2014.

[3] SOLIT² Research Consortium, "Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems," Version 2.0, Germany, November 2012.

[4] H. Ingason, Y. Z. Li and B. Magnus, "Large scale fire tests with different types of fixed fire fighting system in the Runehamar tunnel," SP Report 2016:76, SP Technical Research Institute of Sweden, Borås, Sweden, 2016.

[5] H. Ingason, L. Ying Zhen and A. Lönnermark, Tunnel Fire Dynamics, New York: Springer, 2015.ISBN: 978-1-4939-2198-0

[6] A. Häggkvist, "Fixed Fire Fighting Systems in Road Tunnels. An overview of current research, standards and attitudes," Master thesis,Fire protection engineering,Department of Civil and Environmental Engineering, Lund University, Lund, Sweden, 2009.

[7] N. Harvey, L. Fielding, B. Dandie, R. Brandt, N. Rhodes, R. Hall and H. Ingason, "PIARC and fixed fire-fighting systems: A report on working group activity," in *Symposium on Aerodynamics, Ventilation and Fire in Tunnels (ISAVFT 2015)*, Seattle, 2015.

[8] I. Y. MAEVSKI, Design Fires in Road Tunnels, A Synthesis of Highway Practice, New York: National Academy of Sciences, 2011.ISBN:978-0-309-14330-1

[9] A. Lonnermark and H. Ingason, "Gas Temperatures in Heavy Goods Vehicle Fires in Tunnels," *Fire Safety Journal*, vol. 40, no. 2, pp. 506-527, 2005.

[10] F. Tarada, "“Fires in tunnels – can the risks be designed out?”," *Eurotransport Magazine*, vol. 9, no. 4, 2011.

[11] National Fire Protection Association, "NFPA 502 : Standard for Road Tunnels, Bridges, and Other Limited Access Highways," National Fire Protection Association, Quincy, 2014.

[12] M. Lakkonen, A. Feltman and D. Sprakel, "Impact of AFFF to the Performance of Fixed Fire Fighting Systems in Tunnels," in *Seventh International Symposium on Tunnel Safety and Security*, Montréal, Canada, 2016.

[13] A. Wierer, S. Sperling and M. Patigler, "Fixed Firefighting Systems in Road Tunnels – General Requirements and Capabilities," in *7th International Conference ‘Tunnel Safety and Ventilation*, Graz, 2014.

[14] National Fire Protection Association, "NFPA 750 – Standard for Water Mist Fire Protection Systems," National Fire Protection Association, Quincy, 2010.

[15] D. C. 14972, "Fixed Firefighting Systems – Watermist Systems – Design and Installation," DIN Deutsches Institut für Normung e.V., Germany, 2011.

[16] Technical Committee C.3.3. Road Tunnel Operations of the World Road Association, "Fixed Fire Fighting Systems in Road Tunnels: Current Practices and Recommendations," World Road Association (PIARC), France, 2016.ISBN:978-2-84060-375-7

[17] A. Beard, " Water Mist and Major Fire Spread in a Tunnel: A Theoretical Mode," in *Seventh International Symposium on Tunnel Safety and Security*, Montréal, Canada, 2016.

[18] A. Beard and R. Carvel, The Handbook of Tunnel Fire Safety, London: Thomas Telford, 2005.ISBN: 0 7277 3168 8

[19] Z. G. L. A. Kashef, G. Crampton, G. Lougheed and K. H. Almand., "Findings of the International Road Tunnel Fire Detection Research Project," 2008.

[20] A. K. Z. Liu, G. Lougheed, J. Z. Su, N. Benichou and K. H. Almand., "An Overview of the International Road Tunnel Fire Detection Research Project," 2001.

[21] S. Maciocia, "Fire detection systems," Thomas Telford, London, 2005.

[22] M. Fragkopoulou, "Road Tunnel Fire Safety: Determining the effect of the performance of technological systems for fire detection on fire detection time and on the total evacuation time," Master of Science Thesis, Department of Building Engineering, TU Delft, Delft, 2016.

[23] A. Brinson, "Active Fire Protection in Tunnels," in *Fourth International Symposium on Tunnel Safety and Security,* Frankfurt am Main, Germany, 2010.

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

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

[26] The Research Project UPTUN, "Workpackage 2 Fire development and mitigation measures D241- Development of New Innovative Technologies," The European Commission, 2008.

[27] H. Ignason, "Workpackage 2 Fire development and mitigation measures D221, Target criteria," EU FP5, G1RD-CT-2002-766, 2008.

[28] A. Lonnermark, "On the Characteristics of Fires in Tunnels," Doctoral Thesis, Department of Fire Safety Engineering, Lund University, Lund, Sweden, 2005.

[29] D. A. Purser, "Toxicity Assessment of Combustion Products," in *SFPE Handbook of Fire Protection Engineering (P.J. DiNenno,ED.)*, Masachusetts, 2002, pp. 2-83- 2-171.

[30] A. Kashef, "Ventilation Strategies – an Integral Part of Fire Protection Systems in Modern Tunnels," in *Seventh International Symposium on Tunnel Safety and Security*, Montreal, 2016.

[31] Y. Ko, "A Study of the Heat Release Rate of Tunnel Fires and the Interaction between Suppression and Longitudinal Air Flows in Tunnels," Doctor of Philosophy, Department of Civil and Environmental Engineering,Carleton University, Ottawa, Canada, 2011.

[32] J. R. Mawhinney and J. Trelles, "CFD Modeling of the Interaction of Water Mist and Smoke Control System in Tunnels, in Smoke Control in Buildings and Tunnels," in *Fire safety-Research and Technology*, GIDAI-Fire safety-Research and Technology, 2008, pp. 281-304.

[33] X. Guigas, A. Weatherill and C. Bouteloup, "Water mist tests for the A86 east tunnel," in *2nd International Symposium on Tunnel Safety & Security*, Madrid, 2006.

[34] Y. Z. Li, L. Vylund, H. Ingason and A. Glenn, "Influence of fire suppression on combustion products in tunnel fires," SP Report 2015:09, SP Technical Research Institute of Sweden, Borås, Sweden, 2015.

[35] ISO (2012), "Life-threatening components of fire – Guidelines for the estimation of time to compromised tenability in fires," International Organization for Standardization, SS-ISO 13571:2012, 2012.

[36] R. W. Bukowski, "Technical reference guide for the "Hazard I fire hazard assessment program," in *Tenability Limits*, NIST, 1989, pp. Vol. II, Chapter 7.

[37] ISO/TS 13571:2002, "Life threat from fires - Guidance on the estimation of time available for escape using fire data," ISO, 2002.

[38] H. Ingason, "Correlation between temperatures and oxygen measurements in a tunnel flow," *Fire Safety Journal*, vol. 42, p. 75–80, 2007.

Appendix 1 FED concentrations at different heights

Table 17 Time for test to reach different levels of FED concentrations at a height of 0.6 m.

Time (min)	FED $_{asph}$. with FFFS (2 m/s)	FED $_{asph}$. with FFFS (3 m/s)
30	0.6222	0.5740
Time (min)	FED $_{heat\ conv}$. with FFFS (2 m/s)	FED $_{heat\ conv.}$ with FFFS (3 m/s)
30	0.0011	0.0007

Table 18 Time for test to reach different levels of FED concentrations in large scale Runehamar tunnel test 1 and 6 at a height of 0.6 m

	FED $_{asph}$. with FFFS (2 m/s)	FED a$_{sph}$. with FFFS (3 m/s)
Time when FED $_{asph}$.=1.0?	40.68	60.78
Time when FED $_{asph}$.=0.3?	22.72	21.13
Time when FED $_{asph}$.=0.1?	18.37	13.53
Time when FED $_{heat\ conv}$=1.0?	-	-
Time when FED $_{heat\ conv}$=0.3?	-	-
Time when FED $_{heat\ conv}$=0.1?	-	-

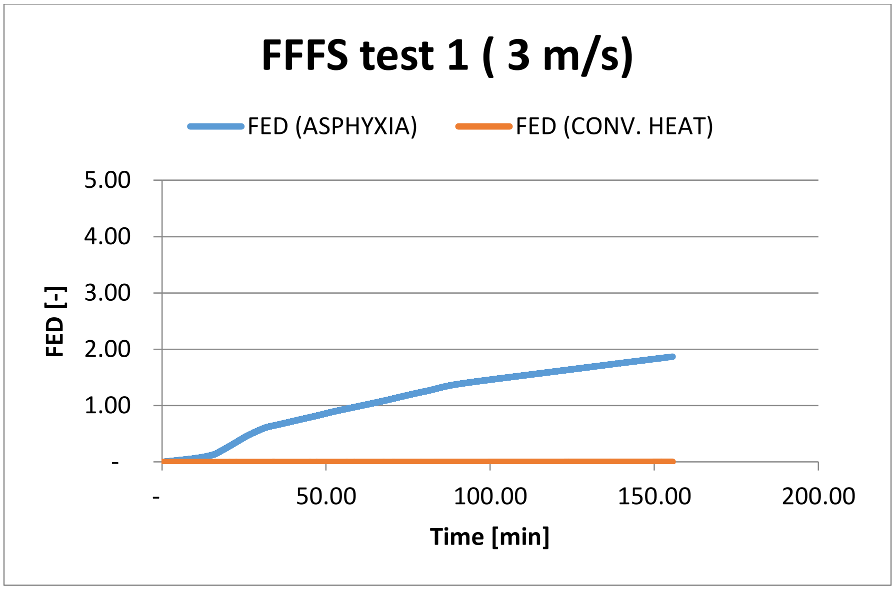

Figure 10 FED (asphyxia) and FED (convective heat) analysis with a FFFS *from test in Runehamar tunnel at 0.6 m.*

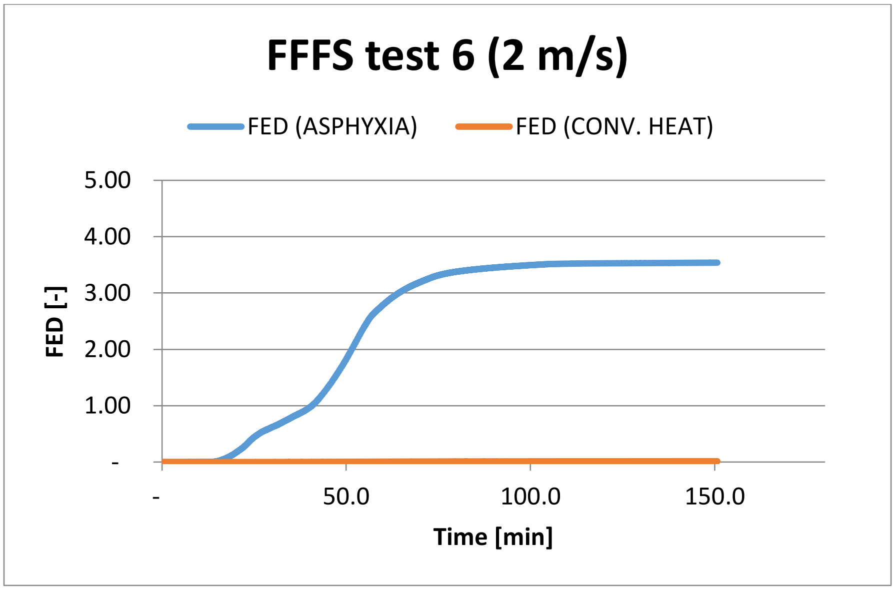

Figure 11 FED (asphyxia) and FED (convective heat) analysis in FFFS test 6 (2 m/s) from test in Runehamar tunnel at 0.6 m

Table 19 Time for test to reach different levels of FED concentrations at a height of 2.8 m.

Time (min)	FED $_{asph}$. with FFFS (2 m/s)	FED $_{asph}$. with FFFS (3 m/s)
30	0.5776	0.3338
Time (min)	FED $_{heat\ conv.}$ sprinkler (2 m/s)	FED $_{heat\ conv}$ with FFFS (3 m/s)
30	0.0013	0.0000

Table 20Time for test to reach different levels of FED concentrations in large scale Runehamar tunnel test 1 and 6 at a height of 2.8 m

	FED $_{asph}$. with FFFS (2 m/s)	FED $_{asph.}$ with FFFS (3 m/s)
Time when FED $_{asph}$.=1.0?	42.25	-
Time when FED $_{asph}$.=0.3?	23.63	28.17
Time when FED $_{asph.}$=0.1?	19.13	20.03
Time when FED $_{heat\ conv}$=1.0?	-	-
Time when FED $_{heat\ conv}$=0.3?	-	-
Time when FED $_{heat\ conv}$=0.1?	-	-

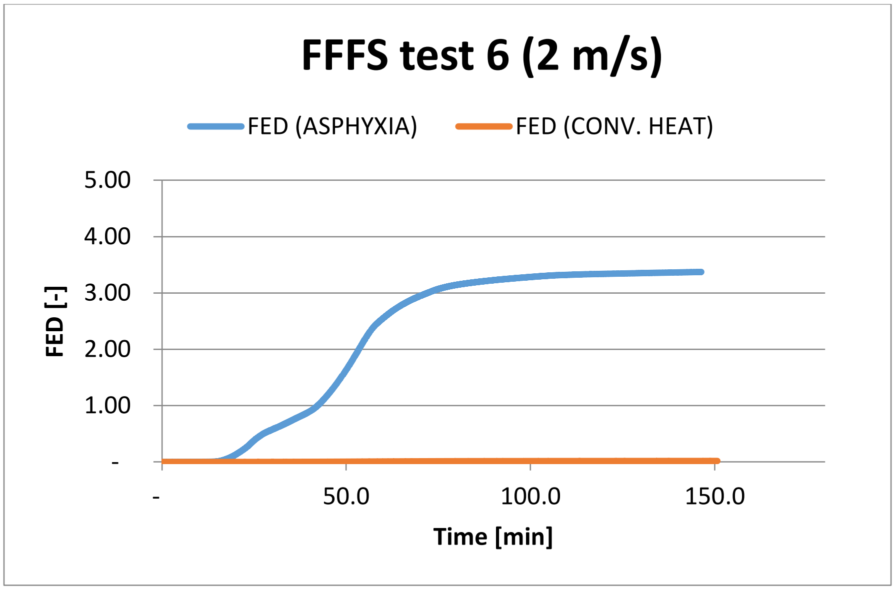

Figure 12 FED (asphyxia) and FED (convective heat) analysis with a FFFS *from test in Runehamar tunnel at 2.8 m*

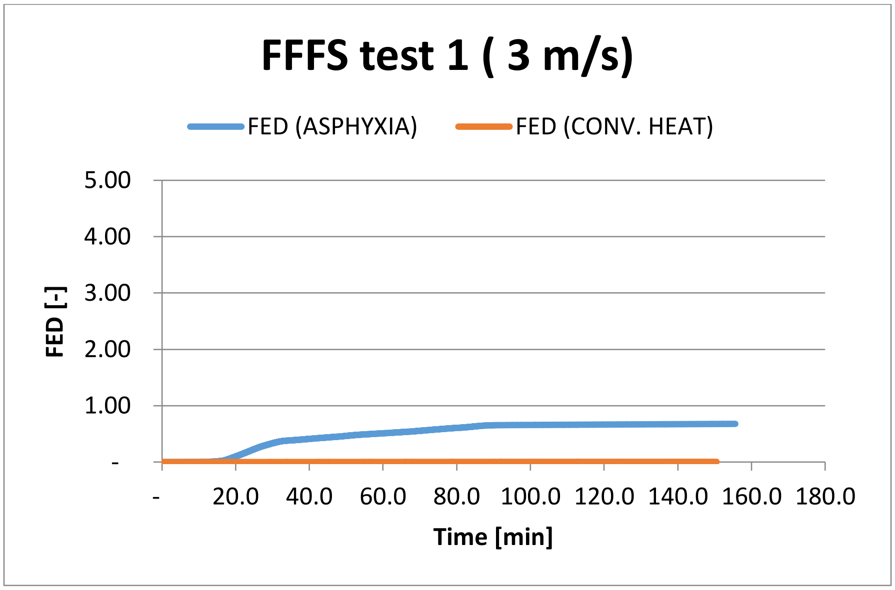

Figure 13 FED (asphyxia) and FED (convective heat) analysis with a FFFS *from test in Runehamar tunnel at 2.8 m.*

Appendix 2 Individual contributions of CO, O_2 and temperature

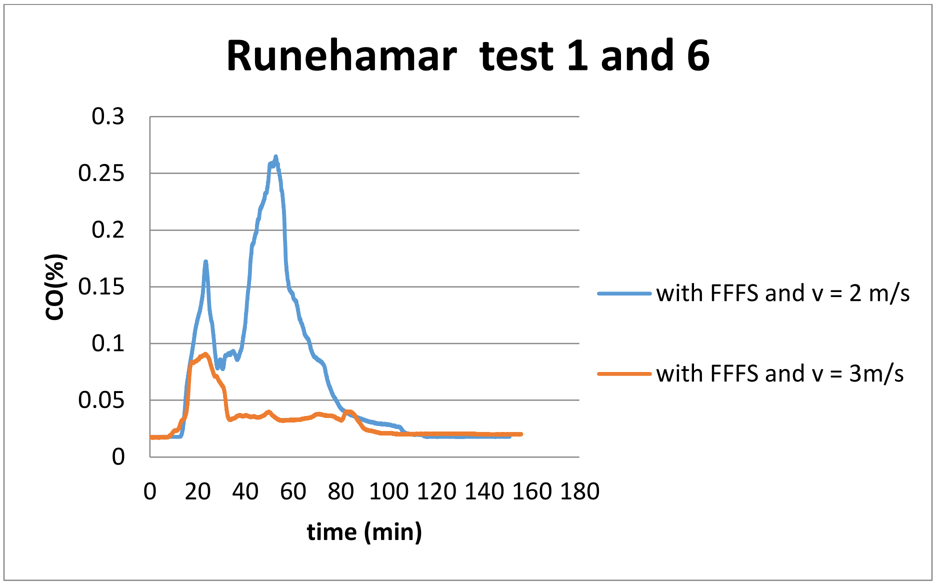

Figure 14 CO (%) gas analyzed from test 1 and 6 in the Runehamar tunnel test 2016 at 0.6 m

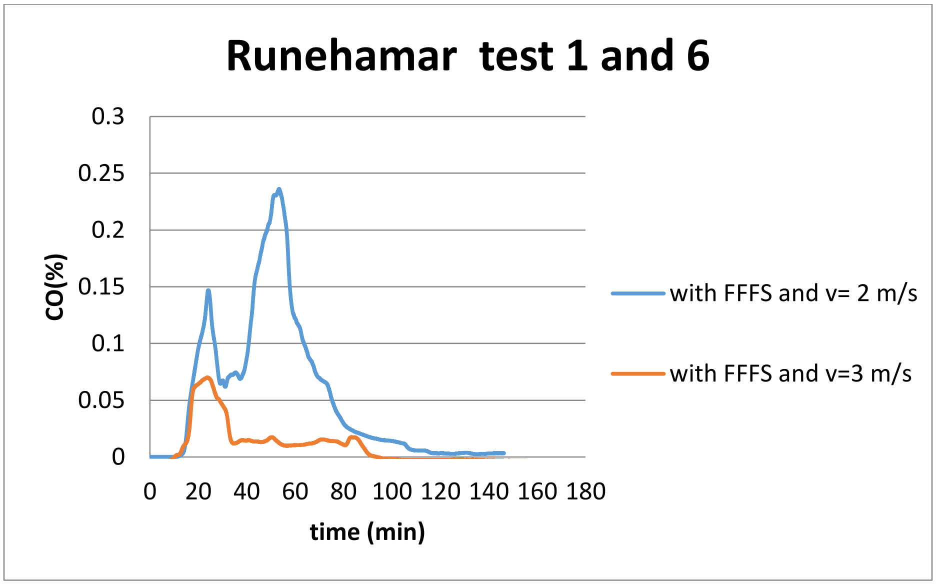

Figure 15 CO (%) gas analyzed from test 1 and 6 in the Runehamar tunnel test 2016 at 2.8m

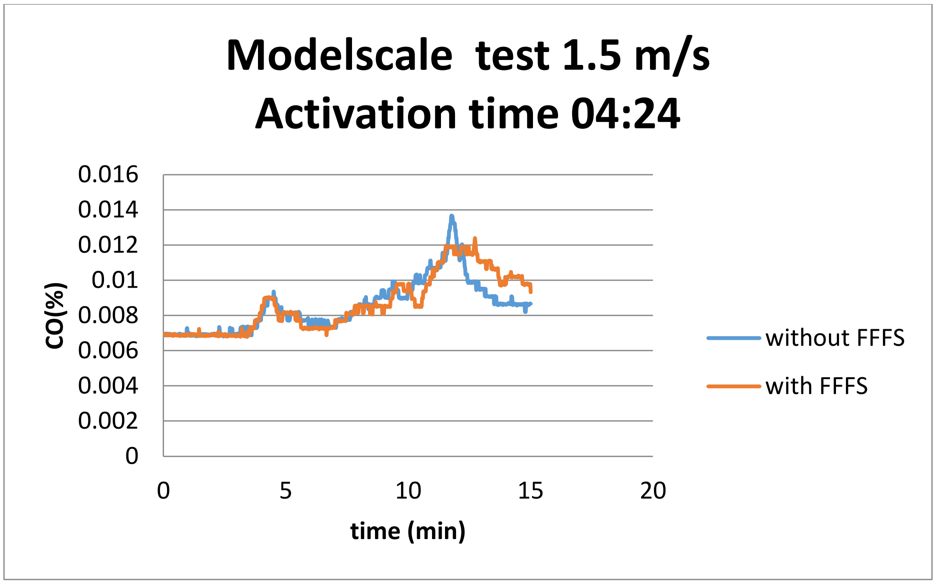

Figure 16 CO (%) gas analyzed from test 1 and 5 with a ventilation velocity 1.5 m/s (3 m/s full scale) in the Model scale tunnel fire (0.6m)

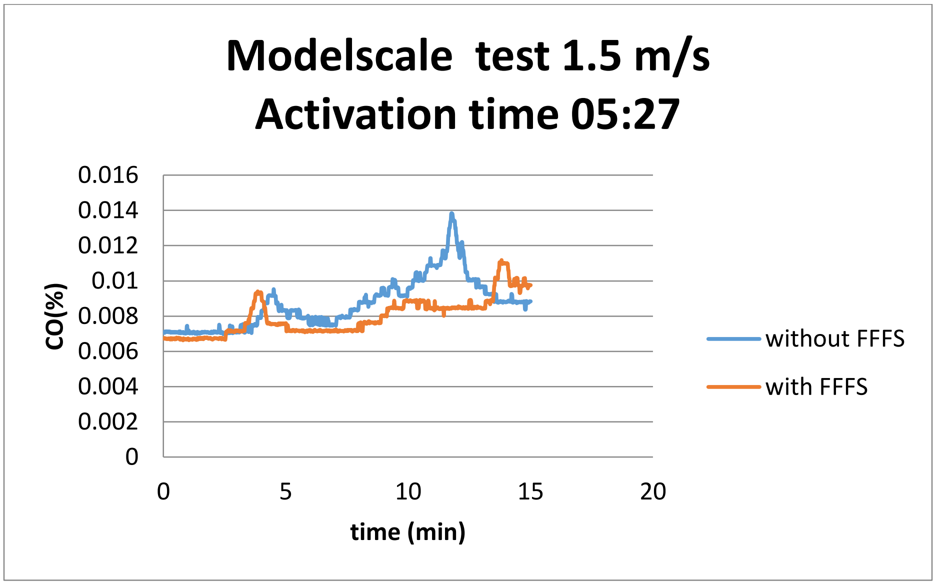

Figure 17 CO (%) gas analyzed from test 1 and 7 with a ventilation velocity 1.5 m/s (3 m/s full scale) in the Model scale tunnel fire (0.6 m)

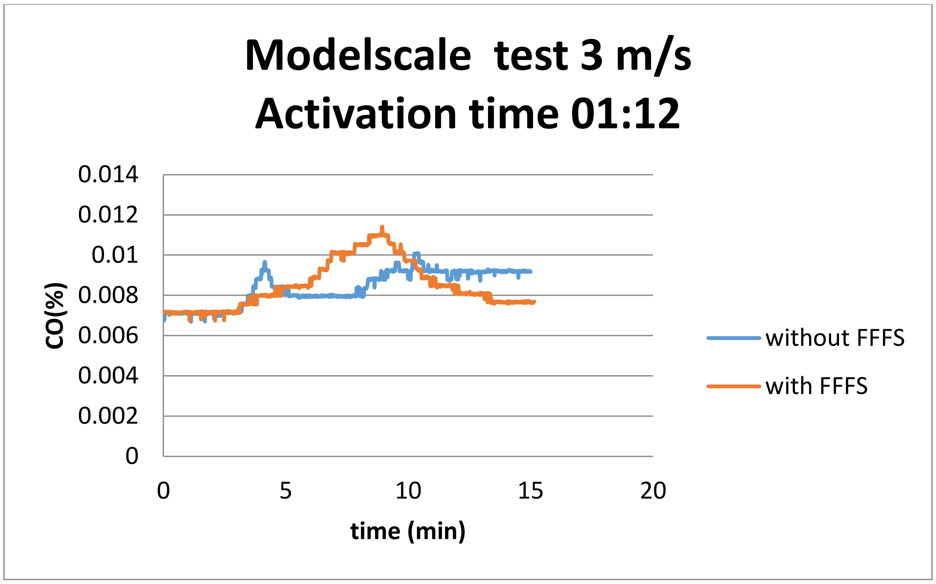

Figure 18 CO (%) gas analyzed from test 14 and 17 with a ventilation velocity 3 m/s (6 m/s full scale) in the Model scale tunnel fire (0.6 m)

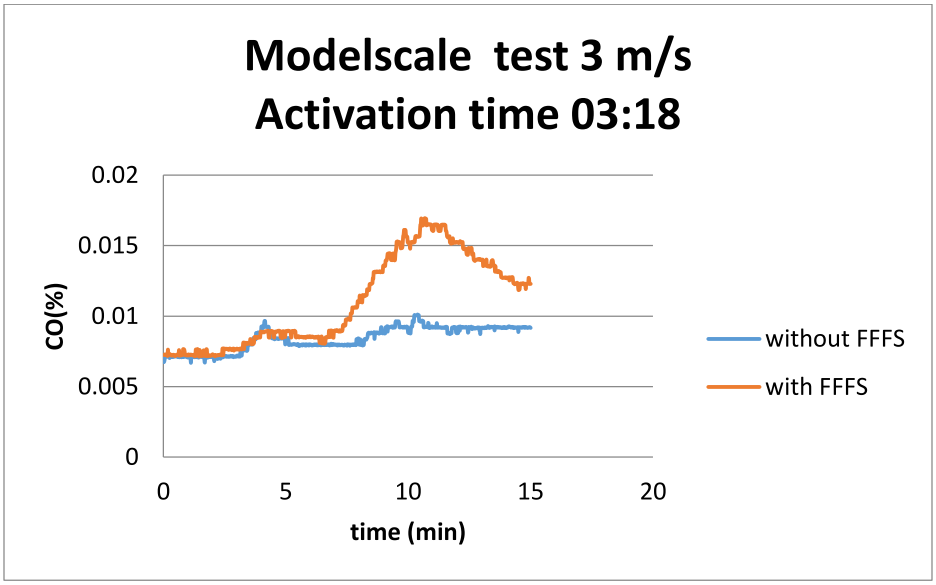

Figure 19 CO (%) gas analyzed from test 14 and 19 with a ventilation velocity 3 m/s (6 m/s full scale) in the Model scale tunnel fire (0.6 m)

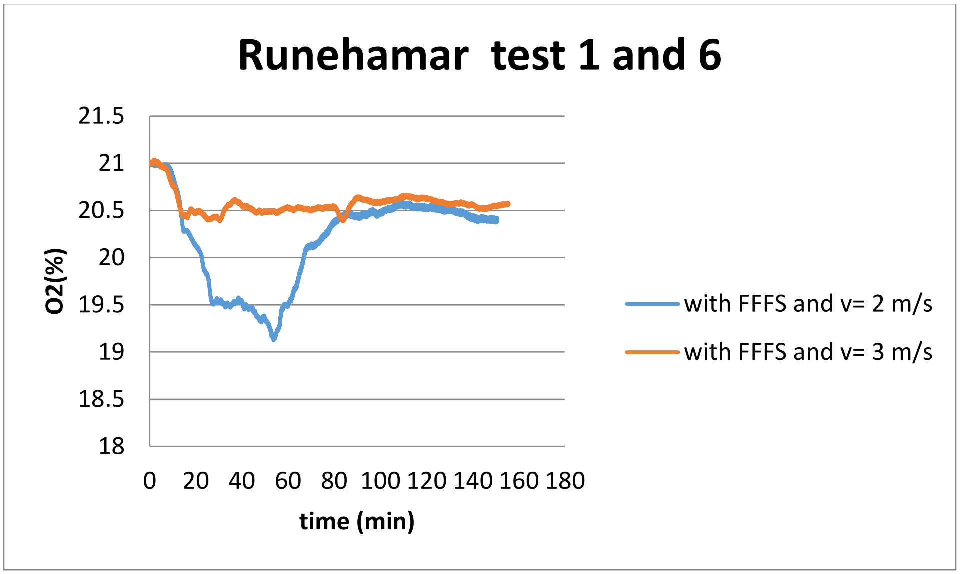

Figure 20 O2 (%) gas analyzed from test 1 and 6 in the Runehamar tunnel test 2016 at 0.6 m

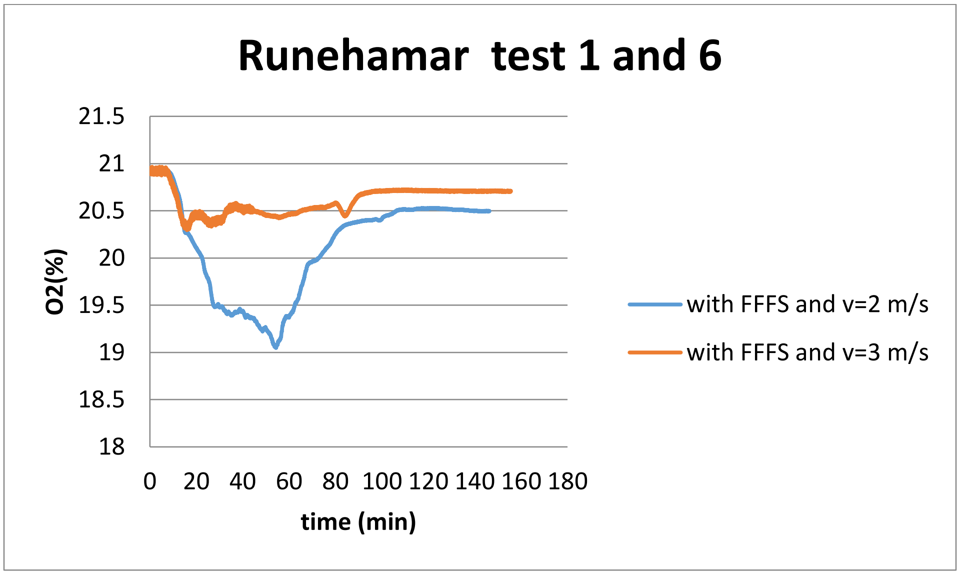

Figure 21 O2 (%) gas analyzed from test 1 and 6 in the Runehamar tunnel test 2016 at 2.8 m

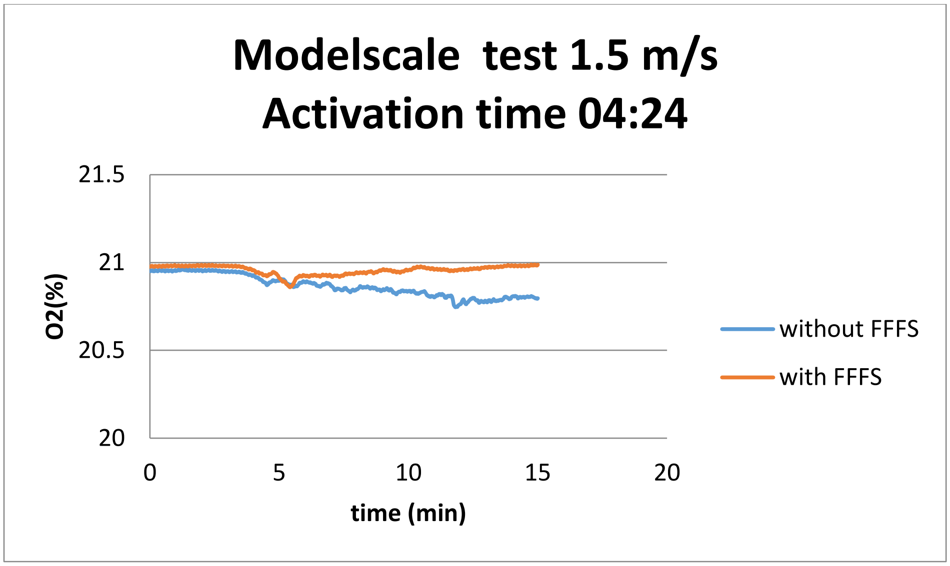

Figure 22 O2 (%) gas analyzed from test 1 and 5 with a ventilation velocity 1.5 m/s (3 m/s full scale) in the Model scale tunnel fire (0.6m)

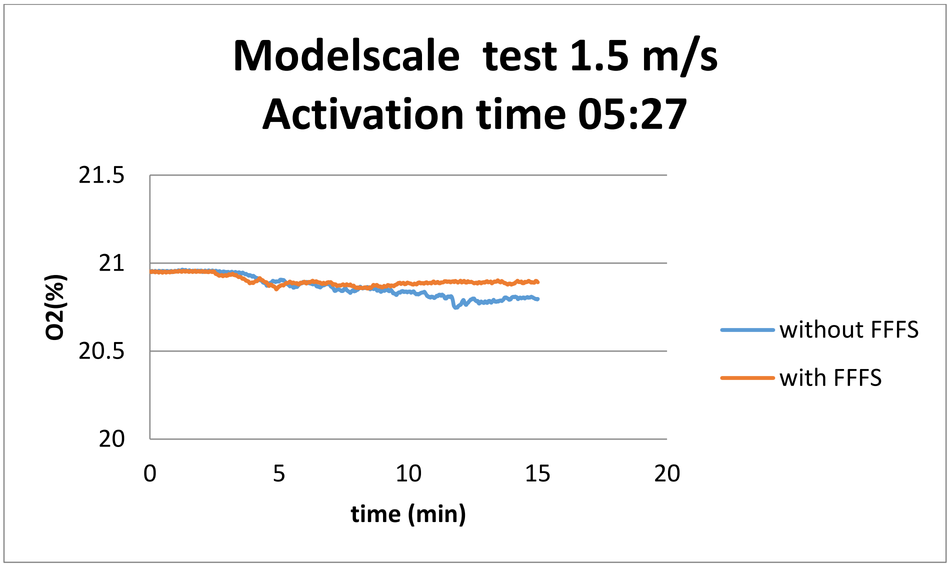

Figure 23 O2 (%) gas analyzed from test 1 and 7 with a ventilation velocity 1.5 m/s (3 m/s full scale) in the Model scale tunnel fire (0.6m)

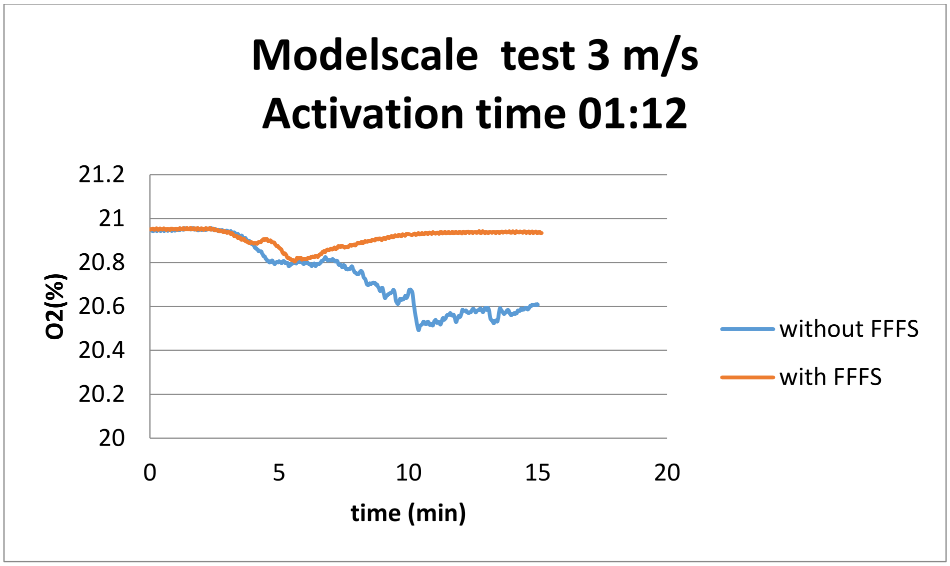

Figure 24 O2 (%) gas analyzed from test 14 and 17 with a ventilation velocity 3 m/s (6 m/s full scale) in the Model scale tunnel fire (0.6m)

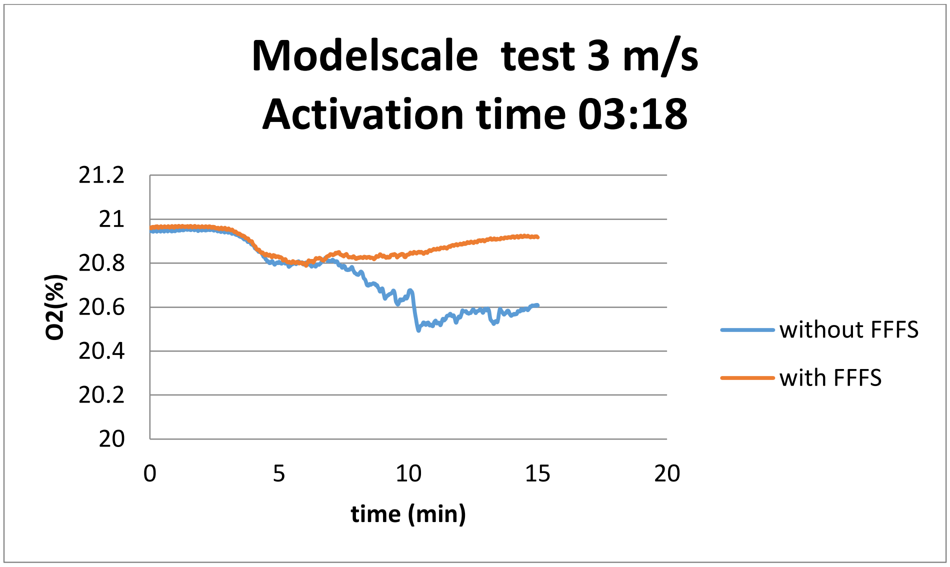

Figure 25 O2 (%) gas analyzed from test 14 and 19 with a ventilation velocity 3 m/s (6 m/s full scale) in the Model scale tunnel fire (0.6m)

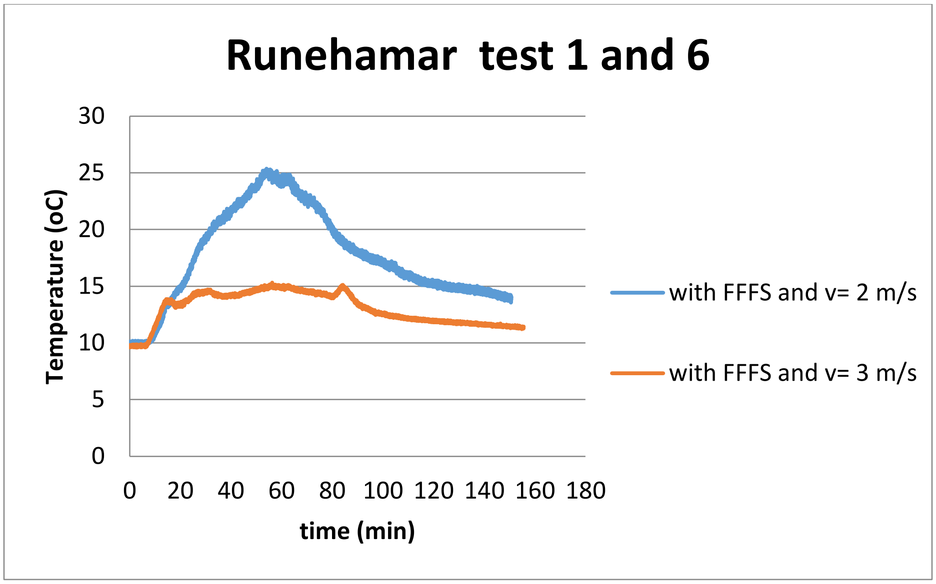

Figure 26 Temperature (ºC) analyzed from test 1 and 6 in the Runehamar tunnel test 2016 at 0.6m

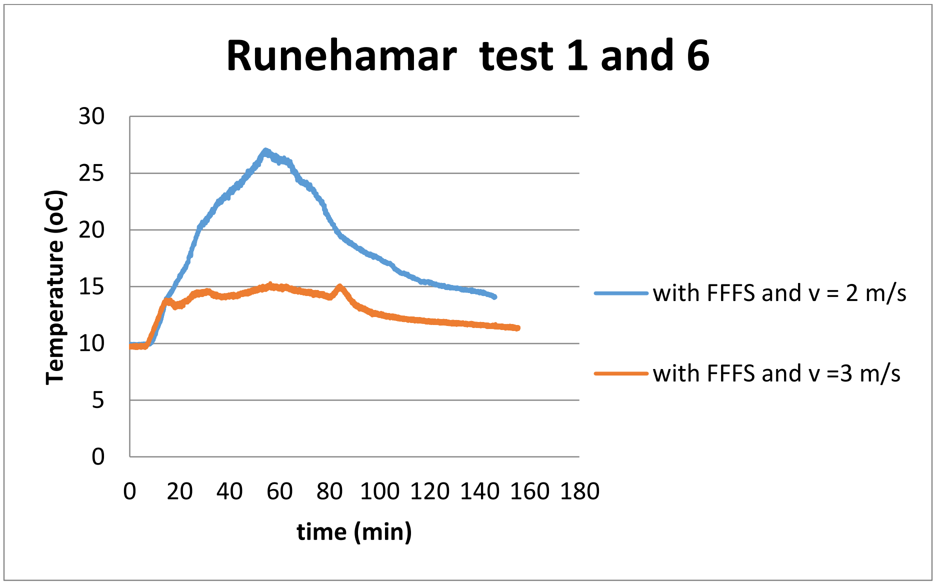

Figure 27 Temperature (ºC) analyzed from test 1 and 6 in the Runehamar tunnel test 2016 at 2.8 m

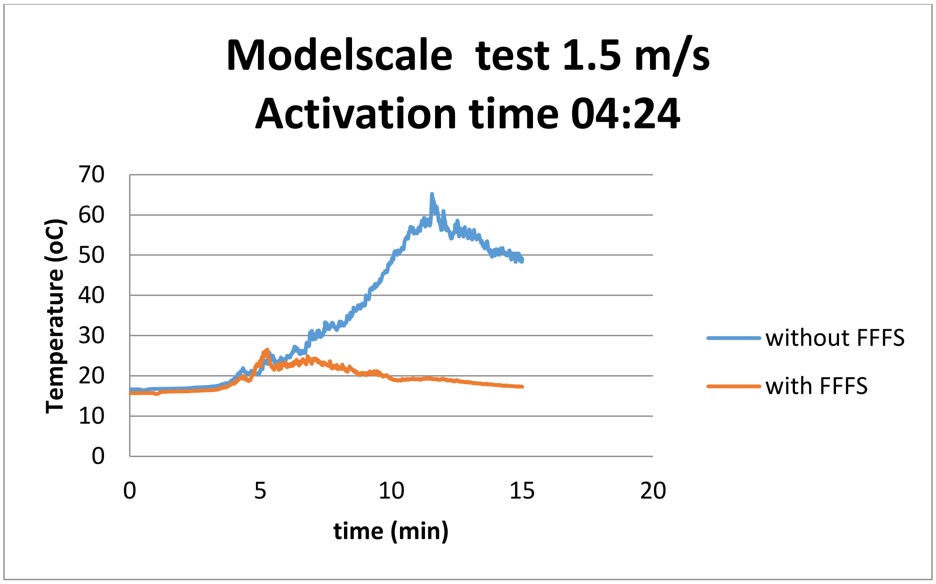

Figure 28 Temperature (º C) analyzed from test 1 and 5 with a ventilation velocity 1.5 m/s (3 m/s full scale) in the Model scale tunnel fire (0.6m)

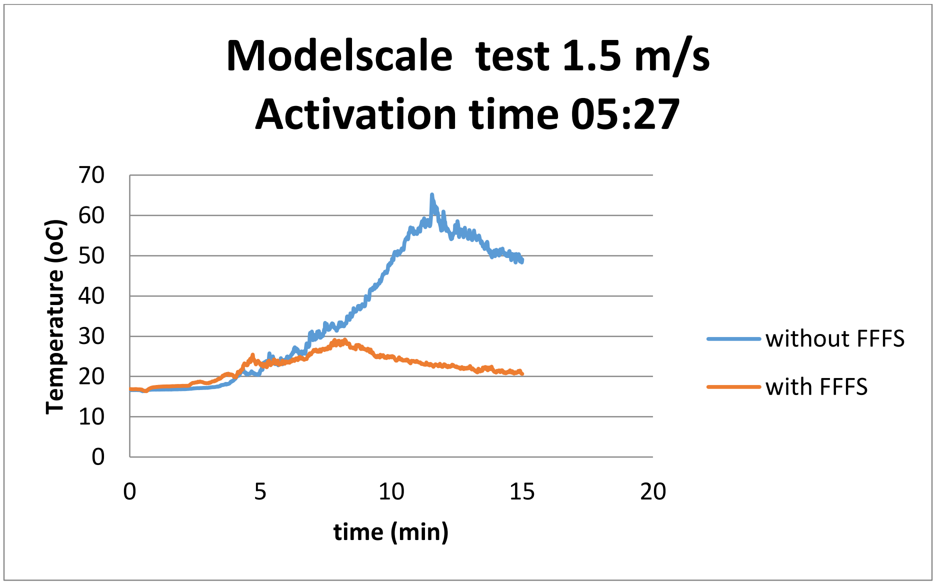

Figure 29 Temperature (º C) analyzed from test 1 and 5 with a ventilation velocity 1.5 m/s (3 m/s full scale) in the Model scale tunnel fire (0.6m)

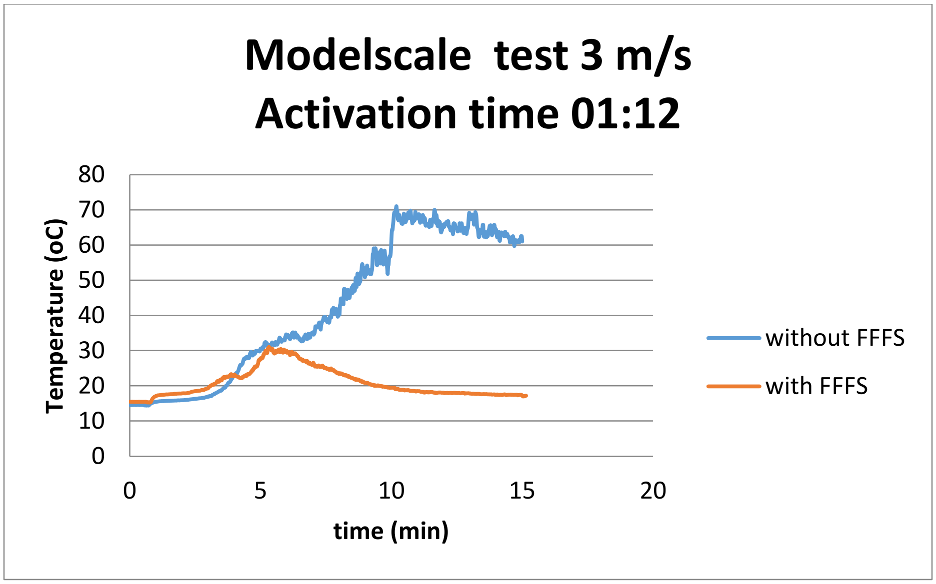

Figure 30 Temperature (º C) analyzed from test 14 and 17 with a ventilation velocity 3m/s (6 m/s full scale) in the Model scale tunnel fire (0.6m)

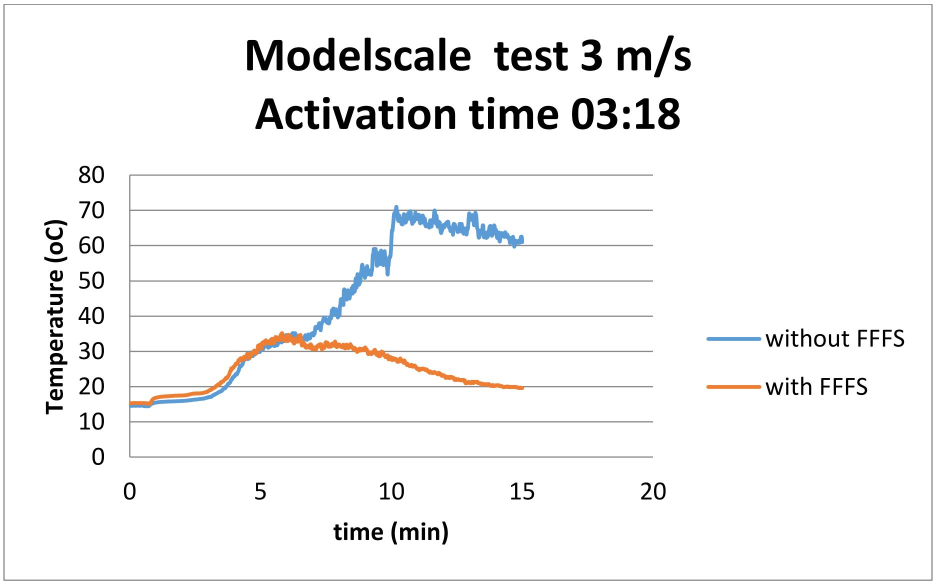

Figure 31 Temperature (º C) analyzed from test 14 and 19 with a ventilation velocity 3m/s (6 m/s full scale) in the Model scale tunnel fire (0.6m)