IMPACT OF FIXED FIREFIGHTING SYSTEMS ON ROAD TUNNEL RESILIENCE

by

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ABSTRACT

ANURAG JHA. Impact of Fixed Fire Fighting Systems on road tunnel resilience
(Under the direction of DR. AIXI ZHOU)

This thesis investigates the impact of different fixed firefighting systems (FFFS) on road tunnel resilience. The road tunnel and fire protection communities are considering a uniform approach for considering the benefits of an integrated design for FFFS on other systems including emergency ventilation in tunnels. However, there is currently a knowledge gap in the evaluation of effectiveness and reliability of the integrated systems. This study provides a comprehensive synthesis of currently available information regarding the performance, effectiveness, reliability, and benefits of FFFS in road tunnel applications. It also helps to scrutinize different assumptions against the use of FFFS in tunnels.

The investigation was based on publically available studies conducted in different countries for different types of FFFS in road tunnels. The FFFSs were analyzed for their impacts on heat release rate, temperature, smoke movement, ventilation load, fire spread, and structural damage. The analysis was followed by an annual economic loss analysis in the case of tunnel fire with and without FFFS.

The study shows that the arguments against the use of FFFS were based on conceptions and were assisted with a failed experiment conducted in the Ofenegg Tunnel in Switzerland in 1965. There has been no FFFS malfunctioning or false activation experienced in Japan and Australia for over fifty years. Available full-scale tests, computational modeling studies, and surveys show that FFFS controlled the spread of fire, decrease peak heat release rate, and peak temperatures when compared to tunnel fires without FFFS. The cost benefit analysis for a tunnel fire with and without an FFFS showed that the tunnel can save a significant amount of money with the FFFS installed. The investigation recommends that a tunnel user should install an FFFS for structural safety. The data available to analyze the cost benefit, reliability, the impact on occupants, and the effectiveness on liquid pool fire is still limited. Further research is needed to address these issues.

DEDICATION

To respected mother and father.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway Transportation Officials
AFAC	Australasian Fire Authorities Council
AFFF	Aqueous Film-Forming Foam
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AUD	Australian Dollar
BEA-TT	Land Transport Accident Investigation Bureau
CAF	Compressed Air Foam
CCSHCC	Second Highway Consultant Co. Ltd
CCTV	Closed-circuit television
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
DMT	Deutsche Montan Technologie
FFFS	Fixed Firefighting Systems
FHWA	The Federal Highway Administration
GIST	Guideline for Installation of Safety Facility in Road Tunnels
HEPC	Hanshin Expressway Public Corporation
HGV	Heavy Goods Vehicle
HRR	Heat Release Rate
JH	Japan Highway
MEPC	Metropolitan Expressway Public Corporation

MOLIT	Ministry of Land Infrastructure Transport
MW	Mega Watt
NATM	New Austrian Tunneling Method
NCHRP	National Cooperative Highway Research Program International Bridges and Tunnel Regulations IBTR
NFPA	National Fire Protection Association
PIARC	Permanent International Association of Road Congresses
PWRI	Public Works Research Institute
RWS	Rijkswaterstaat
SEM	Sequential Excavation Method
SOLIT	Safety of Life in Tunnels
SP	Technical Research Institute of Sweden
STEDI	Shanghai Tunnel Engineering Railway Traffic Design and Research Institute
TBM	tunnel boring machine

CHAPTER 1: INTRODUCTION

A road tunnel is an enclosed roadway for motor vehicle traffic with vehicle access that is limited to portals, regardless of the type of the structure or method of construction. Road tunnels are feasible alternatives to cross physical barriers (such as mountains, roadways, or existing structures/facilities) or a body of water, to minimize the environmental impact or satisfy other special project requirements (Hung et al., 2009).

Road tunnels encompass various types according to the method of construction, including mined and bored tunnels, cut-and-cover tunnels, immersed tunnels, and jacked box tunnels. Depending on the construction method and ground conditions, there are three main shapes of road tunnels: circular, rectangular, and horseshoe (or curvilinear). Rectangular configuration tunnels are constructed by using the cut and cover method, the immersed method, or jacked box tunneling. Circular shape tunnels are constructed by using tunnel boring machine (TBM) or by drill and blast in rock. Horseshoe tunnels are usually constructed using drill and blast in rock or by following the Sequential Excavation Method (SEM) [also as known as New Austrian Tunneling Method (NATM)].

Road tunnels are lined with concrete (or another type of reinforcement if unlined) and internal finish surfaces. Their interior surfaces often have interior finishes for safety and maintenance requirements. The tunnels are equipped with various systems, such as ventilation, lighting, communication, fire and life safety, traffic operation and control (including messaging, operation and control of the various systems in the tunnel).

Today's highway road tunnel owners are faced with the need to protect lives and facilities against potentially catastrophic events, such as heavy goods freight and tanker vehicle fires. These large fires are not mitigated effectively by emergency ventilation alone. Fixed Firefighting Systems (FFFS) have been widely accepted in the building industry, but this technology has only been rarely used in highway road tunnels in the United States.

Concerns about an FFFS in road tunnels include (but are not limited to) the following:

1. An FFFS may cause an explosion in the tunnel while suppression of Class- B fire.
2. An FFFS may lead to steam injuries to the evacuating people.
3. In a vehicle fire, the FFFS can not suppress the fire from the inside of the vehicle.
4. The FFFS activation may lead to the de-stratification of smoke in a tunnel fire.
5. Installation, maintainance, and repair cost of the FFFS may exceed the possible annual economic loss in a tunnel fire.
6. There might be a possibility of a malfunctioning or false activation of the FFFS.

However, experiences in other countries (particularly in Japan and Australia) have demonstrated that this technology provides enormous safety benefits and helps to protect the tunnel structure. FFFS systems can save lives by keeping the fire size low, maintaining a tenable environment for the tunnel user and enhancing the ability of first responders to aid in evacuation and to fight the fire. The use of FFFS can reduce the design fire size and fire growth rate, and thus has significant economic benefits to the tunnel owner as the expense of fire and life safety systems (including passive fire resistance) can be substantially reduced.

The Federal Highway Administration (FHWA), the American Association of State Highway Transportation Officials (AASHTO), the National Fire Protection Association (NFPA), and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) are considering the possibility of reducing the design fire size when integrating FFFS with the emergency ventilation systems. The professional tunnel and fire protection communities agree that the integration of this technology is long overdue. However, there is currently a knowledge gap in the evaluation of effectiveness and reliability of the integrated systems, which limits full realization of the benefits. As such, research is being performed to develop a uniform approach for considering the benefits of an integrated design for FFFS on systems include emergency ventilation.

This study is intended to provide a comprehensive synthesis of currently available information and published reports that have resulted from a significant amount of international research conducted in recent years regarding the effectiveness, performance, and benefits of FFFS in road tunnel applications.

This study reviewed previous full-scale tests and numerical modeling work related to road tunnel fires. Moreover, studies related to road tunnel safety practices, road tunnel construction, and cost benefit analysis were also refered. After analyzing the collected data, conceptions against the use of an FFFS in a tunnel were scrutinized. This analysis of the data includes test results, parameters, major findings, different tunnel fire incidents, cost benefit analysis, and experiences of different countries using FFFS for years. The results from different tests performed in different countries were summarized and compared. A comparison study was completed for a cost-benefit analysis. The chapters of this Thesis are organized as FFFS research data, followed by data analysis, and conclusion.

CHAPTER 2: FIXED FIREFIGHTING SYSTEMS IN ROAD TUNNELS RESEARCH DATA

2.1. Fixed Firefighting System in Road Tunnels

Recent fire statistics data show that between 2006-2010, an average of 152,300 automobile fires occurred every year in the United States (Ahrens, 2012). Accidents occur less frequently in a tunnel than on an open road. For every 100 million cars passing through a tunnel, there will be one or two car fires per kilometer in a tunnel. Heavy goods vehicles (HGV) cause multiple fatalities, and firefighters experience difficulty in reaching the fire because of the high temperatures that are generated. Out of every 100 million HGV traveling through a tunnel, eight HGV fires per kilometer of the tunnel occur (Beard and Carvel, 2004). Fire tests have proven that HGV can cause a fire of 200MW in a tunnel within minutes, and fire brigades cannot reach the tunnel in such a short time (Brinson, 2010).

In the case of a tunnel fire, an FFFS as an active fire protection system, can detect the fire in its early growth stage, prevent the spread of the fire to other vehicles, limit the fire size to help firefighters reach the fire, and completely extinguish the fire. The activation and operation of FFFS can lead to smaller fires that generate less heat and emit less smoke so that the ventilation system will not overload. Thus, ventilation system designers will be able to design a system for smaller fires because they know FFFS will prevent larger fires. A small fire can be easily extinguished and cause less damage to the tunnel structure with a lower cost of repair.

There are two main categories of fires in road tunnels: Class A and Class B fires. Class A fires have combustible solids as fuels, and Class B fires involve flammable liquids as fuels (PIARC, 2016; SOLIT, 2012). While using FFFS in road tunnels, the fuels involved in potential fires should be considered.

While there are many firefighting agents and accompanying systems available, FFFS in tunnels usually have water or aqueous foams as agents with the following accompanying systems: automatic sprinkler system, deluge water spray system, water mist system, and foam system.

An automatic fire sprinkler system consists of sprinklers connected to a water supply and distribution piping system that provides adequate pressure and flow. In the event of a fire and when exposed to sufficient heat, it will release a heat-sensitive element (fusible link or glass bulb) and it sprinklers dispense water. Typical types of automatic fire sprinkler system include wet pipe system, dry pipe system, pre-action system, and deluge system. Except the deluge system, only sprinklers subjected to a temperature at or above their specific temperature rating will operate in an automatic fire sprinkler system. While a deluge system employs open sprinklers that are attached to a piping system. This piping system is connected to a water supply through a valve that is opened by the operation of a detection system installed in the same areas as the sprinklers. When the valve opens, water flows into the piping system and discharges from all sprinklers.

A water spray sprinkler system is operationally a deluge system, but the piping and discharge nozzle spray patterns are designed to protect a specifically configured hazard (usually being three-dimensional (3D) components) while a deluge system is designed to cover the horizontal floor area of a room. The spray nozzles are usually selected for a specific spray pattern to conform to the 3D nature of the hazard. Typical spray patterns include oval, fan, full circle, and narrow jet. Water spray systems have been used in electrical transformers (containing oil) and on the surfaces of tanks containing flammable liquids or gases.

A water mist system is usually used for special applications when creating a heat absorbent vapor is the primary objective, and where water damage is a concern or water supply is limited (NFPA 750). A water mist systems can operate with the same functionality as a deluge, wet pipe, dry pipe, or pre-action system. The difference is that a water mist system uses a compressed gas as an atomizing medium, or uses a high-pressure pump to pressurize the water so it atomizes as it exits the nozzle.

Firefighting foam consists of air-filled bubbles formed from aqueous solutions that are created by mixing a foam concentrate with water in an appropriate proportion. There are different types of firefighting foams. Class A foams are primarily designed for Class A fires (common combustible solids). Class B foams are designed for class B fires (flammable liquids).

In a road tunnel, deluge water-spray systems are preferred over automatic sprinkler systems because the ventilation system in the tunnel causes horizontal air flow in the tunnel, which can drag heat to the sprinkler heads that are not above the fires. Japan and Australia are two countries that have used deluge water spray systems for years (NFPA502, 2017). The deluge sprinkler system works with zones divided in a tunnel and with detection of fire, and the pipe between the valve and sprinkler head is kept dry (PIARC, 2016). When the fire is detected, the tunnel operator checks for any false alarm through CCTV cameras. Within an automatic activation time (generally 4 mins), if the fire is detected, then the operator can activate FFFS earlier. If it is a false alarm, then the operator can turn off the alarm and prevent activation of FFFS. The delude system activates with specific zones above or near the detected fire source (Stroeks, 2001).

Water spray sprinkler systems work on comparatively low pressure (normally < 10 bars) and fight fire in the form of droplets. These droplets in the water spray system are larger than in the water mist system. Usually, a water supply of 6-20 $l/m^2/min$ is required for a conventional water spray as well as for a water mist system; however, a water spray system has a lower maintenance cost and has higher availability in the market (SOLIT, 2012). Water spray system's nozzles have a pressure between 1.5bar to 5bar, and the droplets have a diameter larger than 1mm.

Water mist systems work on high pressure, and 99% of the droplets have a diameter less than 1000µm. The pressure in a water mist system is around 140bar. The surface area of contact for water mist system droplets is larger than the surface area of contact for water spray system. The water mist evaporates easily and the evaporated water displaces air and oxygen from the fire and causes suffocation, extinguishing the fire efficiently. Water mist systems require less water than water spray systems, and thus storage tanks, pumps, and pipes are relatively smaller, which can save some costs. A high-quality stainless steel is used to manufacture nozzles of water mist system. This high-quality stainless steel saves the small nozzles from blockage, and adds up to the overall cost of manufacture of the water mist system.

Foam type systems have a volume expansion ratio of 1:4. Fixed foam suppression systems used in road tunnels includes Compressed Air Foam (CAF) and Aqueous Film-Forming Foam (AFFF) systems. Foam systems are very effective in fighting against Class B (liquid) and Class A (solid) fires. Foam systems work on the suffocation effect. If there is a CAF system activation at the center of a tunnel, it may take too long for the foam to travel from the storage tanks to the nozzles. The CAF system needs an installation of the mechanical room (mechanical room is used to mix foam agent with water) at specific intervals of the tunnel which adds up to the cost of initial installation of the CAF system.

A foam type suppression system cannot reach the fire inside of a vehicle. Foam system has less effect on cooling the hot gasses in the atmosphere because of less area of contact with air. Upon the activation of a foam system, there is a possibility that an occupant gets sprayed with the foam. There is also a hazard of slipping due to the presence of an additive in the foam. In such a situation, rescuing every person is very challenging if possible at all (SOLIT, 2012).

2.2. Regulations and Guides on FFFFS in Road Tunnels

The use of FFFS in road tunnels varies from country to country. The following table 2.1 provides a summary of existing regulations and guides on the use of FFFS in road tunnels.

Table 2.1 Regulations and guides on FFFS in road tunnels in different countries

Country or Region	**Regulations or Guides**
Australia	Fire Safety Guideline for Road Tunnels, AFAC- Australian Fire Authority Council (AFAC, 2001)
Austria	Guidance Document A-13 for fire safety in Road Tunnels, RVS, IBS, Transportation, and Road Research Association (NCHRP, 2011)
	Guidance document A-13 for fire safety in road tunnels, OBFV, Austrian fire department document based on European Directive (NCHRP, 2011)
Canada	International Bridges and Tunnels Regulations SOR/2009-17 International Bridges and Tunnel Regulations (2016) (IBTR, 2016)
China	JTG D70-2014 (CCSHCC, 2014) [National]. DG/TJ08-2033-2008 (STEDI, 2008) [Regional]
EU	Directive 2004/54/EC of the European Parliament and the Council Directive 2004/54/EC European Parliament and the Council (Official Journal of the European Union, 2004)
France	Inter-ministry circular no. 2000-63 of 25 August 2000 relating to the safety of tunnels in the national highways network, Circular 2000t63A2; CETU, CNPP; INERIS, Ministry for infrastructure, transport, spatial planning tourism, and the sea (Appendix N 2, 2000)
	Inter-ministerial Circular no.2000-82 of 30 November 2000 concerning the regulation of traffic with dangerous goods in road tunnels of the national network, Circ2000-82N2, Ministry for infrastructure, transport, spatial planning tourism, and the sea (Tunnel Study Center, 2003)
	Law no. 2002-3 of 3 January 2002 about the safety of infrastructures and transport systems, etc. Law2002-J2, Law 2002-3, art. 2 (BEA-TT, 2006)
	Risk studies for road tunnels: Guide to Methodology, ESD, Guide (European Thematic Network Fire in Tunnels, n.d.)
Germany	Guidelines for equipment and operation of road tunnels RABT, DMT, SOLIT, STUVA, VDS, VFDB, Road Transportation Research Association (NCHRP, 2011)
	ZTV Additional Technical conditions for the Construction of Road Tunnels- Part 1 Closed Construction Part 2 Open Construction ZTV- Tunnel, 1995 1999 (NCHRP, 2011)
Italy	Circular 6 Dec. 1999. Safety to Traffic in Road Tunnels with Particular Reference to vehicles Transporting Dangerous Materials Circular 06. 12. 1999 (NCHRP, 2011)
	Tunnel lighting UNI-Milano U29000240 (NCHRP, 2011)
	Functional and geometrical standard for construction of roads, Ministry of infrastructure and transport, General Inspectorate for Traffic and Road Safety (NCHRP, 2011)

Table 2.1 continues

Japan	Design Principles, Vol. 3 (Tunnel) Part4 Tunnel Safety facilities Japan Highway Corporation- JH (NCHRP, 2011)
	Installation Standards for tunnel Emergency Facilities (JH) (NCHRP, 2011)
	MEPC- Metropolitan Expressway Public Corporation (NCHRP, 2011)
	MOLIT- Ministry of Land Infrastructure Transport (NCHRP, 2011)
	HEPC (NCHRP, 2011)
South Korea	National Fire Safety Codes NFSC, Korea National Emergency Management Agency (NCHRP, 2011)
	Guideline for Installation of Safety Facility in Road Tunnels GIST, Ministry of Construction and Transportation (NCHRP, 2011)
Netherlands	Technical Standards for the provisions and installations RWS curves Rijkswaterstaat; TNO UPTUN, Dutch Ministry of Transport and National Regulator (NCHRP, 2011)
Norway	Norwegian design guide, roads, tunnels Public Roads Administration, Directorate of Public Roads, Handbook 021 (NCHRP, 2011)
	Road Tunnels Staten Vegvesen, SINTEF NBL, Norwegian Public Roads Administration, Directorate of Public Roads (NCHRP, 2011)
	Risk analysis of Fire in road tunnels Norwegian Council (NCHRP, 2011)
Russia	Construction Rules and Regulations (SNIP) # 32-04-97 “Railway and Road Tunnels” SNIP State Construction Committee GOSSTROI (NCHRP, 2011)
Spain	Manual for the Design, Construction, and Operation of Tunnels IOS-98 (NCHRP, 2011)
	Road Instruction, Norm, Alignment IC Norma 3.1 (NCHRP, 2011)
	Road Instruction, Norm, Vertical Signals IC Norma 8.1 (NCHRP, 2011)
Sweden	Comparison and Review of Safety Design Guidelines for Road Tunnels SP Report 2007:08, SP Swedish National Testing and Research Institute Report 2007 (NCHRP, 2011)
	Tunnel 2004 Swedish National Road Administration (NCHRP, 2011)
	Model Scale Tunnel Fire Tests: Sprinkler SP Report 2006:56 SP Swedish National Testing and Research Institute Brandforskprojekt 406-021 (NCHRP, 2011)
Switzerland	Ventilation of Road Tunnels, Selection of System, Design, and Operation ASTRA Swiss Federal Roads Office (NCHRP, 2011)
	Guidelines for Design of Road Tunnels ASTRA, Swiss Federal Roads Office (NCHRP, 2011)
UN	Recommendations of the group of experts on safety in road tunnels, UN TRANS/ AC.7.9, Economic and Social Council, Inland Transport Committee (NCHRP, 2011)
UK	Design Manual for Roads and Bridges, Vol. 2: Highway Structure Design Section 2, Part 9, BD 78/99: Design of Road Tunnels BD 78/99 The Highway Agency (NCHRP, 2011)
U.S.	NFPA502 (National Fire Protection Association), (NFPA, 2017)
	Prevention and Control of Highway Tunnel Fires, US DOT, FHWA (NCHRP, 2011)
	Underground Transportation Systems in Europe, US DOT FHWA, AASHTO (NCHRP, 2011)
	Making Transportation Tunnels Safe and Secure, TCRP, NCHRP (NCHRP, 2011)
	Enclosed Vehicular Facilities, ASHRAE (NCHRP, 2011)

2.3. Full-scale Tests of FFFS in Tunnels

Many full-scale tests have been performed worldwide to study the impact of FFFS in road tunnel fires. Some of the tests related to FFFS in tunnels are not available to the public (Beard and Carvel, 2004 pp-214; Brinson, 2010 pp-50). There are some publicly funded projects which are available in the literature. A summary of these publicly available full-scale tests is shown in Table 2.2.

Table 2.2 Summary of Full-scale Tunnel Fire Tests

Full-scale Tunnel Fire Test	**Year**
IF Oslo, Norway	NA
Ofenegg Tunnel Tests, Switzerland	1965
Zwenberg tunnel, Austria	1975
PWRI Experiments, Japan	1980
Repparfjord Tunnel Tests, Norway	1990-1992
Memorial tunnel tests, US	1993-1995
Benelux Tunnel Tests, Rotterdam	2000-2001
TNO Project, Norway	2005
Runehamar Tunnel tests, Andalsnes, Norway	2011
Singapore Sprinkler tests, Spain	2012
SOLIT	2012
Runehamar Tunnel Tests, Andalsnes, Norway	2014
Runehamar Tunnel Tests, Andalsnes, Norway	2016

A more detailed description of each test in the above table is in the followings.

IF Oslo, Oslo, Norway

(Ingason et al., 2016; Ingason and Lönnermark, 2014; SOLIT, 2012)

Description of tunnel-

The Area of a cross-section of the tunnel was 40m^2 and the length was 100m.

Location of tunnel-

Fringe of Oslo, Norway

Type of FFFS used-

Low-pressure water mist system (< 12.5 bars)

High-pressure water mist system (> 35 bars)

Testing conditions-

Heptane pool fire (20MW), wooden pallet fire (15MW). Longitudinal ventilation system with a speed between 1.0- 2.5m/s.

Test objectives-

To determine capabilities of the Low-pressure (< 12.5 bars) and High-pressure (> 35 bars) water mist system.

Test results-

Both systems can reduce Heat Release Rate (HRR) between 30% to 60%. Tests showed that both the systems worked similarly. The downstream temperature dropped very fast. The visibility increased as back layering was prevented.

Ofenegg Tunnel Tests, Switzerland, 1965

(Liu et al., 2007; NCHRP, 2011; Beard and Carvel, 2004)

Description of tunnel -

Abandoned rail tunnel named Ofenegg tunnel with a cross-section of $24m^2$. The tunnel had a dead end at 190m from the portal.

Location of tunnel-

Switzerland

Type of FFFS used-

Two rows of sprinklers with a capacity of 19 l/sm^2 were installed.

Testing conditions-

Fuel pools from 6.6m^2 to 95m^2 used to perform 11 fires. Pools made of the concrete tub with gasoline poured into the tub. Gasoline used was regular, composed of 86% carbon and 14% hydrogen with a density of 730 kg/m^3 at 15°C. Lower calorific value of gasoline used was 44Mj/kg.

Test objectives-

Investigation of CO concentrations, temperature distribution, visibility, response to ventilation, response to sprinklers, the effect on vehicles, the effect on the structure of tunnel, and effect on people.

Test results-

500-liter fuel tests with semi-transverse ventilation system have no mitigation effect. Longitudinal ventilation system drove flames downwind.

500-liter fuel test with sprinkler showed initial evaporation of droplets forming a cloud of steam. The open fire was extinguished. After 17 minutes, the fire reignited (Sprinkler system flow was not stated that time). Re-ignition did not cause any explosion.

In 1000-liter fuel tests, activation of sprinkler system reduced maximum ceiling temperature, the fire was extinguished in 10 minutes and fuel vapors reignited causing an explosion in 9 minutes after the fire was extinguished. Three technicians were injured and the test facility was damaged.

Zwenberg tunnel, Austria, 1975.

(Liu et al., 2007; NCHRP, 2011; Beard and Carvel, 2004)

Description of tunnel -

Abandoned rail tunnel.

Location of tunnel-

Austria

Type of FFFS used-

None

Testing conditions-

Fuel areas of $6.8m^2$ and $13.6m^2$ with the fully transverse ventilation system. 23 tests were performed with 200-liter gasoline with an area of $6.8m^2$ and 400-liter gasoline with an area of $13.6m^2$.

Test objectives-

Conditions in traffic with different ventilation patterns and improvements with a change in design, operation, and construction of exhaust opening.

Test results-

Rescuing people on exhaust air side is not possible. Maximum exhaust air temperature was found 85 °C.

PWRI Experiments, Japan, 1980 (NCHRP, 2011)

Type of tunnel-

700m long public Works Research Institute (PWRI) built a gallery and a road tunnel of 3300m length.

Location of tunnel-

Japan

Type of FFFS used-

None

Testing conditions-

16 experiments were performed in the gallery and 8 were in the tunnel. The source of the fire was fuel pools and solid fuels. Fuel pools with ten tests of the $4m^2$ surface area and two tests of the $6m^2$ surface area and solid fuels of 6 tests of passenger cars and six tests of busses. Tests were performed with oversized exhaust ports for smoke removal.

Test objectives-

Influence of longitudinal velocity of air flow and oversized exhaust ports.

Test results-

Best smoke removal was achieved by operating east and west fans. Space between fire point and open dampers filled with smoke.

Repparfjord Tunnel Tests, Norway, 1990–1992 (NCHRP, 2011)

Type of tunnel-

2.3km long abandoned mining gallery with cross-section 30 to 40 m^2.

Location of tunnel-

Norway

Type of FFFS used-

None

Testing conditions-

21 tests were performed with rail and metro vehicles, heavy goods vehicles, passenger cars, and pool fires. 400 sensors were installed inside the tunnel. Fire load for cars was 5,000MJ and fire load for heavy goods vehicles was 90,000MJ. One test was performed with n-heptane with a density of 680kg/m^3 at 15 °C. The calorific value of the fuel was 44.4MJ/kg. The mean value of the area of cross-section in the tunnel was between 30 to 35m^2.

Test objectives-

Smoke development and smoke dispersal from the car and heavy good vehicle.

Test results-

The total tunnel was filled with smoke.

Memorial Tunnel tests, United States, 1993-1995 (Liu et al., 2007; NCHRP, 2011)

Description of tunnel -

The length of the tunnel was 853.4m with former two-lane road alignment. Area of a cross-section of the tunnel was 60.5m^2.

Location of tunnel-

West Virginia US

Type of FFFS used-

3% AFFF with 2.4 L/min.m^2 to 3.8 L/min.m^2 discharge rate.

Type of FFFS used-

Foam system

Testing conditions-

Diesel oil was used as fuel with a density of 815kg/m^3 and 855kg/m^3 at 15 °C. The lower calorific value of fuel was 42.5MJ/kg. Diesel pool of 10MW, 20MW, 50MW, and 100MW was used. Longitudinal ventilation with a velocity of 4.2m/s was used.

Test objectives-

To analyze the smoke development and smoke dispersal.

Test results-

The fire was extinguished in less than 30s in all the four tests conducted. The performance of Deluge foam system was unaffected by longitudinal velocities.

Benelux Tunnel tests, Rotterdam, Netherlands, 2000/2001

(Liu et al., 2007; NCHRP, 2011; Brinson, 2010)

Description of tunnel-

N/A

Location of tunnel-

Rotterdam, Netherlands

Type of FFFS-

Water spray system with a discharge rate of 12.5l/m^2/min.

Test objectives-

To analyze the benefits of large droplets sprinklers.

Test conditions-

Six pool fires, four vehicle fires, six tests with piled load, and ten fire detection tests were performed.

Test results-

Temperature reduction was seen from 250-350 °C to 20-30 °C after activation of deluge sprinkler FFFS. This reduction in temperature prevented the spread of fire to other vehicles. Visibility reduction was observed. No deflagration or steam formation was observed in the tests.

DMT (Deutsche Montan Technologie), Dortmund, Germany 2004

(Beard and Carvel, 2004; SOLIT, 2012)

Description of tunnel -

150m long tunnel with cross-section 9.7m^2 area.

Location of tunnel-

Dortmund, Germany

Type of FFFS used-

Water spray system (droplet size 1mm approx.)

Low-pressure water mist system

Testing conditions-

Diesel pool fire of four compartments with the 2m^2 area.

Test objectives-

To determine the capabilities of water spray system and low-pressure water mist system.

Test results-

Cooling effect in the case of water mist and water spray system was observed. The fire was not completely extinguished. Maximum possible airspeed in the tunnel was 3m/s to affect drops of water spray and water mist systems. Water consumption of water mist system was 1/10th of water spray system.

No release of further results of DMT in the public domain (Beard and Carvel, 2004 pp-214)

TNO Project, Norway, 2005 (Liu et al., 2007)

Description of tunnel -

Runahamar tunnel of 6m height, 9m wide and 1600m long.

Location of tunnel-

Norway

Type of FFFS used-

Compressed air foam (CAF) systems with water density of 5.6 L/m^2.min.

Testing conditions-

First experiment with fully developed solid fire with wooden pallets of volume 100m^3. Heat release rate of 300MW was achieved. Second fire with 200MW heat release rate. Jet fans were used for longitudinal ventilation running with 2-3 m/s velocity.

Test objectives-

The impact of ventilation system on CAF systems.

Test results-

CAF system extinguished diesel fire successfully. CAF controlled solid fire but failed to extinguish it. Air temperature at upstream was cooled down to 50 °C and air temperature downstream was cooled down to 100 °C. The fire spread was prevented. Firefighters easily approached fire source. Visibility lost completely. No steam generation and no deflagration were observed.

Runehamar Tunnel tests, Åndalsnes, Norway 2011 (Ingason et al., 2011)

Description of tunnel -

Runahamar tunnel of 6m height, 9m wide and 1600m long.

Location of tunnel-

5 km from Åndalsnes, 40 km south of Molde in Norway

Type of FFFS used-

N/A

Testing conditions-

Test1 was performed with 200-liter pool fire of diameter 2.27m of diesel. Total weight of fuel was 166.4kg with a theoretical calorific value of 6.7GJ and maximum HRR of 6MW.

Test2 was performed with 360 wooden pallets with each wooden pallet measuring 1200* 800* 150mm, 20 wooden pallets with each wooden pallet measuring 1200* 1000* 150mm and 74 PE plastic pallets with each measuring 1200* 800* 150mm. The whole set up was covered with 122m^2 area of polyester tarpaulin. Total weight was 11,010kg with a theoretical calorific value of 244GJ and maximum HRR of 202MW.

Test3 was performed with 216 wooden pallets of 1200* 800* 150mm and 240 PUR mattresses. Setup was covered with 122m^2 polyester tarpaulin. Total weight of 6853kg with estimated calorific value 135GJ and maximum HRR of 157MW.

Test4 was performed with Furniture and fixtures, ten large rubber tires covered with 122m^2 polyester tarpaulin. Total weight of 8506kg with a theoretical calorific value of 179GJ and maximum HRR of 119MW.

Test5 was performed with 600 corrugated paper cartoons with dimensions 600 mm* 400 mm* 500 mm, 18000 unexpanded polystyrene cups, 40 wooden pallets of dimension 1200* 1000* 150mm and 10m^2 area of polyester tarpaulin cover. Total weight of

2849kg with the Theoretical calorific energy of 62GJ and maximum HRR of 66MW.

Test objectives-

Validation of the fire spread, pulsation of main air flow, back layering, gas concentrations and heat flux, fire growth rate, and gas temperature.

Test results-

Maximum HRR ranged from 66MW to 202MW in all tests.
Maximum ceiling gas temperature exceeded 1280 °C.
The critical gas temperature to create fire spread was 600 °C.
The back layering of 100m was observed.

Singapore Sprinkler tests, Spain, 2012 (Cheong et al., 2014)

Description of tunnel -

Two lane road tunnel of 600m length.

Location of tunnel-

Spain

Type of FFFS used-

Deluge water spray system

Testing conditions-

Six tests were conducted with water spray system with the directional nozzle, standard spray nozzle, and the seventh test was an unsuppressed fire. Jet fans produced 3m/s air velocity for ventilation.

228 pallets were used as fire source with 20% plastic pallets and rest 80% wooden pallets.

Test objectives-

To determine the magnitude of HRR generated by HGV with and without fire suppression system.

Test results-

Peak HRR was 27.1MW to 44.2MW when deluge system is operated after 4min of fire. Peak HRR was 96.5MW if deluge system is operated after 8min, and peak HRR was 150MW without deluge system. Reduction of HRR Showed that early activation of deluge system made a huge difference as it affected the fire in the early growth phase.

SOLIT (Safety of Life in Tunnels), 2012 (SOLIT, 2012)

Description of tunnel -

Tunnel of length 600m, width 9.5m and height 8.20m.

Location of tunnel-

Spain

Type of FFFS used-

Water mist system

Testing conditions-

Class-A (wooden pallets) fire with potential to develop up to 150MW, cover, and longitudinal ventilation

Class-A fire without tarpaulin cover tested with water mist system

Class-B diesel pool fire with the potential of 160MW HRR tested with FFFS activations in longitudinal ventilation

Class-B Fire with Semi-Transversal Ventilation

Test objectives-

To determine the effect of water mist system in Class-A and Class-B fires.

Test results-

Test with Class-A fire with cover and longitudinal ventilation showed that without FFFS (water mist), the growth of fire is rapid. FFFS (water mist) activation lowered the rate of growth and reduced maximum HRR to almost 30MW with tarpaulin and 20MW without tarpaulin. No back layering was observed. The temperature of the tunnel at downstream was low enough that firefighters could perform firefighting procedures.

Same Class-A fire without tarpaulin cover tested with water mist system reached maximum 20MW with no back layering. Surrounding temperatures at downstream were low.

Runehamar Tunnel tests, Åndalsnes, Norway 2014 (Ingason et al., 2014)

Description of tunnel -

Runahamar tunnel of 6m height, 9m wide and 1600m long.

Location of tunnel-

5 km from Åndalsnes, 40 km south of Molde in Norway

Type of FFFS used-

Deluge system with 150mm diameter (K factor of 360l/min/bar$^{1/2}$) pipe in tunnel ceiling fitted to nozzles every five meters capable of spraying 375l/min water in two directions. The total water flow of deluge section was 7500l/min. Estimated lifespan of FFFS was 30 years.

Test objectives-

Investigation of the impact of activation time of FFFS and efficiency of fire suppression.

Longest activation time to keep the fire under control.

Testing conditions-

Fire source had 420 wooden pallets representing HVG, 600m from the west portal. The potential energy of 180GJ and estimated HRR was 100MW. Fire source covered with steel plates from front and back and above pallets.

Test1- delay time of 2min after 141 °C in ceiling

Test2- delay time of 4min after 141 °C in ceiling

Test3- delay time of 8min after 141 °C in ceiling

Test4- delay time of 4min after 141 °C in the ceiling with a tarpaulin cover.

Test5- delay time of 4min after 141 °C in the ceiling without steel blockage.

Test6- free burn

Test results-

FFFS could lower HRR to 40MW in the five tests performed and out of five, four tests had HRR lower than 20MW.

The spread of fire was prevented.

Maximum ceiling temperature with FFFS activated was 400 °C to 800 °C. In the last test which was a free burning test, ceiling temperature was 1366 °C. Early activation of FFFS is important.

The fire of 100MW suppressed to lower than 50MW by FFFS activation.

Runehamar Tunnel tests, Åndalsnes, Norway 2016 (Ingason et al., 2016)

Description of tunnel -

Runahamar tunnel of 6m height, 9m wide and 1600m long.

Location of tunnel-

5 km from Åndalsnes, 40 km south of Molde in Norway

Type of FFFS used-

Deluge system zone of 30m with a pipe of 600m length and 140mm diameter width, to deliver water from the tank. Different nozzles of deluge systems,

TN-25 (K factor 362.9 l/min/bar$^{1/2}$) with minimum and a maximum pressure of 0.7 and 2.1 bar. Nozzle pressure of 0.55 to 0.69 bar.

TN-17 (K factor 240l/min/bar$^{1/2}$). Nozzle pressure of 0.95 to 1.25 bar.

SW-24 with glass bulbs removed (K factor 161.3l/min/bar$^{1/2}$). Nozzle pressure of 2.13 bar.

Automatic sprinkler system with nozzle heads,
SW-24 with 3mm thick 93 °C green bulb.

Test objectives-

A new prototype of the nozzle and check the efficiency of fire suppression with lower flow rate.

Automatic sprinkler head type SW-24

Testing conditions-

Fire source of 420 wooden pallets was used to represent HGV placed in the center of the tunnel that was 600m from west portal. The weight of fuel was 10 tons. Potential energy estimated was approximately 180GJ. Pallets covered with steel plates from up, front and back.

Test1- TN-25 nozzle pressure 0.69bar

Test2- TN-17 nozzle pressure 1.25bar

Test3- TN-17 nozzle pressure 0.95bar

Test4- TN-25 nozzle pressure 0.55bar

Test5- SW-24 nozzle pressure 2.13bar

Test6- SW-24 with bulb.

Test results-

Use of TN-25 nozzles (Large droplets at pressure 0.55bar) shows that HRR cannot exceed 15MW in the test with FFFS (4-minute delay for FFFS activations). Best results are experienced with the pressure of 0.55bar. The delay in activation of FFFS affect maximum HRR, as the delay increases, HRR also increases.

In all the tests (from 1-5) with deluge water spray FFFS, gas temperatures were cooled effectively. Ceiling temperatures were ranging from 393°C -531 °C. Maximum HRR ranges from 13.9MW-20.7MW

Test-6 was done with an automatic sprinkler system with bulbs and nozzles of SW-24 and had no back-layering. Maximum HRR reached was of 31MW. The temperature of activation of sprinkler heads with bulbs was 93 °C. All six heads got activated with similar control on fire as deluge water spray FFFS. Gas temperatures got lowered initially but continued to increase later to 500-600 °C. Increase in back-layering of 55m was observed.

The deluge water spray FFFS performed better than automatic sprinkler system in the fire with no back layering and better cooling of gasses.

Class-B diesel pool fire with the potential of 160MW HRR tested with FFFS activations in longitudinal ventilation prevented back layering and extinguished the fire.

Class B Fire with Semi-Transversal Ventilation showed disappeared back layering after activation of FFFS. The fire got extinguished with FFFS activations in few minutes. Results were same for 120m^3/s and 80m^3/s semi-transverse ventilation which were designed for only 30MW fire.

2.4. Other Available Studies

In a master's thesis (Ejrup, 2011), it was mentioned that in the case of a real fire incident, Burnley Tunnel Fire in 2007, the deluge system and the semi-transverse smoke control system activated quickly and controlled smoke to 100m downstream of fire. For water mist systems, there were satisfactory results with back layering, temperatures, and toxicity. A water mist system could prevent the spread of fire and lower the temperature. The high-pressure water mist system saves water usage. In the case of water mist system, visibility was hampered like water spray system. Research studies state that the fire suppression systems prevented damage to the tunnel structure. Approach to a tunnel fire becomes easier for firefighters due to a reduced temperature in the tunnel. Tunnel linings were protected. Research mentions that firefighters and evacuating people, will both be hampered by reduced visibility. Deluge system was considered as more appropriate for a tunnel (Fragkopoulou, 2016). Thus, the impact of deluge suppression systems broadly reduced the load on tunnel linings in a fire scenario.

A literature review of Permanent International Association of Road Congresses (PIARC) concluded following properties of deluge FFFS (PIARC, 2016):

- FFFS prevents the spread of fire from one vehicle to other.
- FFFS causes de-stratification of the smoke layer in the activation area of the tunnel.
- FFFS causes visibility reduction in the activated zone in the tunnel.
- FFFS helps reduction in radiation effects from the tunnel fire.

- With activation of FFFS, there is a significant reduction in peak temperatures and the tunnel is protected from high heat impacts.
- Activation of an FFFS leads to a reduction in HRR.

Steam generation caused while water meets hot surfaces of burning fuel is not enough to consider a threat in a tunnel fire (PIARC, 2016). The conclusions made by PIARC show that ventilation system will experience less load with reduced temperatures and HRR. Fire will not spread and will be contained till firefighters reach the source. Firefighters can reach the source due to a lower temperature in the tunnel. Load on tunnel lining can be reduced and spalling can be prevented due to the protection of tunnel structure from high heat impacts.

Interviews were performed in Japan to understand the experience of using deluge sprinkler systems (Stroeks, 2001). Tunnel authorities in Japan were satisfied with the performance of deluge sprinkler system. Tunnel authorities include Ministry of Land Infrastructure Transport (MOLIT), Japan Highway (JH), Metropolitan Expressway Public Corporation (MEPC), and Hanshin Expressway Public Corporation (HEPC). A rough estimate of the cost of installation of the deluge sprinkler system in Japan was 3,127 USD per meter per tunnel. The smaller the droplet size from the sprinkler system, the larger was the interface of water and air and greater is the absorption of heat. The larger the droplet size, the lesser droplets were blown away. No notable defects were experienced with the installation of sprinkler systems (Stroeks, 2001 pp-48). The lifetime of main pipes of sprinklers was estimated to be more than 20 years. Clogging of heads and physical damage due to the impact of HGV required inspections twice a year and water discharge tests once a year. No malfunctioning of sprinklers was experienced during the operation of deluge sprinkler system in Japan (which includes no sudden discharge, no case where water was not available in pipes where it should be, and no cases with pipes between valve and heads filled with water). JH experienced between 10-16 tunnel fires per year with 2-3 sprinkler activations. MEPC used 5-6 sprinkler activations in tunnel fire where the fire was cooled and prevented from the spread. No case of false operation, malfunctioning or partial functioning of sprinklers was observed in an actual fire. Experiments carried for the New Tomei Expressway showed maximum fire size of 23MW with sprinkler system activated. Prevention of fire spread was verified under longitudinal velocity flow. Detectors notified the operator and then the operator confirmed from CCTV camera before activation of FFFS through a push button. This procedure prevented false alarm activation of FFFS. Back-layering was prevented by longitudinal ventilation in case of a fire due to less load in Japan. There has been no use of foam in sprinklers due to high cost and cleaning work after usage.

2.5. Modeling of FFFS in Tunnels

In addition to tunnel fire experiments, there are very limited number of numerical studies on the effect of FFFS in road tunnel fires. Computational fluid dynamics(CFD) models have been used to simulate the impact of FFFS on tunnel fires. Development of CFD models is due to time and cost reduction in a new design of tunnel. Experiments related to tunnel fires are dangerous, time-consuming and expensive. Thus CFD models are preferred for saving money and time (Beard and Carvel, 2004). Buoyancy forces in a tunnel fire causes a flow. The energy release in the tunnel fire creates buoyancy forces. CFD modeling is developed to analyze these movements. The following is a summary of available CFD studies related to FFFS in tunnels.

CFD modeling 1- (Dix, 2010)

Tunnel-

Burnley Incident, 2007

Type of FFFS-

Water spray system

Results-

Water application rate was less than or equal to 4mm/min which cannot reduce fire although growth can be hindered. Application rate poorly influenced shielded fire but still, fire spread was hindered. The fire inside the vehicle cannot be extinguished. Radiation energy was lowered and risk of flashover was reduced.

With an application of 10mm/min water from FFFS, there is an absence of flashover and prevention of accelerated fire growth. Fixed firefighting system activation leads to reduced need for ventilation requirement to prevent any back layering.

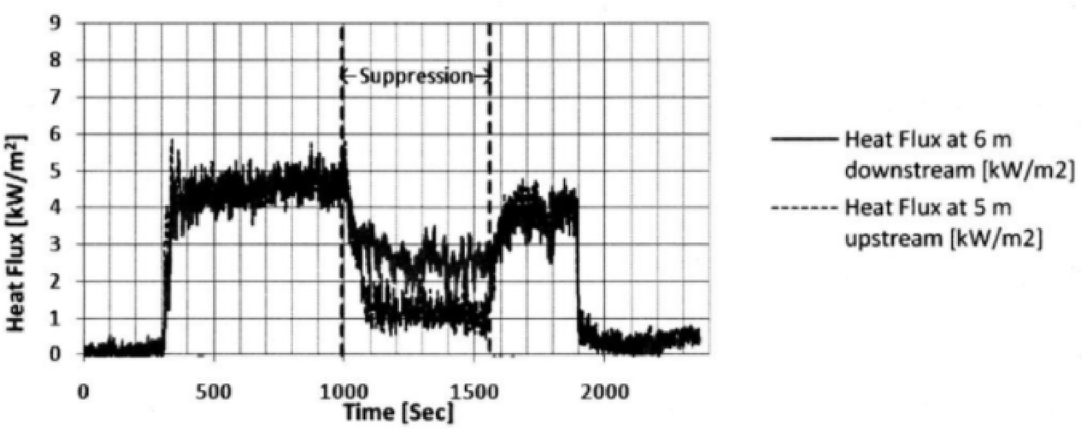

Figure 2.1 Heat flux measured at 5m downstream and 6m upstream with time (Dix, 2010)

Figure 2.1 shows the positive impact of an FFFS from 1000s to 1500s time interval. The reduction of heat flux is observed on an activation of the FFFS.

CFD modeling 2- (Mofidi and Manafi, 2014)

Tunnel-

Resalat tunnel (100m* 13.5m* 9m)

Type of FFFS-

Water mist system with droplet size 100 µm, nozzle spacing 3m, working pressure of 80 bars and K factor of 4.3l/min/bar$^{1/2}$.

Sprinkler system with a droplet size of 750 µm, nozzle spacing of 3m, working pressure of 0.56 bar and K factor of 80 l/min/bar$^{1/2}$.

Test setup- Vehicle of 4.4m* 2m* 1.4m with HRR of 10MW potential. The flow rate of the ventilation system is 33.3m^3/s.

Results-

Both systems successfully reduced fire to 365 °C. Activation of water mist system disturbed smoke layer more than that of sprinkler system. 87.96% reduction of HRR in the case of a sprinkler system and 88.68% reduction of HRR in the case of the water mist system were observed.

However, the accuracy of CFD analysis is considered low. Low accuracy of CFD is due to the limitations of the model, which cannot include all physical phenomena. It is also due to a lack of understanding in some of the physical processes which leads to the development of approximate models. It cannot be trusted solely, and physical tests as aids should be used (McAlpine, 2017). The reliability of evacuation models is considered very low, and there is a need for more research and development to reach the sufficient level of validity. Software developed for evacuation simulation needs more improvement for better results. Conducting real evacuation process and comparing it with simulated models can determine unknown variables of simulation models of evacuation simulation software to address uncertainties (Fragkopoulou, 2016).

The sensitivity of model depends on various factors such as variation in ventilation velocity, the surface of the tunnel, fire source dimensions, and hindrances at surrounding area of the fire.

The critical velocity and back-layering occurrences are very sensitive to the model variables during set-ups.

In summary, limited CFD studies suggest that FFFS can have a positive impact on prevention of fire spread, reduction of heat radiation, and back-layering can be prevented. Water spray system and water mist system have a similar impact on heat release rate reduction.

2.6. Cost-Benefit Analysis Studies

Jönsson and Johnson (Jönsson and Johnson, 2010) performed a cost analysis study for the design and operation of a tunnel for Australia. This is the only publically available cost analysis study for tunnel fire. This study calculated revenue of vehicles, estimated average fires, and its impact on the economic loss. The study compared the cost of the same scenario with FFFS installed in the tunnel and difference in the economic loss including the expenditure in installation, maintenance, and repair. The summary of this study is the following. [The summary is based on the following assumption: The exchange rate in 2009 from Australian dollar to US dollar is approximate $0.8 USD for $1 AUD (Exchange Rate Average -Australian Dollar, US Dollar). Inflation from 2009 to 2016 is $0.8 to $0.89 from 2009 to 2016 (Robert S., n.d.). Thus, $1 AUD (in the year 2009) equals $0.89 USD (in the year 2016).]

The cost analysis study (Jönsson and Johnson, 2010) assumed two unidirectional tunnels of length 6000m with a traffic flow of 100,000 vehicles per day for each tunnel, per kilometer length. Average traffic flow in a tunnel consists of 93% cars and 7% HGV (Jönsson and Johnson, 2010). The research assumed FFFS for the tunnel is a Deluge water spray system with a density of 10mm/min. The capital cost of installation of Deluge water spray system, in the assumed tunnel in the year 2009, was AUD $25 million. Annual maintenance of Deluge system in 2009 costed AUD $3 million. Life expected for the Deluge system was 30 years. According to the statistical report by PIARC (1999), fire frequencies in a road tunnel for car and HGV causing heavy and small damages were used in this study. Car fires were 1.5 per 100,000,000 vehicles.km. and HGV fires were 8 fires per 100,000,000 vehicles.km. Out of HGV fires, “1 fire per

100,000,000 vehicles.km." caused small damage to the tunnel and "0.2 fires per 100,000,000 vehicles.km." caused serious damage to the tunnel. For the road tunnel assumed, revenue earned by HGV was AUD $6,840,000 and for cars was AUD $5,580,000 per day. Thus, total revenue earned per annum was AUD $2,462,400,000. The frequency of car fires was approximately 6.11 and HGV fires was approximately 2.45 fires per year. Out of the HGV fires, HGV causing small damages to tunnel was approximately 0.31 and causing serious damage to tunnel was approximately 0.06 per year.

The results of this study are discussed in Chapter 3, "Analysis of existing data".

CHAPTER 3: ANALYSIS OF EXISTING DATA

3.1. Impact of FFFS on Tunnel Fires and Tunnel Resilience

The analysis of the data collected is done according to the impact of FFFS on the specific parameters of a tunnel in the case of a tunnel fire. These parameters are heat release rate (HRR), fire spread, radiant heat, back-layering, temperature, and visibility. The purpose of an FFFS in the tunnel is to reduce HRR, hinder the fire spread, reduce the radiation heat, prevent the back-layering, and improve visibility in a tunnel fire to aid firefighters with firefighting operations. In addition to these functions of FFFS, the cost benefit analysis is also an important criterion to be fulfilled.

Tables 3.1.a. provides a summary of the impact of FFFS on ventilation systems, temperature, and fire suppression. All the full-scale tests with FFFS had a reduction of ventilation system load, temperature, and prevention of structural damage. Besides that, visibility was hindered in all the tests. In all the tests with FFFS, the HRR was reduced. The fire was either completely suppressed or was controlled if not completely suppressed. In the case of the Ofenegg Tunnel tests, the early deactivation of FFFS caused reignition of liquid fuel vapors. However, the reignition of fuels was not observed in any other tests than the Ofenegg tunnel tests, which shows that early deactivation of FFFS can be harmful. Some tests showed that the application of water on fire increased concentrations of CO, when compared to tests without FFFS. Oxygen level in tunnel fire tests with FFFS was higher than those tunnel tests without FFFS (Ingason et al., 2016; McManus, 2009).

Table 3.1.b is a summary of the impact from fires without FFFS. The table shows that a fire in a tunnel without FFFS causes overloading of the ventilation system, high temperatures, back layering of smoke, and structural damage. The environment in the case of a tunnel fire without FFFS will hinder firefighters from reaching the fire source and carry the firefighting procedures. On the other hand, Table 3.1.a. shows that the FFFS creates a tenable environment for the firefighters to carry firefighting procedures. Table 3.1.a. also shows that the activation of FFFS prevented the structural damage by reducing peak HRR and temperature.

Table 3.1.a Summary of full-scale experiments (with FFFS)

Tests with FFFS	Impact on Ventilation system	Impact on temperatures	Fire Suppression
IF Oslo, Oslo, Norway (Ingason et al., 2016; Lönnermark, 2014; SOLIT, 2012)	Reduced HRR, smoke temperature and travel, prevented back layering, reduced ventilation system load	Reduced	Not fully suppressed but controlled.
Ofenegg Tunnel Tests, Switzerland, 1965 (Liu et al., 2007; NCHRP, 2011; Beard and Carvel, 2004)	Reduction in temperature led to a reduction in ventilation system load	Reduced	Fire extinguished in 10min and then got reignited because of early deactivation of FFFS in the tunnel
Memorial Tunnel tests, United States, 1993-1995 (Liu et al., 2007; NCHRP, 2011)	No smoke showed no increased load on the ventilation system	Reduced	Suppressed (extinguished the fire within 30-second).
Benelux Tunnel tests, Rotterdam, Netherlands, 2000/2001 (Liu et al., 2007; NCHRP, 2011; Brinson, 2010)	Ventilation system load reduced	Reduced the temperature from 250-350 °C to 20-30 °C, structural damage prevented.	Fire not completely suppressed but controlled.
DMT, Dortmund, 2004 (Beard and Carvel, 2004; SOLIT, 2012)	Ventilation system load reduced	Water mist system and water spray system both were effective in reducing temperature and preventing fire spread.	Fire not completely suppressed but controlled.
TNO Project, Norway, 2005 (Liu et al., 2007)	Ventilation system load reduced	Air temperatures were cooled down and fire spread was prevented	CAF system completely extinguished pool fire, solid fire was not extinguished.
Singapore Sprinkler tests, Spain, 2012 (Cheong et al., 2014)	Early activation of FFFS succeeded in control of HRR and reduced ventilation system load	Reduced	Not suppressed completely but prevented the spread of fire.
SOLIT (Safety of Life in Tunnels), 2012 (SOLIT, 2012)	Water mist system prevented back layering, reduced HRR	Reduced	Not suppressed completely but prevented the spread of fire.
Runehamar Tunnel tests, Åndalsnes, Norway 2014 (Ingason et al., 2014)	Reduced HRR and temperature, indicating less smoke and less load on the ventilation system.	Ceiling temperature was reduced from 1366 °C to 400 °C.	Not suppressed completely but prevented the spread of fire.
Runehamar Tunnel tests, Åndalsnes, Norway 2016 (Ingason et al., 2016)	Specific nozzle (TN-25) of deluge water spray system at pressure 0.55 bar showed best results in a reduction of ventilation system load.	Reduced	Not suppressed completely but prevented the spread of fire.

Table 3.1.b Summary of full-scale test (without FFFS)

Tests without FFFS	**Ventilation system**	**Temperatures**	**Fire Suppression**
Zwenberg tunnel, Austria, 1975. (Liu et al., 2007; NCHRP, 2011; Beard and Carvel, 2004)	Ventilation system could not prevent back layering, and smoke extraction was not sufficient.	Air temperature of 85 °C showed that temperatures were much higher without FFFS.	Could not suppress.
PWRI Experiments, Japan, 1980 (NCHRP, 2011)	Longitudinal ventilation system needed oversized exhaust vents to extract smoke. (Overloaded ventilation system)	High	Could not suppress.
Repparfjord Tunnel Tests, Norway, 1990–1992 (NCHRP, 2011)	Tunnel filled with smoke.	High.	Could not suppress.
Runehamar Tunnel tests, Åndalsnes, Norway 2011 (Ingason et al., 2011)	Back layering which showed overloaded ventilation system.	Max. HRR reached 202MW and max. ceiling temperatures reached 1280 °C.	Could not suppress.

In the case of the tunnel with FFFS, headache, nausea, and dizziness are a possible symptom after 45 minutes of 0.08% CO exposure and person may collapse and become unconscious after 1 hour of 0.08% CO exposure. Death may occur within 2-3 hours of exposure. In the case of the tunnel without FFFS, a person may suffer a headache and nausea after 1-2 hours of exposure of 0.04% CO. The person will die in 3 hours (CO Health Risks, n.d.). After analyzing CO and O_2 concentrations in both of the cases, with and without FFFS, the situations were very similar. CFD model analysis showed that, with the presence of FFFS, no back layering was observed leading to an increase in efficiency of the ventilation system and reduction of ventilation system load.

Table 3.2 shows the comparison of the impact of different FFFS (deluge water spray, water mist, and foam system) on tunnel fire characteristics: The comparison shows that the deluge water spray system and water mist system are similar with suppression of fire. Water mist system needs more maintenance and their cost of installation is high. The deluge water spray system has lower maintenance requirements and has lower installation cost. Japan’s experiences showed how reliable FFFS are. CAF and Foam type FFFS suppressed fire but created hazards to evacuees.

Table 3.2 Impact of various FFFS on road tunnels

Impacts of FFFS		**Deluge water spray system**	**Water mist system**	**Foam**
Temperature	Temperature at different distance from fire	Decreased (Ingason et al., 2016)	Decreased (SOLIT, 2012)	decreased
	Ceiling temperature	Decreased (Ingason et al., 2016)	Decreased (SOLIT, 2012)	decreased
	Radiant heat	Decreased (Ingason et al., 2016)	Decreased (SOLIT, 2012)	decreased
	Heat Release Rate	Decreased (Ingason et al., 2016)	Decreased (SOLIT, 2012)	decreased
	Temperature at breathing height	Decreased (Ingason et al., 2016)	Decreased (SOLIT, 2012)	decreased
Fire	Growth of fire	Growth hindered (Ingason et al., 2016)	Growth hindered (SOLIT, 2012)	Growth hindered
	Spread of fire	Hindered (Ingason et al., 2016)	Hindered (SOLIT, 2012)	hindered
Smoke		Controlled (Ingason et al., 2016)	Controlled (SOLIT, 2012)	controlled
Smoke stratification		Destroyed at activation area (Ingason et al., 2016)	Destroyed at activation area (SOLIT, 2012)	-
Spalling of concrete		Prevented (Ingason et al., 2016)	Prevented (SOLIT, 2012)	prevented
Visibility on activation		Hindered (Ingason et al., 2016)	Hindered (SOLIT, 2012)	hindered
Cost of installation		Lower compared to other FFFS	High	High
Cleaning requirements for activation		No	No	Yes
Possible health hazards		CO concentrations increase	CO concentrations increase	Suffocation, Slippery surface
CO concentrations		6ppm	6ppm	-
O2 concentrations		19.5 approx.	19.5 approx.	-
Maintenance requirements		low	High	High
Ventilation system load		reduced	reduced	reduced
Malfunctioning, defects, and errors till now in existing tunnels.		No (not in Japan) (Ejrup, 2011 PP-30; Stroeks, 2001 PP-49)	-	-
Slipping hazard		-	-	yes
Operating pressure		low	high	high
Water usage		high	low	high
Positive impact of early activation of FFFS on suppression efficiency		Yes (Cheong et al., 2014)	yes	-

In Table 3.3, the impact of different FFFS on the characteristics of Class-A tunnel fires is compared with the Class-A tunnel fire without FFFS. Similar comparison is done on the characteristics of Class-B tunnel fires in the Table 3.4.

Table 3.3 Impact of FFFS on Class-A tunnel fires

Impact on Tunnel fire characteristics	Water mist	Deluge water spray (4-min. delay)	Automatic sprinkler system	Foam	Without FFFS
Maximum Heat Release Rate	20MW (for 150MW potential)	13.9-14.9MW (for 80MW potential)	31.1MW (for 80MW)	-	80MW, 150MW
Maximum Heat Release Rate with tarpaulin	30MW (for 150MW potential)	14MW (for 80MW potential)	-	-	80MW, 150MW
Maximum ceiling temperature	600 °C	393-531 °C	800 °C	-	1366 °C
CO concentrations	-	0.07%- 0.12%	0.24%	-	0.039%
Maximum gas temperatures	150 °C	400 °C	500-600 °C	-	1366 °C
O_2 concentrations	-	20.1%- 20.4%	19.3%	-	17%
Visibility	hindered	hindered	hindered	Hindered (Maevski et al., 2015)	hindered
Back layering with longitudinal ventilation of 2m/s	none	none	-40m	None (Maevski et al., 2015)	-55m

Table 3.4 Impact of FFFS on Class-B tunnel fires

Impact on Tunnel fire characteristics	Water mist		Deluge water spray	Automatic sprinkler system	Foam (Fire extinguished)	Without FFFS
	120 m^3/s	80 m^3/s				
Maximum Heat Release Rate	65MW (for 100MW potential)	80MW (for 100MW potential)	-	-	-	80MW, 150MW
Maximum ceiling temperature	750 °C	800 °C	--	-	-	80MW, 150MW
CO concentrations	-	-	-	-	-	1366 °C
Maximum gas temperatures	600 °C	800 °C	-	-	-	0.039%
O$_2$ concentrations	-	-	--	-	-	1366 °C
Visibility	-	-	-	-	-	17%

Table 3.4 shows the impact of different FFFS on Class-B tunnel fires. Since many information is not available, the impact of FFFS in a case of liquid fuel fire cannot be compared. However, with the available data, it can be observed that the water mist system can lower the HRR to 65MW and the temperature to 750□ at a discharge rate of 120 m^3/s.

3.2. Impact of FFFS on Tunnel Structure, Ventilation, and Life Safety

Table 3.5 summarizes the impact of various FFFS on structural protection, ventilation systems, tunnel occupants, and firefighters.

The FFFS reduced the ventilation system's load. The ventilation system of 30MW can control the fire of potential 150MW HRR with activation of FFFS (both water mist and deluge water spray systems). This reduction of the load wa due to the reduction of a peak HRR to approximately 30MW. This resulted in back-layering being destroyed after the FFFS activation.

The research showed that the fireproofing and tunnel lining efficiency increased with the reduced temperature of gasses, ceiling, and HRR. Furthermore, the FFFS assisted fireproofing in preventing spalling of the concrete.

Table 3.5 Impact of FFFS on structure, ventilation, occupants and firefighters

Impacts	**Water mist**	**Deluge water spray**	**Automatic sprinkler system**	**Foam**
Structural protection	Temperatures and HRR lowered to safe levels (SOLIT, 2012)	Temperatures and HRR lowered to safe levels (Ingason et al. 2016)	Temperatures and HRR lowered but not to safe level (Ingason et al. 2009)	Fire extinguished (Maevski et al., 2015)
Ventilation system	Back layering prevented, load reduced (SOLIT, 2012)	Back layering prevented, load reduced (Ingason et al. 2016)	Back layering seen, load not effectively reduced (Ingason et al. 2009)	Fire extinguished (Maevski et al., 2015)
Tunnel occupant	CO and O_2 levels increased, Temperatures decreased. Overall better tenability (SOLIT, 2012)	CO and O_2 levels increased, temperatures decrease. Overall better tenability (Ingason et al. 2016)	CO and O_2 levels increased, temperatures decreased. (Ingason et al. 2009)	Can cause suffocation. Breathing apparatus needed. Slippery hazard (SOLIT, 2012)
Firefighters	Temperatures reduced, firefighters reached to fire (vs. difficult without FFFS activation). Firefighters safer due to preventing of spalling. (SOLIT, 2012)	Temperatures reduced, firefighters reached to fire (vs. difficult without FFFS activation). Firefighters safer due to preventing of spalling. (Ingason et al. 2016)	Not enough reduction in temperatures. (Ingason et al. 2009)	Fire extinguished. (Maevski et al., 2015)

3.3. Benefits of Using FFFS in Road Tunnels

Limited cost benefit analysis studies showed the benefits of having FFFS. Table 3.6 shows the categories of fires in a tunnel, the expected asset damage, and the operational interruption estimated without a deluge water spray system installed (Jönsson and Johnson, 2010). Table 3.7 shows the estimated asset damage and operational interruption with a deluge water spray system installed (Jönsson and Johnson, 2010).

Table 3.6 Estimated asset damage and operational interruption without FFFS

Fire type	Fire size (MW)	Damage (AUD million)	Interruption (days)	Interruption (AUD million)	Total cost (AUD million)
Car	5	0.5	1	1.14	1.64
HGV	10	2	5	5.7	7.7
HGV small damage	30	10	10	11.4	21.4
HGV severe damage	100-200	200	250	285	485

Table 3.7 Estimated asset damage and operational interruption with FFFS

Fire type	Fire size (MW)	Damage (AUD million)	Interruption (days)	Interruption (AUD million)	Total cost (AUD million)
Car	2	0.1	0.25	0.285	0.385
HGV	5	1	1	1.14	2.14
HGV small damage	15	2.5	2.5	2.85	5.35
HGV severe damage	25	5	5	5.7	10.7

Table 3.8 presents data based on the predicted tunnel and frequencies in fire loss and loss analysis performed (with deluge spray system) (Jönsson and Johnson, 2010). In comparison, Table-3.9 shows the loss without a deluge system installed (Jönsson and Johnson, 2010).

The frequency of vehicle fires in tunnels can be estimated in the following:

(1.5/100,000,000)* 407,340,000 cars= 6.11 car fires approximately per year

HGV fires-

(8/100,000,000)* 30,660,000 trucks= 2.45 HGV fires approximately per year

HGV fires with small damage to tunnel-

(1/ 100,000,000)* 30,660,000 = 0.31 approximately per year

HGV fires with serious damage to tunnel-

(0.2/ 100,000,000)* 30,660,000= 0.06 approximately per year

Table 3.8 Estimated fire loss with FFFS

Fire type	Frequency of fire per year	Total loss per event (AUD million)	Total loss per year (AUD million)
Car	6.11	0.385	2.4
HGV	2.45	2.14	1.7
HGV small damage	0.31	5.35	5.2
HGV severe damage	0.06	10.7	0.7
Total			10

Table 3.9 Estimated fire loss without FFFS

Fire type	Frequency of fire per year	Total loss per event (AUD million)	Total loss per year (AUD million)
car	6.11	1.64	10
HGV	2.45	7.7	18.9
HGV small damage	0.31	21.4	6.6
HGV severe damage	0.06	485	29.6
Total			65

The study showed that the potential tunnel fire loss with the installation of FFFS had a total loss of 10 million AUD per year. While the potential tunnel loss without the installation of FFFS had a total loss of 65 million AUD per year. The difference is 55 million AUD (or 55*0.89 USD = 48.95 million USD (in 2016)) saved in economic damage per year. Annual maintenance cost and capital installation cost added up to 28 million AUD (24.92 million USD (2016)).

Thus, in a case of the expected number of accidents in the presence of FFFS and cost of installation and maintenance of FFFS together costs, 10 million + 28 million AUD = 38.00 million AUD (38*0.89 USD in 2016)

= 33.82 million USD

The 33.82 million USD is compared with annual loss due to estimated number of accidents without FFFS in tunnel,

65*0.89 million USD = 57.85 million USD (without FFFS)

Installation of FFFS can thus save approximately 24.03 million USD per year in a tunnel.

This cost benefit analysis concluded that a deluge water spray system installation is cost effective. Figure 3.1 shows a comparison of capital loss with and without FFFS in a tunnel fire. The red bar shows the loss in a tunnel fire without FFFS installed, and the blue bar shows the loss in a tunnel fire with FFFS installed.

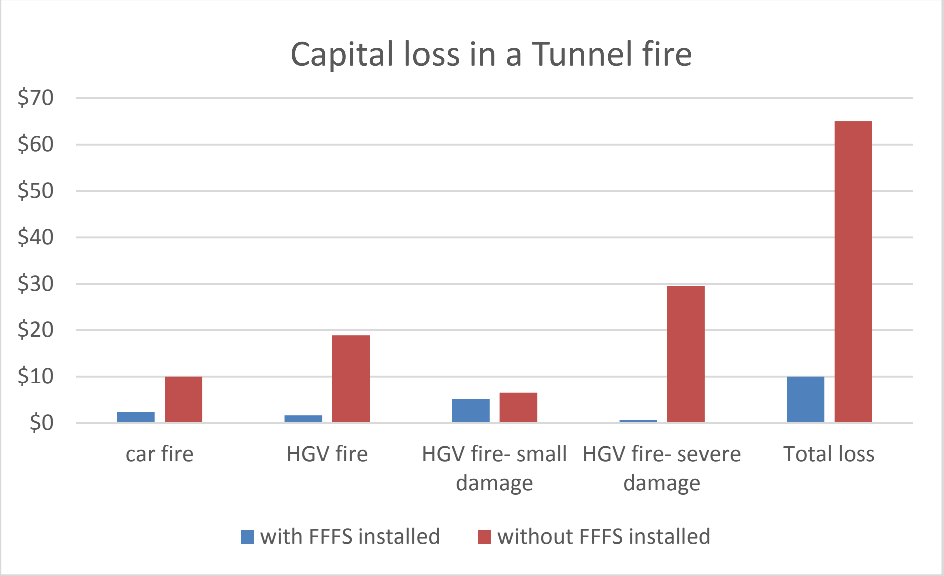

FIGURE 3.1: Comparison of capital loss (in AUD) in a tunnel fire with and without FFFS

3.4. Knowledge Gaps

Available experimental and modeling data showed that FFFS is effective in reducing the severity of fires in road tunnels, especially for Class A fires. Properly installed FFFS can also reduce the tunnel's ventilation load and mitigate structural damage in case of a fire. Previous studies showed that FFFS could increase CO concentration. More data are needed to investigate CO generation after FFFS activations in a tunnel. There is a gap in the impact of FFFS on evacuees due to a CO concentration increase and a time limit to evacuate during exposure to CO in the tunnel. CO concentration increases from incomplete combustion of fire due to activation of a specific type of FFFS, which is an important life safety issue. More knowledge about this issue will help us to detect and prevent any harmful effects of CO generation with incomplete burning. There is also a need for more data on the impact of FFFS on the visibility of exit signs and egress routes. The benefits of installing a certain FFFS and the disadvantage of visibility reduction due to the FFFS needs to be evaluated. The impact of FFFS on drainage requirements needs to be examined to check whether there is a need to upgrade the drainage system in a tunnel before installing FFFS.

More data and knowledge is needed regarding the reliability, maintenance, testing, and inspection of each FFFS, such as malfunctioning, false activation, partial activation, water present in the pipe between the valve and head, water not present in pipe required, and sudden discharge. A survey of existing operators of tunnels with FFFS may be used to collect additional data on this issue.

The impact of weather, location, and temperature on the expected life of an FFFS in US tunnels has not been sufficiently researched. Water or other foam additives can reduce friction in the tunnel and cause a hazard. The extent of a reduction in friction, the critical coefficient of friction, and areas mostly affected needs more research analysis. Other issues include the impact of the type of water source on clogging of sprinkler heads, water droplets traveling horizontally inside the shield, impact of the type of construction on the requirement for FFFS, impact on fire proofing material using different FFFS, and research on human behavior and evacuation efficiency on different lighting devices (such as LED lights) during activated FFFS in a tunnel.

Limited cost benefit analysis studies showed the advantages of using FFFS (deluge system). The actual cost of installing and maintaining FFFS is different from country to country. Knowledge in this area will help various stakeholders make an informed decision about the use of FFFS. Cost analysis can further be precise and reliable if performed in different tunnels in different countries. A short survey can give a rough estimate of economic loss and installation cost followed by any malfunctioning or manufacturing defects experienced by tunnel owners.

CHAPTER 4: CONCLUSION

Experiences with FFFS in road tunnels in some countries have demonstrated that this technology provides enormous safety benefits and helps to protect the structure. A deluge sprinkler system is preferred on an automatic sprinkler system. Deluge water spray and water mist systems work similarly with expected peak HRR reduced below 30MW in the case of a Class-A fire of HGV. Water mist and deluge water spray systems both can aid ventilation and reduce peak temperatures, prevent the spread of fire, prevent structural damage, and support fire proofing and tunnel lining, and prevent spalling of concrete. The cost of damage from a fire is much higher than the installation and maintenance of a deluge system in a tunnel.

This thesis provides a comprehensive synthesis of currently available information and published reports that have resulted from a significant amount of international research conducted in recent years regarding the effectiveness, performance, and benefit of FFFS in road tunnel applications. After reviewing and analyzing available data in the literature on the use of FFFS in road tunnels, some major concerns are CO generation from incomplete combustion due to activation of FFFS, visibility reduction, and reliability of FFFS (such as the possibility of malfunctioning or manufacturing defects, which so far seem low for both). The knowledge gap analysis presented in the report may assist various stakeholders to assess future research activities concerning the use of FFFS in road tunnels.

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