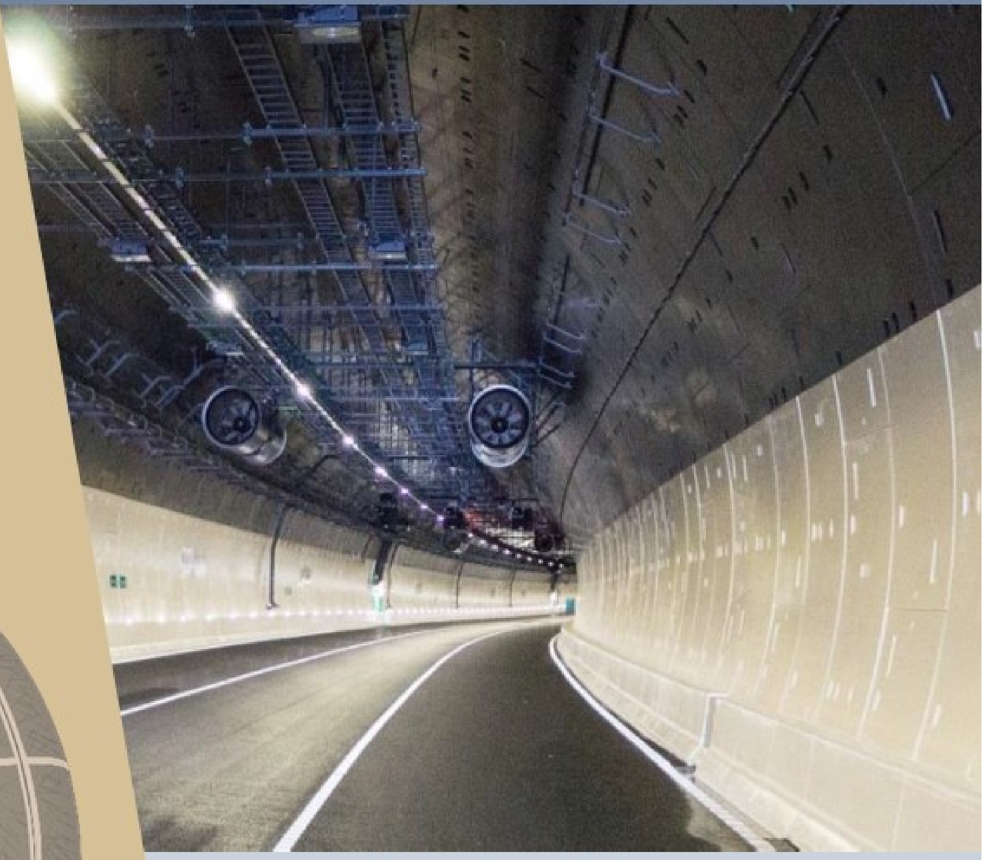
U.S. Department
of Transportation
**Federal Highway
Administration**

TUNNEL FIRE PROTECTION USING FIXED FIREFIGHTING SYSTEMS:

Advanced Practices in Australia and New Zealand



FHWA Global Benchmarking Program

Technical Report Documentation Page

1. Report No. FHWA-PL-18-030	2. Government Accession No.		3. Recipient's Catalog No.
4. Title and Subtitle Tunnel Fire Protection Using Fixed Firefighting Systems: Advanced Practices from Australia and New Zealand			5. Report Date September 2018 6. Performing Organization Code
7. Principal Investigator(s): Steve Ernst (FHWA), Bill Bergeson (FHWA), Steve Harelson (Colorado Department of Transportation), Dan Williams (Maryland Transportation Authority), Matt Bilson (WSP)			8. Performing Organization Report
9. Performing Organization Name and Address WSP USA, Inc. One East Pratt Street Suite 300 Baltimore, MD 21202			10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH6114D00048
12. Sponsoring Agency Name and Address Federal Highway Administration U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590			13. Type of Report and Period Covered 14. Sponsoring Agency Code FHWA-HPIP
15. Supplementary Notes			
16. Abstract Recognizing tunnels as an increasingly popular solution for significant highway system improvements, this report examines the use of fixed firefighting systems (FFFSs) in tunnels to produce safety improvements, increase long-term resilience, and add functional benefits for tunnels and highway systems. It provides detailed information from site visits and interviews with international experts and includes details about FFFS design, construction, operation, and maintenance. In addition to confirming the effectiveness of FFFSs in tunnels, investigations revealed that New Zealand and Australia are established world leaders in the use of FFFSs in road tunnels. In both countries, FFFSs assure transportation systems provide reliable long-term functionality. Tunnels can be a cornerstone for effective community engagement and prosperity, and their safe operation is an obligation for owners as well as an opportunity to gain support from the public for these expensive infrastructure projects.			
17. Key Works			18. Distribution Statement No restrictions.
19. Security Classif. (of this report) UNCLASSIFIED	20. Security Classif. (of this page) UNCLASSIFIED	21. No. of Pages 111	22. Price

Form DOT F 1700.7(8-72) Reproduction of completed page authorized

FOREWORD

New highway tunnels in the United States produce positive impacts on the communities they serve. In Miami, port traffic has been removed from the downtown area thanks to a modern and safe tunnel facility. A new tunnel to replace a viaduct in Seattle will connect the waterfront, facilitate creation of a new public space, and allow drivers to more easily reach or bypass the downtown area. Tunnels built in Boston have replaced a congested highway and created open spaces, gardens, and walkways. In the future, it is likely that urban areas and mountainous regions in the United States (U.S.) will include more tunnels.

Recognizing tunnels as an increasingly popular solution for significant highway system improvements, the Federal Highway Administration (FHWA) has undertaken several studies to examine state-of-the-art best practices. One study, completed in 2006, looks at safety and operations of underground transportation systems in Europe. One of the technologies from this study that captured FHWA's attention was the use of fixed firefighting systems (FFFSs) to produce safety improvements, increase long-term resilience, and add functional benefits for tunnels and highway systems. At the time of the 2006 study, research on FFFSs was not extensive and reviews of effectiveness were mixed. Through an implementation workshop, it became clear that Australia had effectively used FFFSs for several years and Japan also had good experiences. To follow-up, FHWA conducted a desk review in 2017 to investigate worldwide experience with design and operation of FFFSs. Findings from these efforts led to a Global Benchmarking study. As part of the Global Benchmarking study, technical site visits were made to New Zealand and Australia to better understand how FFFSs are used to safely and efficiently operate tunnels.

This report, which is part of the Global Benchmarking study, includes details about FFFS design, construction, operation, and maintenance based on site visits and interviews with international experts. Investigations revealed that New Zealand and Australia are established world leaders in the use of FFFSs in road tunnels. In both countries, FFFSs assure transportation systems provide reliable long-term functionality. Tunnels can be a cornerstone for effective community engagement and prosperity, and their safe operation is an obligation for owners as well as an opportunity to gain public support for these expensive infrastructure projects. What the team learned from visiting several tunnels and tunnel operation facilities, and through discussions with owners and operators, was eye-opening. The team hopes that the information shared in this report will inform and improve tunnel safety and operation approaches.

ACKNOWLEDGMENTS

The success of this Global Benchmarking study was the result of the knowledge and experience shared by representatives of the host agencies, tunnel facilities, and private firms during the meetings and field visits. The team members thank their hosts for their hospitality and for taking time from their busy schedules to meet and discuss the latest developments in their respective countries. Each facility provided valuable information and the study team members look forward to continued interaction and partnership with the hosts to advance safety, operations, and emergency response in underground transportation systems. The study team would like to acknowledge the following individuals and organizations:

- Auckland Traffic Operations Center (ATOC) and Victoria Park Tunnel: Claire Howard, David Barron, Paul Musson, Andrew Musgrave
- Waterview Tunnel: Craig Hiscock, Sonia Fernandez-Martin, Joel Maturan
- Wellington Tunnels: Terry McGavin, Nigel Lloyd, Conrad Stacey, Nick Agnew, Jonathan Sadler
- Austroads: Nick Koukoulas
- M2 Tunnel: Greg Pipikios
- Sydney Harbor Tunnel: Bob Allen, Nigel Casey, Garry Briggs, Jacques Calluaud
- M5 East Tunnel: Hasan Reslan, Bernie Chaplin, Nadir Hashmi, Garry Hamilton Fire and Rescue NSW
- New Zealand Transport Agency
- Roads and Maritime Services NSW
- The Sydney Harbor Tunnel Company
- Transurban
- Ventia
- Austroads
- Well-Connected Alliance

The study team also thanks the American Association of State Highway and Transportation Officials (AASHTO), and National Cooperative Highway Research Program (NCHRP) Project Panel 20-36 for their leadership and support.

ACRONYMS

AASHTO	American Association of State Highway Transportation Officials
AHJ	Authority Having Jurisdiction
ASHRAE	American Society of Heating Refrigeration and Air-conditioning Engineers
ATOC	Auckland Traffic Operations Center
ATOG	Australasian Tunnel Operators Group
AVID	Automatic Video Incident Detection
CCTV	Closed-Circuit Television
CFD	Computational Fluid Dynamics
FEMA	Federal Emergency Management Agency
FFFS	Fixed Fire Fighting System
FHRR	Fire Heat Release Rate
FHWA	Federal Highway Administration
GBP	Global Benchmarking Program
LHD	Linear Heat Detector
LUS	Lane Use Sign
NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
NCHRP	National Cooperative Highway Research Program
NEC	National Electric Code
NSW	New South Wales
NZBC	New Zealand Building Code
NZD	New Zealand Dollars
NZFS	New Zealand Fire Service
NZTA	New Zealand Transport Agency
PA	Public Address
PIARC	World Road Association, Permanent International Association of Road Congresses
PLC	Programmable Logic Controller
PTZ	Pan-Tilt-Zoom
RAMS	Reliability, Availability, Maintainability and Safety
RMS	Roads and Maritime Services
RONS	Roads of National Significance
SCADA	Supervisory Control and Data Acquisition
U.S.	United States
VMS	Variable Message Sign

UNIT CONVERSIONS

SI	US
1 mm/min = 1 L/min/m^2	0.02455 gpm/ft^2
40.7 mm/min = 40.7 L/min/m^2	1 gpm/ft^2
1 km	0.6 miles
1 km	3,280 ft
3 m/s	9.84 ft/s
3 m/s	591 fpm
100 m^3/s	212 kcfm
10 m^2	107.6 ft^2
1 MW	3.41 MBtu/hr

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1 INTRODUCTION

Today's tunnel owner is faced with protecting life and the facility against potentially catastrophic fire events caused by heavy goods freight vehicles. Hazards from these fires may not be effectively mitigated by emergency ventilation and egress alone, and more effective mitigation is needed. Installing fixed firefighting systems (FFFSs) in highway tunnels can save lives and protect the facility by limiting fire growth and enabling more effective evacuation. This fire suppression technology is widely accepted and required by building codes, but less commonly used in highway tunnels.

The National Fire Protection Association's (NFPA) Standard for Road Tunnels, Bridges, and Other Limited Access Highways (NFPA 502) defines an FFFS as a *system permanently attached to the tunnel that is able to spread a water-based extinguishing agent in all or part of the tunnel* [Ref 1]. FFFSs in highway tunnels limit fire growth and fire heat release rate (FHRR), improving the environment for evacuation, rescue, and firefighting. FFFSs also support the design performance of other tunnel systems such as emergency ventilation and passive structural fire protection materials by reducing the potential design FHRR.

The Federal Highway Administration (FHWA) and various U.S. associations and professional organizations, including the NFPA and American Society for Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), are interested in developing the tools necessary to reduce costs and improve safety by integrating FFFSs into highway tunnels. Based on this interest and the potential benefits, FHWA undertook an international study to understand effective practices and lessons learned from the long-term use of FFFSs in Australia and New Zealand. FFFSs have been successfully deployed in highway tunnels in New Zealand and Australia, and learning from their experiences will advance the state-of-the-practice within the U.S.

The study was conducted under the FHWA Global Benchmarking Program (GBP). GBP is a tool for accessing, evaluating, and implementing proven global innovations that can help FHWA respond to highway challenges in the U.S. Instead of recreating advances that other countries have developed, GBP focuses on acquiring and adopting available technologies and best practices already used abroad. This is accomplished by connecting FHWA's technical experts with global transportation advances and the people involved in applying them. GBP provides structured implementation support to facilitate the implementation or adaptation of promising findings in the U.S. context. Ultimately, GBP's goal is to avoid duplicative research, reduce overall costs, and accelerate improvements to the American transportation system.

A desk review identified, analyzed, and documented noteworthy and current information on activities, expertise, and experiences related to FFFSs in Japan, Australia, Europe, and Canada. Based on findings from the desk review, technical site visits were conducted in New Zealand and Australia to observe FFFS facilities first-hand and engage in technical discussions with tunnel owners and operators on designing, constructing, operating, maintaining, and inspecting FFFSs in highway tunnels. Japan was considered for a technical site visit, but was ultimately not included.

The study team included four members: Steve Ernst (FHWA), Bill Bergeson (FHWA), Steve Harelson (Colorado Department of Transportation), and Dan Williams (Maryland Transportation Authority). Participating in the capacity of Report Facilitator, was Matt Bilson of WSP. The team members are pictured in Figure 1-1 with biographical information included in Appendix B.

Figure 1-1: Team members (left to right); Dan Williams, Bill Bergeson, Steve Ernst, Steve Harelson, and Matt Bilson.

Source: FHWA

The GBP team met with representatives in New Zealand and Australia and visited several tunnels. The study itinerary included the following cities and facilities:

- May 7, 2017 - Auckland, New Zealand:
    - Auckland Traffic Operations Center (ATOC) – Met with representatives from the New Zealand Transport Agency (NZTA)
    - Victoria Park Tunnel – Site visit with NZTA representatives
    - Waterview Tunnel – Site visit with Well-Connected Alliance representatives
- May 8-9, 2017 - Wellington, New Zealand:
    - Meetings with NZTA representatives
    - Terrace Tunnel – Site visit with NZTA representatives
    - Mount Victoria Tunnel – Site visit with NZTA representatives
- May 10, 2017 - Sydney, Australia:
    - Meeting with Austroads
    - M2 Tunnel – Meetings with Transurban representatives and site visit
- May 11, 2017 - Sydney, Australia:
    - Sydney Harbor Tunnel – Meetings with Roads and Maritime Services (RMS) and Sydney Harbor Tunnel representatives, site visit, car fire and FFFS activation demonstration
- May 12, 2017 - Sydney, Australia:
    - M5 East Tunnel – Meetings with RMS and Ventia representatives

2 FINDINGS ON FIXED FIREFIGHTING SYSTEMS IN ROAD TUNNELS

The NFPA Standard for Road Tunnels, Bridges, and Other Limited Access Highways (NFPA 502) defines a road tunnel as *an enclosed roadway for motor vehicle traffic with vehicle access that is limited to the portals* [Ref 1]. NFPA 502 requires an engineering analysis for any length of roadway that falls within the standard's scope. The standard includes road tunnels, bridges, and underpasses. When a tunnel's length is less than 300 ft (91 m), the standard requires only traffic control and structural protection. If the tunnel is more than 800 ft (244 m) long, all standard provisions must be applied. The provisions set out in NFPA 502 are the minimum requirements and engineering analysis is necessary to determine any additional provisions.

NFPA 502 defines an FFFS as a *system permanently attached to the tunnel that is able to spread a water-based extinguishing agent in all or part of the tunnel* [Ref 1]. An FFFS is not a mandatory requirement of the standard. Inclusion of an FFFS is subject to engineering analysis and agreement with the authority having jurisdiction (AHJ) (typically the local fire brigade) on the most appropriate fire safety strategy.

The use of FFFSs in tunnels within the U.S. varies. The city of Seattle requires installation of FFFSs in their transportation tunnels, and all tunnels in Seattle have FFFSs [Ref 2]. Seattle is an exception, and most tunnels in the U.S. are not fitted with an FFFS. This trend is changing, though. Many recently constructed tunnels have been fitted with an FFFS, including the Presidio Parkway Tunnel in San Francisco, Elizabeth River Midtown Tunnel in Norfolk, Virginia, East End Tunnel in Louisville, Kentucky, and Port of Miami Tunnel. One older U.S. tunnel, the Eisenhower-Johnson Memorial Tunnel in Dillon, Colorado, has recently been fitted with an FFFS.

The road tunnel industry in the U.S. and Europe has been moving toward inclusion of FFFSs in tunnels for the past decade [Ref 3]. The motivation for the shift has partly been due to several significant fire incidents. In 1999, a fire in the Mont Blanc Tunnel in France and Italy led to the deaths of 39 people [Ref 4]. In 2007, a tractor-trailer fire erupted in the Newhall Pass in California. The fire was due to a collision and caused major damage to the structure after the fire spread to and destroyed an additional 30 trucks trapped behind the collision [Ref 3]. Neither of these tunnels were equipped with an FFFS and both facilities were closed for an extended period (months to years) for repairs.

In contrast, the Burnley Tunnel fire in Australia involved a fire in a heavy goods vehicle and had the potential to be as serious as the Mont Blanc or Newhall Pass incidents [Ref 4]. Although there was loss of life, it was due to vehicle collisions and not the resulting fire. After the fire, the tunnel reopened to traffic in a matter of days as damage to the structure was minimal. Within the industry, the event was acknowledged as potentially having much more serious consequences were it not for the beneficial impact of the tunnel's FFFS [Ref 3].

Road tunnels of a certain minimum length in Australia, New Zealand, and Japan (in Japan vehicle flow rate also applies) require installation of an FFFS. Tunnels in Japan have required FFFSs for decades [Ref 6]. Australia's first major road tunnel, the Sydney Harbor Tunnel, opened in 1992 and installed an FFFS [Ref 7]; this set a precedent in Australia that has been followed ever since. New Zealand followed Australia's approach, and included FFFSs in their road tunnels. Because of these requirements, Japan, Australia, and New Zealand all have significant experience with FFFSs in road tunnels.

As part of this study, the team visited New Zealand and Australia to investigate tunnels with FFFSs and obtain firsthand knowledge from designers, owners, maintainers, and operators. Tunnels and facilities visited in New Zealand and Australia as part of the study include the following:

- ATOC, Smales Farm (Auckland, New Zealand)
- Victoria Park Tunnel (Auckland, New Zealand)
- Waterview Tunnel (Auckland, New Zealand)
- Terrace Tunnel (Wellington, New Zealand)
- Mount Victoria Tunnel (Wellington, New Zealand)
- Austroads (Sydney, Australia)
- M2 Tunnel (Sydney, Australia)
- Sydney Harbor Tunnel (Sydney, Australia)
- M5 East Tunnel (Sydney, Australia)

The M2 Tunnel, Terrace Tunnel, and Mount Victoria Tunnel were rehabilitations, while all the other tunnels were original systems or new builds. A more in-depth summary of each location visited is provided in Appendix C.

2.1 Design

2.1.1 System Components

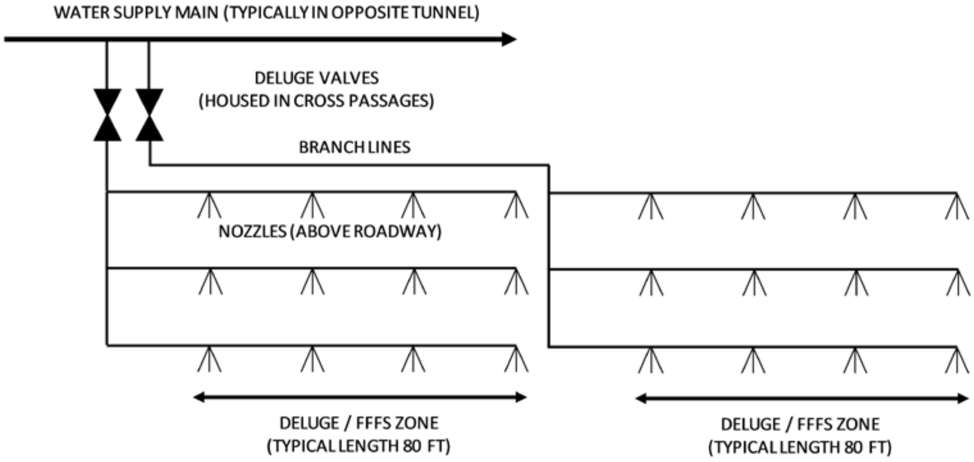

Figure 2-1: FFFS basic schematic. Source: FHWA

The term FFFS defines a system permanently attached to the tunnel that delivers a water-based suppression agent for firefighting [Ref 1]. The nozzles have open heads and a deluge zone valve is opened to provide water flow to the nozzles. The FFFS valves are typically located in tunnel cross passages. Figure 2-1 shows a simplified system schematic. Several key system components are needed to achieve the design objective, including the following:

- Water supply main (typically an 8 in/0.2 m diameter galvanized steel pipe)
- Water storage tank(s)

- Deluge valves (refer to Figure 2-2)
- Branch and distribution lines (refer to Figure 2-3)
- Freeze protection such as insulation, heat tracing or water circulation (note that none of the tunnels visited had issues with freezing and so none of these features were observed)
- Nozzles
- Drainage
- Sumps
- Hydrocarbon detection and fire suppression equipment for sumps
- Pumping equipment
- Controls
- Power supply and backup generators (for pumps)
- Ancillary area suppression (not a part of the tunnel roadway FFFS), including electrical rooms

Figure 2-2: M2 Tunnel, FFFS zone (deluge) valves.

Source: FHWA

Figure 2-3: M2 Tunnel, cross passage with FFFS branch pipework above door.

Source: FHWA

System component design guidelines refer to standards and other design guidelines [Ref 8, Ref 9, and Ref 10; Ref 3 and Ref 11]. In many cases, detailed requirements are included and defined on a project-specific basis in Australia and New Zealand.

All FFFSs observed during the study were deluge systems, as opposed to water mist systems. The two systems are fundamentally similar in that a series of pipes, valves, pumps, and nozzles are used to provide zoned application of water to target a fire. The primary difference between the two systems is the size of water droplets. Water mist systems use a smaller droplet size than deluge systems and use less water. Deluge and water mist systems have certain performance features, as well as advantages and disadvantages. A detailed account of these systems, adapted from PIARC documentation, is provided in Appendix D.3.4. Note that none of the systems observed use a foam additive.

2.1.2 Water Application Rate and Supply

Water application rate is a key parameter in FFFS design, whether the system is a deluge or water mist system. Water application rate to the roadway surface is defined in units of gpm/ft^2

Figure 2-4: FFFS activation in the Terrace Tunnel at water application rate of 0.16 gpm/ft ^{2} ***(6.5 mm/min).***

Source: FHWA

(L/min-m^2).[1] The required volumetric flow rate of water is based on the number of zones activated, the roadway width to be covered, and the zone length. The volume flow rate equals application rate times number of zones times zone length times covered width of road.

Water application rates govern the FFFS infrastructure, which includes water supply and storage, pipework for delivery, drainage, sump dimensions, and water treatment. FFFS performance during a fire is also influenced by water application rate. Tunnels around the world with FFFSs have a range of water application rates, and there is currently no accepted methodology or standard to achieve design objectives related to suppression, control, or cooling. Noting that many vehicle fires are interior to the vehicle and hence shielded, at all tunnels visited, the goal of the FFFS was to control the fire rather than fully extinguish. The fire brigade is ultimately relied on to extinguish the fire.

Figure 2-4 shows an FFFS discharge at a water flow rate of 0.16 gpm/ft^2 (6.5 mm/min). The amount of water is substantial, and there is an appreciable obstruction to visibility. Figure 2-5 provides a summary of water application rates that have been used.

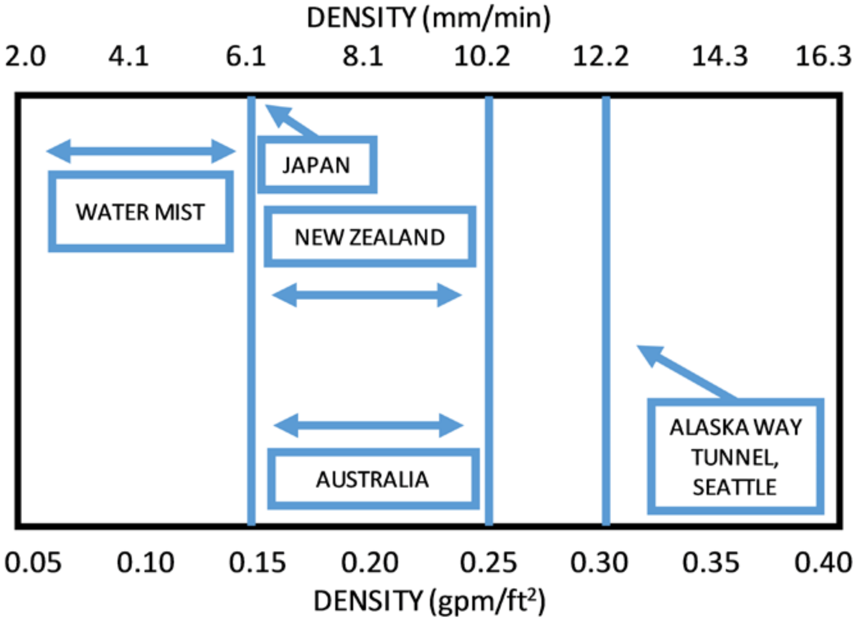

Figure 2-5: Water application rates in road tunnels [image adapted from Ref 8].

Source: FHWA

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[1] Note that a unit of mm/min is equivalent to L/(min · m^2).

To decide on the required water application rate for a tunnel, available water supply (whether the project is a new build or rehabilitation), reliability requirements, and the design objectives, including the design fire, must all be considered. Decision-making to define the water application rate, particularly on a rehabilitation project, uses these factors in a systematic risk-based approach.

The water application rate is typically 0.25 gpm/ft^2 (10 mm/min) in the new tunnels, and zone lengths are on the order of 80 to 100 ft (approximately 25 to 30 m). This application rate has been consistently applied to new tunnel projects in Australia and New Zealand. On rehabilitation tunnels, such as the Terrace Tunnel and Mount Victoria Tunnel, the water application rate is on the order of 0.16 gpm/ft^2 (6.5 mm/min) because this is the quantity of water locally available without supplementing the supply such as with the use of water tanks. The water application rate used at these two tunnels is comparable to the rate used by the Japanese in their tunnels for many years, which has generally demonstrated good performance [Ref 6].

The Sydney Harbor Tunnel was the first project in Australia to use an FFFS. The water application rate was selected based on tests of a plastic commodity using sprinklers [Ref 7]. In the tests, the fire was controlled but not extinguished [Ref 7]. The water application rate selected was 0.25 gpm/ft^2 (10 mm/min). At the design phase, a water application rate twice this amount was considered as a requirement fire extinguishment [Ref 7].

The water application rates necessary to achieve for each tunnel visited are summarized in Table 2-1, along with data on water supply measures, such as the use of a water tank or town mains. An example of a storage tank from the Clem7 Tunnel in Brisbane, Australia is provided in Figure 2-6.

Figure 2-6: Clem7 (Brisbane, Australia) Tunnel water storage tank.

Source: FHWA

Table 2-1: Tunnels visited and water application rate and supply information.

Source: FHWA

Tunnel	Type of FFFS	Water application rate gpm/ft^2 (mm/min)	Tank or town mains, tank volume, duration of supply	Zones and water flow rate	Pumps	New tunnel or rehab
Victoria Park, New Zealand	Deluge	0.25 (10)	Tank at 153,220 gal (580,000 L), 60-minute supply	Two zones active, 82 ft (25 m) long, flow rate 2,774 gpm (175 L/s)	Electric and diesel	New
Waterview, New Zealand	Deluge, hydrants on same water supply system	0.25 (10)	Five tanks at 66,050 gal (250,000 L) each, 60 minute FFFS supply + 240-minute hydrant supply	3 zones active, 98 ft (30 m) long, flow rate, 3,044 gpm (192 L/s) plus 317 gpm (20 L/s) from hydrants	Diesel, two duty, one standby	New
Terrace Tunnel, New Zealand	Deluge	0.16 (6.5)	Town, pumped to a tank and gravity fed	Two zones active, 82 ft (25 m) long each	Pump to supply tank	Rehab
Mount Victoria Tunnel, New Zealand	Deluge	0.16 (6.5)	Town, gravity supply from a tank	Two zones active, 98 ft (30 m) long zone, end zone 82 ft (25 m) long	Pump to supply tank	Rehab
M2, Australia	Deluge	0.25 (10)	Two tanks, 92,460 gallons (356,813 L)	98 ft (30 m) long zones	Diesel	Rehab
Sydney Harbor, Australia	Deluge	0.25 (10)	Town	Two zones active, 98 ft (30 m) long zone, flow rate 1,141 gpm (72 L/s)	Fire brigade boosting points provided	New
M5, Australia	Deluge	0.25 (10)	Town with two tanks, tank capacity is equal to 75,289 gal (285,000 L) (Arncliffe town mains) and 184,920 gal (700,000 L) (Bexley town mains), 90-minute supply	Three zones active, maximum area of a single zone 2,797 ft^2 (260 m^2), total flow rate 2,061 gpm (130 L/s) + 476 gpm (30 L/s) from hydrants	Electric pumps	New

NFPA 502 defines FFFS performance objectives, which can be used to develop design objectives, and hence a basis for a water application rate. The objectives are defined as follows [Ref 1]:

- **Fire suppression.** A system to sharply reduce the FHRR
- **Fire control.** Limit the size of the fire, essentially preventing fire spreading
- **Volume cooling.** Provide substantial cooling of products of combustion that does not affect FHRR directly
- **Surface cooling.** Provide cooling of critical infrastructure without directly affecting the FHRR

Methods to demonstrate that a given water application rate is sufficient include testing or analysis such as Computational Fluid Dynamics (CFD). CFD can model some aspects of fire suppression [Ref 3] and investigations have been conducted into water application rate effects [Ref 12]. The field of CFD is not advanced enough to make deterministic predictions of water application rate, but some studies have revealed useful insights that can be improved upon as tests and models evolve. Several full-scale tests have been conducted, and a detailed summary can be found in the PIARC documents and textbooks [Ref 3, Ref 4].

Rational analysis of standard water application rates is further complicated by the lack of definitive information on the relative effectiveness and cost of various water application rates. Japan uses an application rate of 0.16 gpm/ft^2 (6.5 mm/min) and this has been very effective. The Burnley Tunnel in Melbourne, Australia uses a rate of 0.18 gpm/ft^2 (7.5 mm/min), which was effective during the major incident in that tunnel [Ref 13]. In the U.S., the Alaska Way Viaduct Tunnel is currently under construction and will employ a rate of 0.3 gpm/ft^2 (12 mm/min).

It is possible that water application rates lower than those used in Japan may be effective. For instance, in road tunnel incidents in New South Wales, Australia, where the water application rate is typically 0.25 gpm/ft^2 or 10 mm/min, only 20 percent of fires required fire brigade intervention while 80 percent of fires were managed by other means, including FFFSs and hand-held extinguishers.

Because of the subjectivity and variability in water application rates, it is helpful to note the decision process used for the water application rate at the Mount Victoria Tunnel and Terrace Tunnel. Factors considered in determining the water application rate there included:

- Available water supply
- Tunnel geometry
- Prevailing wind and varying conditions
- Operational goals for the system and the design fire
- Drainage
- Inspection and maintenance costs
- Weather conditions and freeze protection

None of the tunnels visited experience freezing weather, and freeze protection and dry mains were not generally considered as part of the design. These factors are important for some U.S. tunnels, such as the Eisenhower-Johnson Memorial Tunnel in Colorado.

2.1.3 Ventilation and Nozzle Selection

Interaction with ventilation should be considered in design of an FFFS. PIARC notes that the ventilation system can displace water droplets [Ref 3]. When considering FFFS operation, both systems should operate in a complementary manner. Whether the ventilation system can be reduced due to the inclusion of the FFFS should also be considered. Each of these topics is addressed below.

Figure 2-7: Water droplet drift due to wind in the Mount Victoria Tunnel (upstream boundary of FFFS zone at traffic cones).

Source: FHWA

FHRR. Projects in Australia and New Zealand have not taken any direct reduction of the FHRR into account based on inclusion of an FFFS [Ref 14, Ref 7]. For example, in the Clem7 tunnel in Brisbane, the design FHRR was set to 170.6 MBtu/hr (50 MW) with no reduction permitted based on the inclusion of the FFFS [Ref 14]. Based on recent U.S. practice, an FHRR of 170.6 MBtu/hr (50 MW) in a tunnel with an FFFS allowing heavy goods vehicle traffic would represent a reduced FHRR relative to a tunnel with no FFFS.

Smoke stratification. The FFFS destabilizes the smoke layer in the region of the active FFFS zone, which is well documented in literature [Ref 15]; however, it should be noted that during a previous demonstration at the Sydney Harbor Tunnel, the smoke layer re-stratified outside the active FFFS zone [Ref 15].

Water droplet displacement. Longitudinal ventilation causes the water droplets of the FFFS to drift downstream of the active zone. This outcome has also been demonstrated through extensive computer modeling [Ref 16]. All tunnels visited had the ability to activate at least two zones simultaneously, with an upstream zone typically activated to provide assurance that any water drift is mitigated and to mitigate further upstream fire spread. This practice was observed in the closed-circuit television (CCTV) footage from a truck fire response in the M5 East Tunnel (refer to Section 2.5.1).

During the site visit to the Mount Victoria Tunnel, the FFFS was activated in a situation where there was a strong prevailing natural airflow of comparable magnitude equivalent to an emergency ventilation system. This situation allowed the team to observe the water droplets impacting the roadway within the zone boundaries with some smaller droplets drifting downstream. Figure 2-7 shows an example of the droplet drift observed.

Nozzle selection: Nozzle selection and water drift also need to be considered. It was noted during the site visits that the supplier for the Terrace Tunnel and Mount Victoria Tunnel nozzles could have provided the design team with modeling data for an offset spray pattern prediction for a given tunnel velocity or wind impact. An example of a nozzle from the Mount Victoria Tunnel is shown in Figure 2-8. The nozzle is an open head configuration, and, unlike a building sprinkler nozzle, there is no glass bulb.

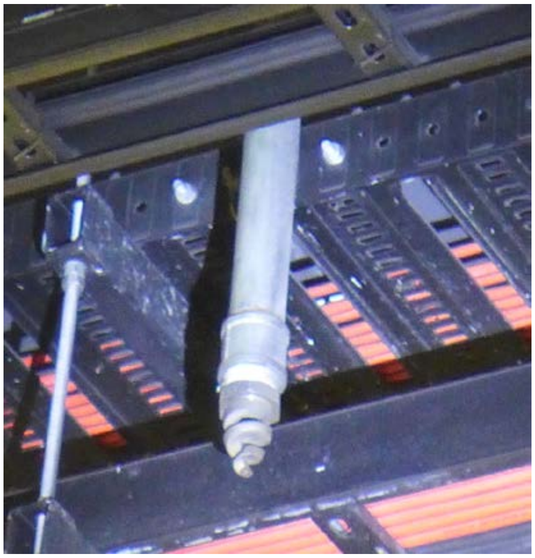

Figure 2-8: FFFS nozzle in the Mount Victoria Tunnel.

Source: FHWA

Typical provisions for FFFS water drainage include catch pits, flame traps at drainage catch pits, noncombustible components, sumps, hydrocarbon sensors in the sumps, foam suppression systems for the sumps, pumping equipment, and water treatment or containment infrastructure.

The volume of water in an FFFS discharge is typically thousands of gallons per minute. Tunnel drainage systems are usually designed to capture the water by the second catch pit downstream of the active FFFS zone. There is also a flame trap inside of the catch pit to be used in case of a hydrocarbon spill and subsequent fire. While the large volume of water makes it difficult to catch all volume flow at the nearest catch pit, the design of the catch pit can be augmented to assist. Figure 2-9 shows an example where slot drains were used in the Waterview Tunnel. At one of the tunnels visited, caution had to be taken when designing catch pits. If the catch pit was too large and the shoulder too narrow, the catch pit would protrude into the roadway space, creating challenges to drainage and pavement maintenance.

Figure 2-9: Example of a slot drain in the Waterview Tunnel.

Source: FHWA

For a tunnel rehabilitation project, the space might not be readily available to fit all the necessary drainage infrastructure. Figure 2-10 shows an example of water overflow at the Terrace Tunnel where the width of the water stream is approximately 5 ft (1.5 m). In this situation, fitting all necessary drainage infrastructure was a tradeoff between the desired design feature, capturing all the water, and solutions that were cost-effective. When weighing the decision for that rehabilitation project, it was considered safer to risk overflow of water and fuel spills from the drainage catch points, than to have no FFFS coverage in the tunnel.

One feature repeatedly observed in several tunnels visited was the provision of a hydrocarbon sensor in the drainage sump and a deluge type foam suppression system. The sensor detects a flammable liquid fuel spill and initiates the foam suppression system. Figure 2-11 shows a hydrocarbon sensor and Figure 2-12 shows a foam suppression system in the Victoria Park Tunnel. This tunnel allows for the passage of dangerous goods vehicles, and the foam system is a key part of the safety provisions. Additionally, the sump in the Victoria Park Tunnel is ventilated and keeps gas concentrations from reaching an explosive level. Figure 2-13 shows a photo of the ventilation system.

In addition to hydrocarbon detection, the Victoria Park Tunnel has a 376,445-gallon (1.4 ML) tunnel water detention tank. Any water from the tunnel is pumped to this location. The tunnel also has a groundwater detention tank, and the operator needs to receive approval to discharge this water to the sewer.

Figure 2-10: Water overflowing a drain in the Terrace Tunnel during an FFFS test.

Source: FHWA

Figure 2-11: Hydrocarbon sensor in the Victoria Park Tunnel.

Source: FHWA

Figure 2-12: Foam suppression system for a tunnel sump in the Victoria Park Tunnel

Source: FHWA

Figure 2-13: Tunnel sump ventilation system in the Victoria Park Tunnel.

Source: FHWA

Water treatment was also discussed. In some instances, water from an FFFS discharge is collected and tested before being released into the local river and stream system. For water that is not sufficiently clean, filtration or treatment was noted as a possible mitigation.

The Terrace Tunnel has a storm water treatment system, while the Mount Victoria Tunnel has no storm water treatment. For both tunnels, NZTA has a resource consent to discharge water into the storm water system. Both tunnels have diverters and water is diverted into the sewer system under a Trade Waste Discharge Permit during testing. This procedure can be applied during an emergency, although there would be a delay in implementation. At the M5 East Tunnel, water is always treated and tested before being discharged.

2.1.4 Incident Detection and Operational Integration

Detection of incidents in road tunnels typically relies on a closed-circuit television (CCTV) camera system with both trained operators and automatic video incident detection (AVID). A linear heat detector (LHD) is also employed for fire incidents. All tunnels visited used some heat detection system. Technologies included microchip-based detection at the Mount Victoria Tunnel, Terrace Tunnel, and Victoria Park Tunnel, spot type heat detection at the Sydney Harbor Tunnel, optic fiber based detection at the Waterview Tunnel, and cable-based detection at the M5 East Tunnel and M2 Tunnel.

All tunnels were equipped with CCTV cameras and full time 24/7 operators. In all the tunnels, the heat detection system was a backup measure for fire detection. The operational staff noted that that these systems were not typically the first indicator of a fire. Rather, AVID systems or the operator viewing cameras were first to detect a stopped vehicle and a fire.

Both the Terrace Tunnel and Mount Victoria Tunnel are remotely monitored and operated 24/7 from the Wellington Traffic Operation Centre (WTOC). The Auckland Traffic Operation Center (ATOC) can carry out this function if the WTOC is ever out of action. This is a historical development, as originally the WTOC operated during the day and the ATOC took over at night. The tunnel operator noted that the LHD offered a good backup to this historical remote operation scenario.

For all facilities, if the LHD is activated and provides no intervention within a set time, the FFFS activates. The period of inaction is typically between 60 to 90 seconds. No operators were aware of any spuriously false alarms with the LHD, although operators can stop the FFFS in case of a false alarm.

In the tunnels visited the experience is that, operators are made aware of a fire incident via the CCTV system well before a heat detection alarm activates. The camera is the operator’s most important tool for detecting and responding to a fire event. Every facility visited relied on the CCTV system to detect and manage incidents, including fires. Some features common to the facilities include:

- AVID analytics to alert the operator to a stopped vehicle
- Integration of the camera layout with FFFS zones
- Ability to record and play back the incident
- Combination of pan-tilt-zoom (PTZ) and fixed cameras

One useful feature of the CCTV system for fire brigade response is ability to record the incident and play it back to the responding crews. In the Waterview and Victoria Park Tunnels, video playback facilities at the tunnel's fire command location allow the responding crew to quickly see the incident. Figure 2-14 shows an example at the Waterview Tunnel. A phone is also provided at this location with a direct link to the tunnel operator.

Figure 2-14: Waterview Tunnel fire command post showing screens for incident playback to the response crew.

Source: FHWA

As noted at the Sydney Harbor Tunnel, there must be enough cameras in the tunnel to identify the location and nature of an incident. The Sydney Harbor Tunnel has 112 fixed cameras spaced every 197 ft (60 m) to identify the location and nature of an incident, which was found to be typical application for achieving continuous coverage in all tunnels visited. The fixed CCTVs in the Sydney Harbor Tunnel face toward the oncoming traffic. This camera positioning was developed by the tunnel operators after their experience with tunnel incidents. Operators found that having the cameras facing toward traffic enabled them to see the incident without having it potentially obscured if the cameras are oriented in the other direction.

Figure 2-15 shows a view of the Sydney Harbor Tunnel camera screen layout. On the camera screen, operators can see the superimposed camera ID, FFFS zone numbers, and cross passage ID for fire brigade access. Two FFFS zones are visible on each camera view. Using fixed cameras ensures that the view is always the same and there is certainty about what zones can be seen. Operational experience at Sydney Harbor Tunnel is that there can be some uncertainty about where the camera is pointing with PTZ cameras. It also was noted that cameras need to be kept clean. The M5 East Tunnel has bi-monthly cleaning of cameras and the Sydney Harbor Tunnel uses regular maintenance to keep the cameras clean.

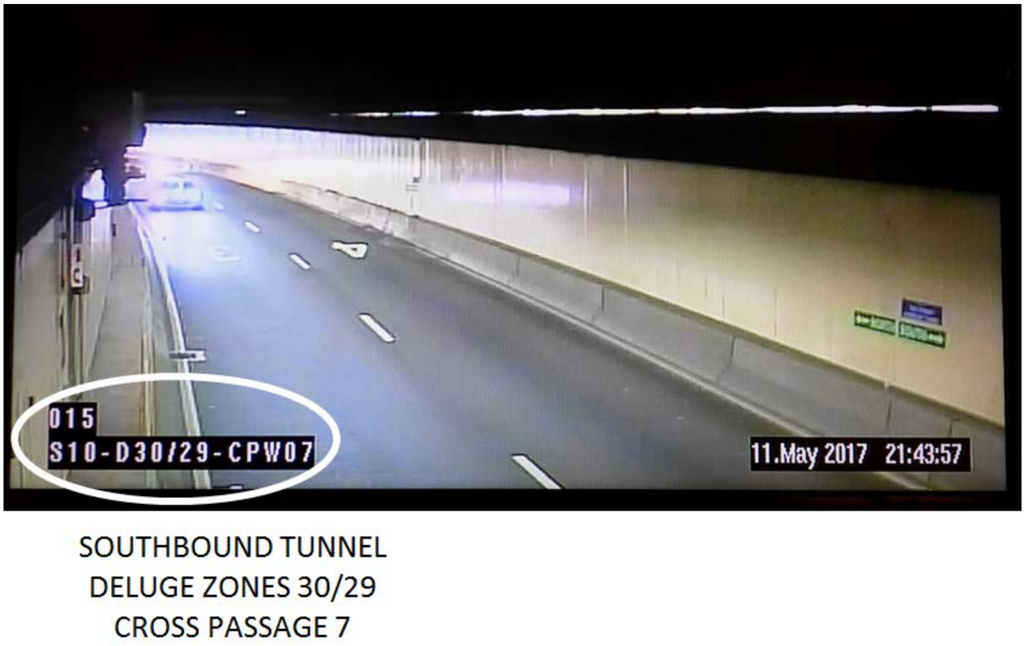

Figure 2-15: Sydney Harbor Tunnel camera view showing zone numbers and view into oncoming traffic.

Source: FHWA

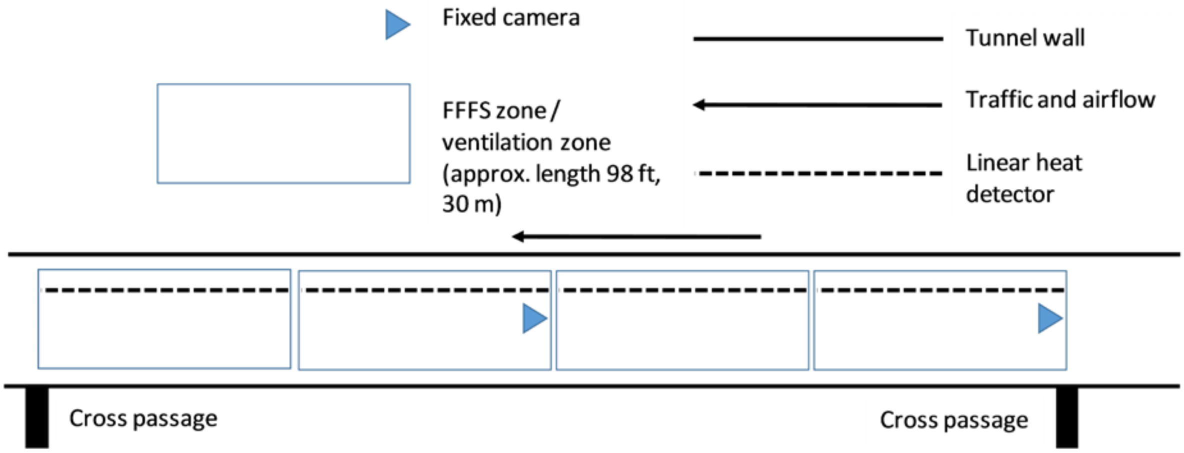

Figure 2-16: Example schematic of FFFS zone and camera integration.

Source: FHWA

Figure 2-16 shows an example of FFFS and camera location integration. Further integration efforts to locate an incident with CCTV cameras identify markings of FFFS zone boundaries. The tunnels in New Zealand all use markings on the walls that display the zone number. The M2 Tunnel uses small signs mounted on the walls, while the Sydney Harbor Tunnel provides zone markings on the roadways. A unique feature of the New Zealand tunnels is a perspective view of zone numbers that are designed to provide a clearer view of the numbers relative to the angle of the viewing camera. With this approach, the lettering is foreshortened with the camera angle in mind to appear as normal typeface in the camera image. Figure 2-17 and Figure 2-18 show some examples.

The Sydney Harbor Tunnel uses signs that identify the tunnel name ("You are in the Sydney Harbor Tunnel") above the north-south direction indicators; this is shown in Figure 2-19. This signage enables motorists having trouble, say with a flat tire, mechanical difficulty, or a fire, and who are calling for help on a cell phone, to clearly identify the tunnel. This is particularly important in Sydney where there are many tunnels and previous incidents have occurred where motorists incorrectly identified their location.

Figure 2-17: Road markings of FFFS zone boundaries in the Sydney Harbor Tunnel.

Source: FHWA

Figure 2-18: FFFS zone markings on the wall in the Mount Victoria Tunnel.

Source: FHWA

Figure 2-19: Sydney Harbor Tunnel location signage.

Source: FHWA

2.1.5 Regulations – Australia

The Australian standard for tunnel fire safety, AS 4825, was first published in 2011 [Ref 17]. The standard covers road, rail, and bus tunnels. AS 4825 was the first Australian standard on tunnel fire safety and requires an FFFS be considered if the tunnel is greater than 394 ft (120 m) long. Redundant water supply sources are also required.

In 2010, prior to the release of AS 4825, Austroads published a guide for road tunnel planning, design, and commissioning [Ref 18]. The guide noted that the release of AS 4825 would form the basis for fire-life safety (FLS) requirements.

Prior to the publication of AS 4825 and the Austroads guide, the Australian Fire Authorities Council published a road tunnel guideline [Ref 19]. This guideline was published in 2001 and strongly recommended including FFFSs in road tunnels on the basis that the suppression system, if properly designed, would control a growing fire, promote safe evacuation, and aid the fire brigade in controlling the fire.

The first tunnel in Australia to include an FFFS was the Sydney Harbor Tunnel. Since the Sydney Harbor Tunnel opened in 1992, other tunnels have been required to install an FFFS. The requirements for an FFFS are becoming more formalized through documents such as AS 4825. However, AS 4825 does not make this a prescriptive requirement; it only notes that the FFFS would typically be required and leaves it up to the individual project to define prescriptive requirements. Australian road tunnels are not required to conform to a building code. Project specification is generally the relevant compliance document, which typically references standards for design of the tunnel FLS systems (AS 4825), FFFS design (AS 2118), and system maintenance (AS 1851).

From the perspective of an Australian contractor, tunnel safety designs should be kept simple. For example, during discussion it was stated that tunnels for the WestConnex project in Australia are being designed with a focus on simple operation for all systems because over-prescription can cause complications. It is considered better to have a performance-based design that encourages a well-performing system, is simple to operate, and economical to maintain.

One of the regulatory difficulties in Australia has been trying to fit building code requirements to the tunnel environment. The area-based FFFS zone for a building is unlikely to function well in a tunnel. In Australia, the common-sense understanding, verified by data, is that current tunnels are performing well in real incidents, and new tunnels should be built the same way. In this context, it was noted that tunnels should be designed to optimize reliability, availability, maintenance, and safety (RAMS). In some cases, however, not enough reliable data is available.

2.1.6 Regulations – New Zealand

In New Zealand, a tunnel is categorized as an ancillary building under the building code [Ref 20]. This type of building is exempt from some amenity provisions, but is still required to comply with the structural and safety aspects of the building code. The building code maps out a set of acceptable solutions and prescriptive criteria for regular buildings such as houses. There is no explicit solution for tunnels in the building code. Rather, the building code includes performance requirements be demonstrated by the proposed design. Areas of the building code applicable to tunnels include:

- Outbreak of a fire
- Means of escape
- Spread of fire
- Structural stability during a fire
- Access routes (to escapes)
- Emergency lighting
- Warning systems
- Signage
- Ventilation

Code compliance certification is administered by a local government authority, such as the Local Council (municipal government). However, for a facility such as a tunnel, the Local Council will rely on qualified personnel to demonstrate that the design satisfies the New Zealand Building Code (NZBC) requirements. Due to the complex nature of tunnels, the council will frequently rely on a similarly qualified independent reviewer to conduct technical design reviews. To open a new tunnel, building code consent documentation is needed. Consent documentation outlines the justification for how the tunnel conforms to the code.

For the construction and operation of an FFFS for road tunnels on the state highway network, namely those tunnels under the jurisdiction of the NZTA, there is a partnership between the federal government and the Local Council. The Local Council serves as the AHJ and issues permits and Certificates of Public Use. NZTA, which oversees facility design and construction, and makes sure permits and certificates meet the requirements of the Local Council.

The building code consent documentation also includes the compliance schedule, which provides a list of systems and standards to check as part of the annual inspection and testing regime. An annual Independent Qualified Person sign-off for the functionality of systems must be performed. The Independent Qualified Person is a person recognized by the Local Council and is typically a licensed professional. After a successful inspection is completed annually, a Building Warrant of Fitness Certificate is issued; this certificate provides the legal basis for the owner to keep the tunnel operating.

To conduct a refurbishment while the facility is in use, the tunnel owner must apply for building consent and obtain a Certificate of Public Usage. Minimum standards for inspection in New Zealand are regulated by the Local Council, which is guided by the NZBC [Ref 20].

While the NZBC defines a minimum level of performance, it is focused on buildings. The NZBC is not developed specifically for tunnels and there is no dedicated tunnel annex. A supplement to the Austroads guideline is provided specific to New Zealand and notes that a tunnel less than 263 ft (80 m) in length is not considered a tunnel for imposing system requirements [Ref 21]. If the tunnel is between 263 to 787 ft (80 m and 240 m) long, an engineering assessment is required. If the tunnel is more than 787 ft (240 m) long, all requirements apply [Ref 21]. In general, this document defers to the Australian Standard AS 4825 regarding fire safety features and requires a qualified person to carry out the design process.

The New Zealand perspective on design requirements is consistent with those in Australia. Both consider the absolute risk for major incidents very small. Because of the difficulty in assigning a quantitative value for life safety, the industry is left with the primary justification of asset protection and continuity of operations when selecting safety systems for a tunnel. Certain systems such as an FFFS, egress, and ventilation are common to all design options. One way to measure benefit is to develop quantitative assessments of the relative benefits amongst various options. The result of this approach is high-quality life safety measures for users.

2.1.7 Rehabilitation versus New Projects

Rehabilitation efforts in an aging road tunnel can range from repairing existing systems to a state of good repair to upgrading the design to meet modern FLS standards. Upgrading to meet modern FLS standards is desired, but can be impractical. However, simply repairing existing systems might not be satisfactory with respect to community expectations.

Rehabilitation efforts can be further complicated because existing standards do not provide explicit requirements. Often, it is typical for a standard to define a process. For example, NFPA 502 states the following with respect to existing tunnels [Ref 1]:

> *1.4 Retroactivity. The provisions of this standard reflect a consensus of what is necessary to provide an acceptable degree of protection from the hazards addressed in this standard at the time the standard was issued.*
>
> *1.4.1 Unless otherwise specified, the provisions of this standard shall not apply to facilities, equipment, structures, or installations that existed or were approved for construction or installation prior to the effective date of the standard. Where specified, the provisions of this standard shall be retroactive.*
>
> *1.4.2 In those cases where the authority having jurisdiction determines that the existing situation presents an unacceptable degree of risk, the authority having jurisdiction shall be permitted to apply retroactively any portions of this standard deemed appropriate.*

> *1.4.3 The retroactive requirements of this standard shall be permitted to be modified if their application clearly would be impractical in the judgment of the authority having jurisdiction and only where the determined level of life safety and fire protection provisions required is approved.*

The Australian standard AS 4825 does not state any requirements for existing tunnels except that the standard is not specifically intended for existing tunnels and the general principles may be applied to improve fire safety when upgrading existing tunnels [Ref 17]. Guidelines are currently in development to cover refurbishment of existing tunnels in Australia.

In New Zealand, the guideline document explicitly addresses existing tunnels [Ref 21]. The document notes the following:

- The Building Act only requires a tunnel to be brought up to current standards when an alteration occurs, such as a refurbishment.
- The guidelines note that there are few or no regulatory requirements for upgrading existing tunnels, and a risk approach is required. The guide further states that upgrades for FLS in existing tunnels are to be assessed on a *cost-benefit basis to comparable risks on the open road*.
- Decisions on providing significant upgrades to an existing tunnel are made by the NZTA.
- A business case must be prepared for a road tunnel upgrade. It must cover topics such as societal and environmental aspects, risk, design reports (including a fire engineering brief), consultation with the New Zealand Fire Service (NZFS), peer review and value assurance. In addition, the business case must consider a “do nothing” option for all upgrade projects.
- Prescriptive design requirements are not provided, however, there is a need for consultation and peer review to agree on an acceptable solution for the rehabilitation or upgrade effort.

For a tunnel refurbishment, structural constraints generally make full compliance with standards not possible and rehabilitations need to be approached on a case-by-case basis. In New Zealand, risk assessment is recognized as a tool to address these factors and make decisions.

The following expands on experience in New Zealand using risk assessment for tunnel refurbishments. When using risk assessment to compare options and justify an approach, road tunnels generally have a very small fire risk. However, risk assessment and cost-benefit analysis do not always provide enough information for decision-making [Ref 22, Ref 23]. This manifests in two ways:

- A design option may appear best after an assessment is conducted, but with the uncertainty in the input parameters, coupled with the very low fire likelihoods and the (typically) high cost of upgrades, there may not be sufficient spread in the results to make a meaningful conclusion based on quantitative assessment alone.
- The risk of tunnel fire is typically so low that, from a societal perspective, an assessment may show that it is more effective to spend the money elsewhere in the community [Ref 22].

While the above two points are accurate, they do not address community expectations for tunnel safety, expectations that the new or refurbished tunnel will be safer than the current system, and the need for tunnel owners and operators to explain their rationale for installing or not installing the systems after a catastrophic incident. [Ref 22]. To address this issue, certain systems such as an FFFS are typically required in New Zealand (and Australia) irrespective of the cost-benefit analysis results. For instance, in the Terrace Tunnel and Mount Victoria Tunnel, refurbishing an FFFS was required for any design option [Ref 24].

The approach taken in New Zealand identifies vital parts of the new system, such as an FFFS, that will likely have a substantial positive impact on safety such that they are required for any design option. With common design features defined, a cost-benefit analysis based on other factors unique to each design option [Ref 24] can be conducted. Smoke management and provision of means of egress might be assessed during this analysis. Design features identified as "common," such as an FFFS, are not assessed on a cost-benefit basis, but the impact of these "common" features on the fire engineering performance may be included. Other design features are analyzed on a cost-benefit basis to help determine an optimal design to meet fundamental safety objectives. This approach was used on the Terrace Tunnel upgrade, and an assessment was conducted based on design options that varied traffic characteristics, ventilation, and egress [Ref 24].

Providing FLS in road tunnels requires several key actions, which include preventing traffic from entering during a fire event, smoke control, providing opportunities for self-rescue, aiding fire fighter operations, and protecting the asset. To compare the different systems, the actions for tunnel FLS can be visualized as a "fire triangle" analogy [Ref 22]. The fire triangle describes a concept for sustaining a fire where all three sides must be available for a fire to exist. For a fire to exist, there must be oxygen, fuel, and an ignition source. Based on this analogy, one or more of the branches of the FLS triangle (fire control, smoke control, or egress) needs to be addressed to provide safety for tunnel users. Figure 2-20 shows the concept.

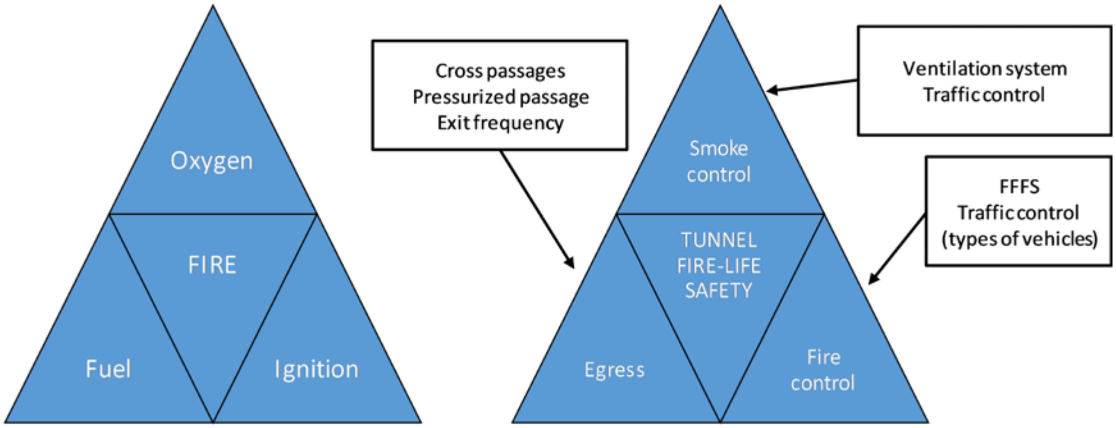

Figure 2-20: Fire triangle concept applied to tunnel FLS [Ref 22].

Source: FHWA

Following established legislative framework can help assure that community expectations of safe passage through the tunnel are met. For example, the NZBC was applied to the Terrace Tunnel and Mount Victoria Tunnel refurbishment since the tunnels are considered ancillary buildings. Key parts of the NZBC applied include outbreak of fire, means of escape, spread of fire, structural stability during fire, access routes, emergency lighting, warning systems, and signage [Ref 24]. On any project, these NZBC elements, if properly addressed, will likely provide adequate safety during a fire for any road tunnel situation.

Another factor to consider with an upgrade is Safety in Design. This is a legislated approach in Australia and New Zealand [Ref 25]. The essence of Safety in Design is to identify risks throughout the whole life of a design, which includes construction, operation, maintenance, and decommissioning, and address those risks wherever possible. With this approach, decisions need to be taken on a whole-of-life risk basis. For example, it should be considered whether risk during construction of a specific feature is higher than the possible safety benefit [Ref 22]. Construction of cross passages in a tunnel provides a good example. If the ground is unstable, building a new cross passage could be high risk due the possibility of ground collapse. Compared to the risk during construction, the operational fire risk mitigation provided over the life of the tunnel is marginal since cross passages are not used frequently. In this instance, the holistic risk approach advocated by Safety in Design provides guidance on the best design enhancement to adopt.

The consequences of a catastrophic event to the facility must also be considered in a risk-based approach. Even with alternative routes available, a tunnel that is out of commission for several years will significantly disrupt traffic and cause major congestion.

The final point to consider in the upgrade process is decision-making. Project governance is a shared responsibility among owners, designers, operators, and responders [Ref 23]. However, even though it is a logical approach, it may not be in the interest of a project to assign design approvals to just one stakeholder group, such as the fire brigade. While it is beneficial to get input from all stakeholders, one opinion expressed is that the tunnel owner is the best stakeholder to have final determination on whether a design is approved, as it is the owner who is simultaneously accountable for the cost of the design and the safety [Ref 22, Ref 23]. This point is reflected in the New Zealand guide to road tunnels, which nominates NZTA to make key decisions [Ref 21].

2.1.7.1 *Rehabilitation Case Study – The Terrace and Mount Victoria Tunnels*

Both the Terrace Tunnel and Mount Victoria Tunnel were constructed over 30 years ago and underwent refurbishment efforts in the past few years using the decision-making practices discussed above. The fire events in the Burnley Tunnel, Channel Tunnel, and Mont Blanc Tunnel were key motivators for NZTA’s rehabilitation of the Terrace and Mount Victoria Tunnels. There was recognition that the older tunnels were at risk, and thus, rehabilitation projects were initiated. The overall project costs and duration for both tunnels were as follows:

- 62,000 hours of work
- 15 months of construction, total duration of project from early 2010 to late 2012
- 520 closures
- 900 drawings
- No lost time injuries
- Total cost of $68M NZD (circa 2012)

Terrace Tunnel

The Terrace Tunnel, opened in 1978, is 1,510 ft (460 m) long, and carries bidirectional traffic in two northbound lanes and one southbound lane. The traffic flow in the tunnel is around 45,000 vehicles per day with three percent heavy goods vehicles.

Prior to rehabilitation, the Terrace Tunnel had a timber ceiling and combustible wall lining panels. Figure 2-21 shows the ceiling plenum prior to rehabilitation. Fifteen jet fans were installed into wooden niches, and only two of the eight new jet fans achieved the same airflow as the original fans. A frangible bulb sprinkler system, modeled after a building type system for activation and controls, was installed in the plenum space and on the roadway. This sprinkler system had never been activated. Seismic factors were a key criterion for consideration as Wellington is in a very active seismic region, with a one in 2,500-year return period event for a Richter 8 earthquake.

Figure 2-21: Terrace Tunnel wooden ceiling plenum prior to rehabilitation.

Source: FHWA

Rehabilitation work on the Terrace Tunnel included [Ref 24]:

- Removal of the plenum and sprinkler system
- Installation of a new FFFS
- Jet fan replacement
- Lighting upgrade, including emergency exit lights
- Power supply duplication
- Fire detection
- Drainage with flame traps and water treatment for storm water
- New cabling
- New tunnel wall cladding
- Electronic systems renewal, including new and rehabilitated switchgear rooms, control system, PLC, CCTV, SCADA, public address (PA), and radio rebroadcast

All in-tunnel work on the Terrace Tunnel was restricted to nighttime closures. A deck was constructed and could be raised during the day and lowered during construction to enable efficient work. The deck provided a level of protection from construction debris during the day and a working area for construction during the night. While there was a requirement to achieve a lighting level of 5 lux for normal operations, lighting levels were already low and were worsened by plenum removal. To remedy this, crews painted the wall white after each plenum and wall panel segment were removed.

The cost of the Terrace Tunnel FFFS was $1.26M (2012 NZD). This cost was for the supply and installation associated with the FFFS (such as pipes, valves, and nozzles). Other items required, such as the CCTV system, controls, fire panels, and water management, were priced separately. Delivery times for FFFS components were in the following order of magnitude:

- Nozzles: 12 to 14 weeks
- Deluge valves: 11 to 12 weeks
- Cabinets for hydrants and valves: 8 to 14 weeks
- Stainless steel actuation tube: 6 weeks
- Hot dipped galvanized pipe (water main, 10 inch, 254 mm): 4 to 6 weeks
- Hose reels: 8 weeks
- Hydrant valves: 6 weeks

Rehabilitation efforts typically attempt to achieve compliance with current standards. However, this may not be possible in every case. Examples from the Terrace Tunnel demonstrate design practices unique to a rehabilitation effort and are outlined below. These examples are not meant to point out deficiencies, but rather illustrate where minor concessions may need to occur to enable the best possible infrastructure within the confines of an existing facility.

- The water application rate chosen for the tunnels was 0.16 gpm/ft^2 (6.5 mm/min). As discussed in Section 2.1.2, the water application rate was chosen primarily based on available water supply in the area. Other tunnels and jurisdictions were also considered in making this decision. For instance, Japan uses an application rate of 0.15 gpm/ft^2 (6 mm/min), and there is evidence from a good operating track record that this rate can be very effective. The Burnley Tunnel in Australia uses a rate of 0.18 gpm/ft^2 (7.5 mm/min), and this rate was effective in a major incident in that tunnel [Ref 5, Ref 13].
- A very minor encroachment into the vehicle envelope was allowed for the FFFS branch line. A deflector plate was installed to reduce the risk of a vehicle impact (see Figure 2-22). Without this allowance, it is unlikely that the FFFS could have been constructed.
- Drainage from the tunnel was challenging because the capacity of the system was not designed for an FFFS discharge event. Figure 2-23 shows an example of drainage overflow. The ability to modify in-tunnel drainage was limited by time and lane availability issues, as trenching in the tunnel floor is a slow process. Installing cross laterals took approximately two nights, and required steel plates over the trenches. Longitudinal trenches would have been more difficult, time consuming, and expensive to upgrade.
- Egress was from the tunnel portals, at 1,510 ft (460 m) apart. This is much more than typical. However, construction of an intermediate means of egress would have required a dedicated passage in the tunnel, or new excavation. Risk assessment showed that portal egress was acceptable [Ref 24].

Figure 2-22: Deflector plate installed on the Terrace Tunnel branch main to overcome minor traffic envelope overlap.

Source: FHWA

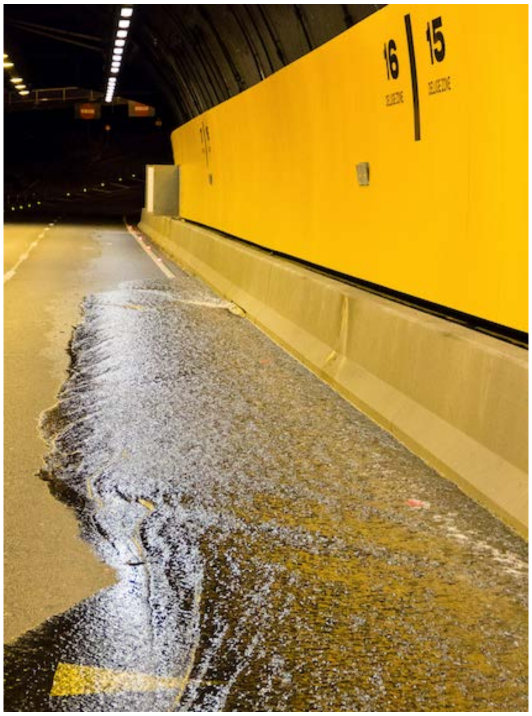

Figure 2-23: Drainage overflow example in the Terrace Tunnel.

Source: FHWA

Mount Victoria Tunnel

Figure 2-24: Mount Victoria Tunnel prior to rehabilitation.

Source: FHWA

During the Terrace Tunnel and Mount Victoria Tunnel rehabilitation projects, there was a change of government in New Zealand and the Roads of National Significance (RONS) program was initiated. In response to the new program, the Mount Victoria Tunnel rehabilitation project was altered as there was already a RONS project to duplicate the tunnel. FLS upgrades, including removal of deteriorating concrete ceiling panels and installation of a new FFFS, were carried out on the Mount Victoria Tunnel despite the change. Figure 2-24 shows a cross section of the tunnel and Figure 2-25 shows the ceiling plenum prior to rehabilitation. A lighting upgrade, electrical equipment upgrade, smart stud installation, and a radio-rebroadcast and PA system replacement were also installed.

Figure 2-25: Mount Victoria Tunnel ceiling plenum prior to rehabilitation.

Source: FHWA

The Mount Victoria Tunnel had a pressing safety issue with its concrete ceiling panels and the hangers holding them up that needed to be addressed. Pieces of concrete were prone to fall and there was a concern that the ceiling could exhibit a catastrophic unzipping failure. Despite the comprehensive rehabilitation project being taken off the table, the need to remove the ceiling was acknowledged and the work carried out. The ceiling duct was an exhaust plenum that contained hazardous materials like lead and asbestos. A movable hopper was used to collect the pieces of air duct, and a 'pincher' fitted to an excavator was used to remove the duct. Removal of the plenum altered the ventilation system slightly, but did not negatively impact performance. Figure 2-26 shows a schematic of the ventilation before and after plenum removal.

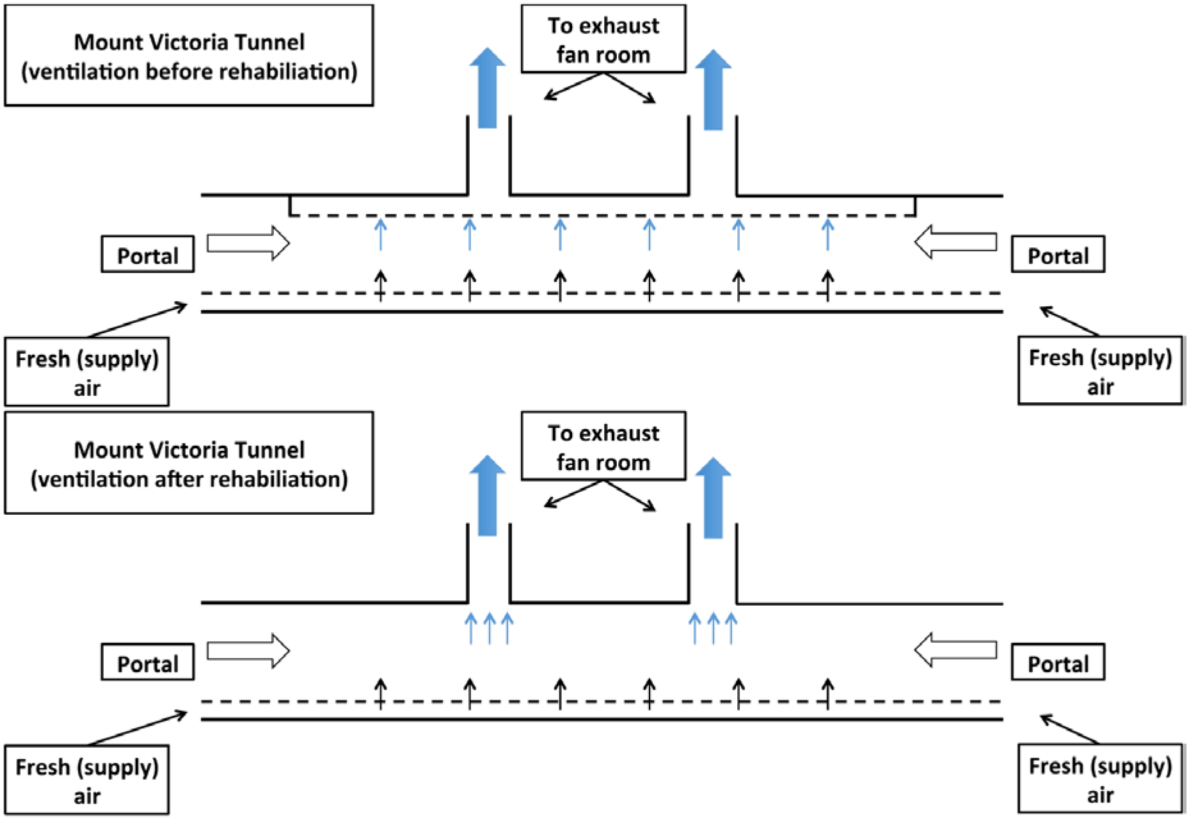

Figure 2-26: Mount Victoria Tunnel ventilation schematics before and after plenum removal.

Source: FHWA

Changes to the sprinkler system were also made. A sprinkler system was mounted to the underside of the air duct, and this was removed as part of the ceiling removal. The NZFS required a replacement FFFS to be installed after removing the old system. From May 2011 to December 2011, the tunnel ceiling was removed and the deluge system installed. Costs for the Mount Victoria Tunnel FFFS were around $1M (NZD 2012), and due to the need to minimize construction duration the Contractor was offered a bonus for early completion. The cost was for the supply and installation associated with the FFFS only (such as pipes, valves, and nozzles). Other items required were priced separately.

A unique design feature in the Mount Victoria Tunnel was the location of the FFFS valves. There was no space in the roadway or next to the roadway, so the valves were installed inside a fire-rated enclosure in the apex region of the tunnel. This is shown in Figure 2-27 and Figure 2-28.

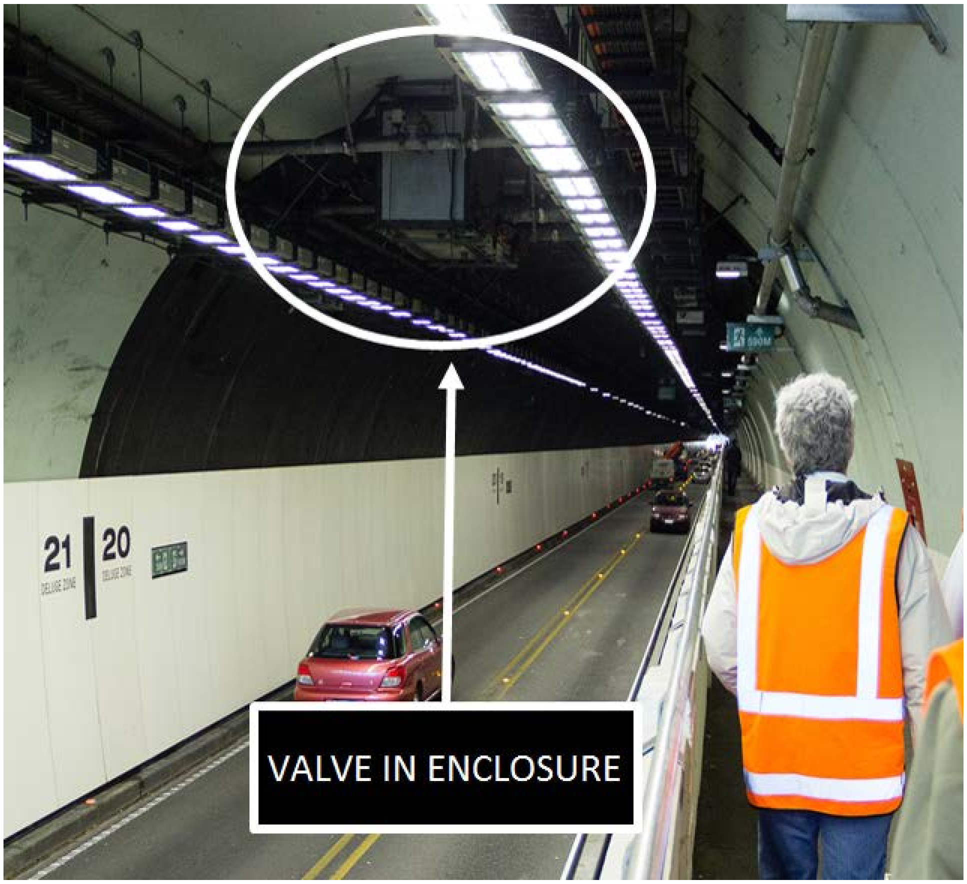

Figure 2-27: Mount Victoria Tunnel FFFS (deluge) valve in a fire rated enclosure.

Source: FHWA

Figure 2-28: Mount Victoria Tunnel close-up of FFFS (deluge) valve in the tunnel apex.

Source: FHWA

2.2 Construction

Figure 2-29: Waterview Tunnel demonstration of the FFFS operation.

Source: FHWA

The construction of an FFFS is typically conducted by contractors specialized in the provision of fire protection systems, such as sprinklers. During the site visits, the Waterview Tunnel in Auckland was still under construction and in the final stages of commissioning; the tunnel opened July 2017.

On the day that the GBP team visited the Waterview Tunnel, a demonstration of the FFFS was conducted (see Figure 2-29) and some discussion took place about commissioning issues. The contractor was working through numerous control issues, primarily related to integrating the individual systems into a fully operational tunnel life safety system. As with any complex system, the way these elements are interrelated can cause unexpected feedbacks. The approach used at Waterview appeared to be systematic and well-planned for resolving these issues.

One commissioning issue related to the FFFS involved determining the need for a pressure relief valve. Some pressure reduction orifice plates were also required in the pipe network, as shown in Figure 2-30. This issue was not immediately obvious in the design phase, but was easily fixed at commissioning. The ease of fixing this problem without a need for claims or defensiveness from any party is one of the positive features of the project alliance method of project delivery used on the $1.4B NZD project (see Section 2.6.1 for more detail regarding project delivery). A problem with debris blocking a regulator in the valve, see Figure 2-31, was also encountered. That problem was easily fixed as well, but highlighted the importance of regular maintenance to make sure the system is reliable and fully functioning.

Figure 2-30: Waterview Tunnel FFFS valve with orifice plate.

Source: FHWA

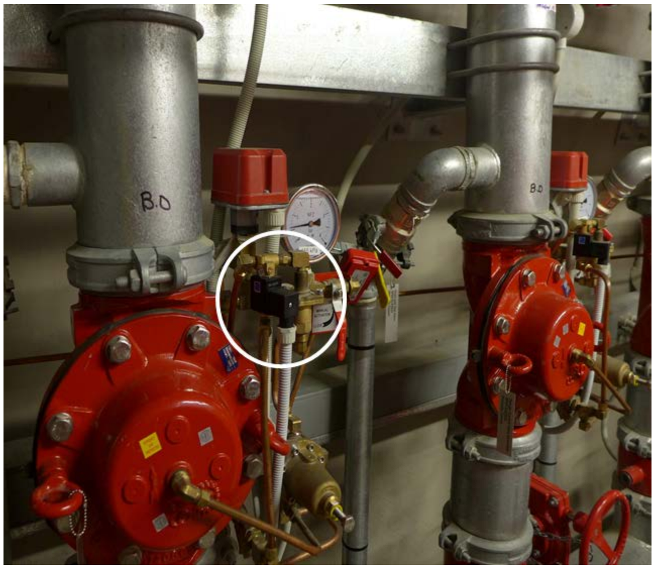

Figure 2-31: Waterview Tunnel FFFS valve regulator.

Source: FHWA

The project at the Waterview Tunnel demonstrates the vast knowledge and experience of New Zealand and Australia in tunnel design, operation, and maintenance. It also demonstrates innovation and effective integration of safety with design. The Waterview Tunnel has the most advanced safety features available and was designed to fit well in the community with a focus on operability and maintainability. Tunnel safety features, including operational protocols and operation training materials and procedures, have been integrated in the design. One example of an innovation from this project is a fire hose attachment that allows for easier and quicker attachment than traditional systems (see Figure 2-32).

The Auckland Traffic Operations Center (ATOC) is the primary operator for the Waterview Tunnel. In conjunction with the commissioning process, the staff were trained for operation of the tunnel and worked with the design team to develop training software well ahead of the tunnel's opening.

Figure 2-32: Waterview Tunnel fire hose attachment detail.

Source: FHWA

2.3 Operation and Training

Operations and training are among the most critical elements of FFFS installation. For optimal use of an FFFS, experts note it is necessary to have an operational culture that can actively respond to incidents [Ref 26]. Operations, training and certification, incident response plans, fire brigade operations, collaboration, and public outreach all contribute to the overall effectiveness of an FFFS. Stakeholders, designers, owners, and emergency agencies are critical agents in developing a multi-disciplinary and integrated approach to the design. Figure 2-33 provides an overview of the many factors that create an environment for successful FFFS design and operation.

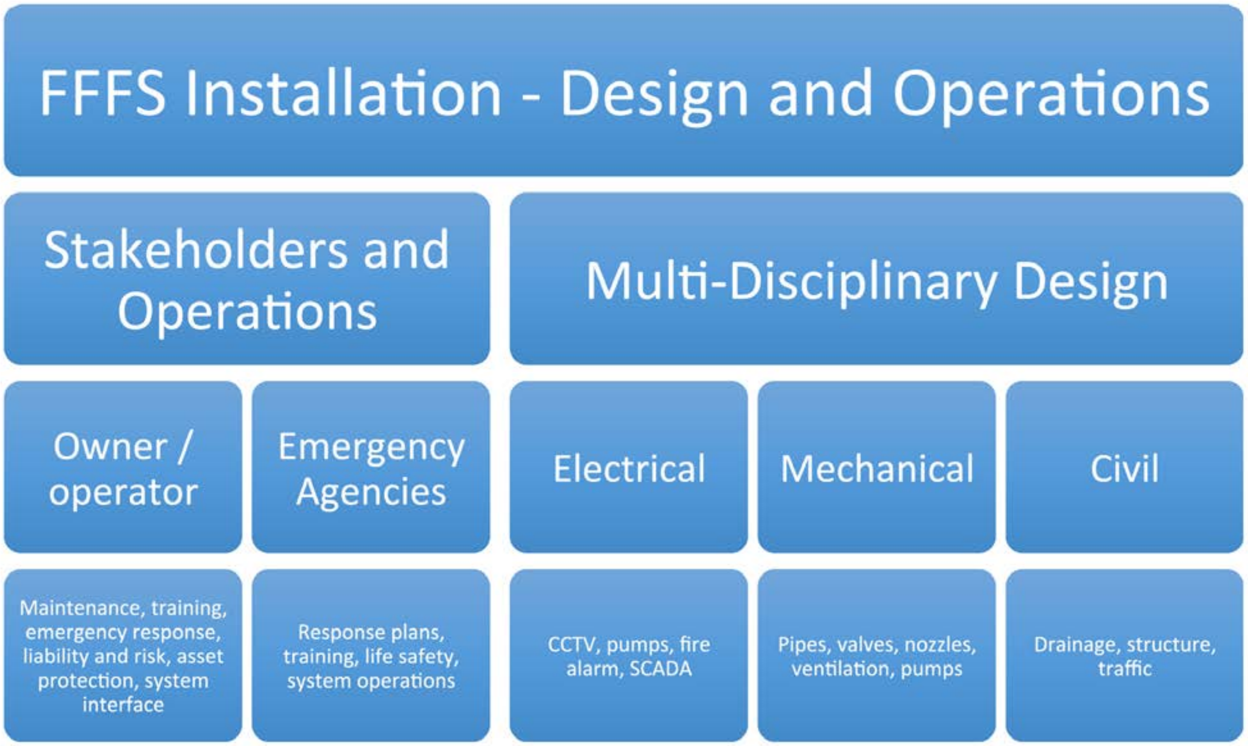

Figure 2-33: Considerations in the design and operation of a tunnel FFFS.

Source: FHWA

2.3.1 Operations

The tunnels visited in New Zealand were all operated by the government agency, the NZTA, with some maintenance activities carried out on a contract basis by private companies. Private companies, either as a concessionaire holder or on contract to RMS for NSW, operated the tunnels visited in Sydney, Australia. Despite this operational mix, there is a lot of collaboration between the various tunnel operators. The facilities visited had the following operational aspects in common:

- Control room with trained operators monitoring traffic 24/7 to respond to incidents, including fire and other emergencies.
- Backup control facilities, typically local to the tunnel, from where the tunnel could be operated if the main control facility was out of service.

- Provisions and procedures for manual activation of the FFFS, with automatic operation on fire detection (heat) a backup feature only.
- Incident response plans for fire response were very similar across all facilities visited.

2.3.1.1 New Zealand

Figure 2-34: Auckland Traffic Operations Center control room.

Source: FHWA

The NZTA takes a "one-network" approach to their transport network, including tunnels and their operation. At the Auckland Traffic Operations Center (ATOC), bus, ferry, and road network elements are managed. Figure 2-34 shows a view of the ATOC control room. The ATOC operations originally began with the Harbor Bridge in Auckland, but expanded as more facilities were constructed, adding to the center's scope. The ATOC's scope has expanded to include the Johnstone's Hill Tunnel situated north of Auckland, the Victoria Park Tunnel and the Waterview Tunnel in the Auckland City region, and the backup operation of the Terrace Tunnel and Mount Victoria Tunnel in Wellington. Internal procedures and operating standards have been developed as ATOC operations have expanded and matured.

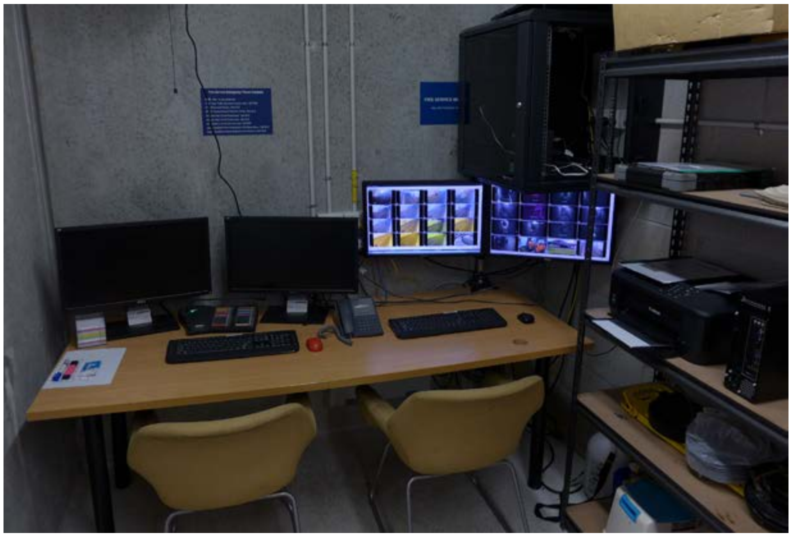

Figure 2-35: Victoria Park Tunnel backup control room

Source: FHWA

Tunnel control rooms exist in Wellington and Christchurch to manage operations for the tunnels in those cities; there are also backup control rooms in Auckland (see Figure 2-35). Control of the Wellington Tunnels, namely the Terrace Tunnel and Mount Victoria Tunnel, is possible from the ATOC. A dedicated fiber network provides connections between the various locations, and efforts are underway to standardize operating procedures between all locations. In Wellington, all tunnels are serviced with dedicated NZTA fiber cable from WTOC to the tunnels, with redundant fiber cable links provided by leasing from utility suppliers. The fiber link between the various tunnel operation centers is also provided via leased fiber connections.

2.3.1.2 Australia

Tunnels visited in Australia were operated from dedicated control rooms for each facility. There are also backup control rooms. The Australian tunnels visited were operated under the following arrangements:

- Sydney Harbor Tunnel, private concessionaire
- M2 Tunnel, private concessionaire
- M5 East Tunnel, RMS NSW with a private contract to operate and maintain

2.3.2 Training and Certification

Training was a critical part of the operations in all facilities visited. In Australia, the Logistics Skill Council has a recognized course for tunnel operators, and operators can obtain a Certificate IV in tunnel operations [Ref 27]. Table 2-2 provides an example of some of the occupations associated with different training level certificates. The tunnels visited in Australia and New Zealand currently use the Certificate IV approach or are working toward incorporating the approach.

Table 2-2: Transport and logistics training occupation examples [adapted from Ref 28].

Source: FHWA.

Certificate II	Certificate III	Certificate IV	Diploma
Community driver Express driver Mail delivery driver Taxi driver Tow truck driver	Agitator driver Bus driver Pilot vehicle driver Local heavy general freight driver Tip truck driver Waste vehicle driver	Chemical tank driver Fuel tanker driver Heavy recovery driver Open road operator Tunnel road operator	Fleet manager (buses)

Certificate IV training involves eight units of education, six core units specific to road operations, and two units specific to road tunnels [Ref 27]. The certificate competencies, such as first aid and environmental compliance, are transferable to areas other than a tunnel environment. Core and elective units are noted below [Ref 27].

- Core units:
  - Equipment checking and maintenance:
    - Check and assess operational capabilities of equipment
  - Communication:
    - Use of electronic communication systems
  - Safety management:
    - Apply fatigue management strategies
    - Coordinate breakdowns and emergencies
  - Quality:
    - Apply quality systems

  - Technology:
    - Use info-technology devices in the workplace
  - Imported:
    - Manage personal stressors in the work environment
- Road tunnel operator:
  - Safety management:
    - Implement and coordinate accident-emergency procedures
    - Monitor and respond to traffic flow
    - Operate fire and life safety system within a road tunnel
    - Manage emergencies
  - Environment:
    - Monitor plant and equipment in an environmentally sustainable manner

Bob Allen, the General Manager at the Sydney Harbor Tunnel, was instrumental in the development of road tunnel operator certification through the Logistics Skills Council. Development of this program was nearly a six-year-long process. One of the key aspects to the acceptance of certification was the necessity of having all tunnel operators' participation and support.

The certification requires three to six months of study and experience. Recipients must pass an exam and have experience in the tunnel in which they are certified to operate. As part of the recertification process, certain portions of the training must be revisited every six months. The impact of the certification has been beneficial to everyone, elevating the stature of operators and recognizing their vital role in tunnel safety. The final part of certification is a mock fire exercise in the tunnel where the operator is being certified. Certification requires successful operation of the FFFS and other safety systems, such as traffic control and ventilation operation, per a pre-planned scenario. The operator must complete the Certificate IV course before they are considered qualified to operate the tunnel unsupervised.

In Australia and New Zealand there are always two operators on duty for all tunnels, at least one of whom must be certified. Operators typically work 12-hour shifts, two days on and two days off with occasional periods of four to five days off, producing an average working week of 30 hours. This schedule is popular with workers, reduces fatigue, and promotes safe and effective operation.

2.3.3 Incident Response Plans

Incident response plans are critical to the safety infrastructure in a tunnel. The plans represent the merging of the engineered systems with the human operators responsible for incident management. Common to all tunnels visited, is a simplification of the incident response plan for operators and responders. In the Sydney Harbor Tunnel, the key to this simplification is having response activities for emergency scenarios that are confined to one page of instructions. The FFFS activation policy and two examples of an incident response procedure are provided below. Some practical coverage of incidents is provided in Section 2.5.

2.3.3.1 *FFFS Activation Policy*

One of the major questions that arises during the development of an FFFS design and operation procedure is related to when the FFFS should be activated. There is a risk to moving traffic if the FFFS is activated on live traffic because the water will obstruct visibility and cause the roadway to become slippery. However, if the fire incident is serious, there is also a risk associated with not activating the FFFS as early as possible. During tunnel visits, each operator was asked how they decide when to activate the FFFS. The response was generally the same across all facilities and included the following elements:

- The operator relies on the CCTV footage, training, judgment, and experience to determine if there is a fire incident requiring FFFS activation.
- Prior to activating the FFFS, the operator will initiate the necessary traffic management plan to stop traffic entering the tunnel, and to direct traffic inside the tunnel to stop. The FFFS will cause a loss of visibility in the tunnel (see Figure 2-36), and it is necessary to attempt to stop traffic prior to activation. Motorists will not always stop their vehicles when told to do so. Tools used to stop traffic include radio rebroadcast of live messages, tunnel message signs, and traffic signals.
- The operator will activate the FFFS if traffic has been told to stop and a fire confirmed. If people are ignoring the directions from the operator to stop, the FFFS will be activated regardless. The final decision to activate the FFFS rests with the operators, and their training and experience will inform their judgment.

Figure 2-36: M2 tunnel with no FFFS activated (top) and FFFS activated (bottom)

Source: FHWA.

2.3.3.2 *Sydney Harbor Tunnel Incident Response*

The incident response plan in the Sydney Harbor Tunnel assures a rapid and accurate set of actions by the operator. Figure 2-37 shows the control room. By design, the response plan at the Sydney Harbor Tunnel fits onto a single page on the operator's SCADA interface. A typical fire incident response flow is as follows:

Figure 2-37: Sydney Harbor Tunnel control room.

Source: FHWA.

Figure 2-38: Sydney Harbor Tunnel fire test showing traffic control signage.

Source: FHWA

- **Traffic management.** Tunnel is closed using signals, radio rebroadcast, variable message signs (VMS), and lane use signs (LUSs), as well as a moveable barrier outside of the tunnel to divert traffic away from the tunnel.
- **Deluge.** The operator will activate the deluge when they perceive there is a fire, based on experience and visuals from the CCTV. The operator will activate deluge once he or she has told traffic to stop moving, even if people are ignoring the instruction and not stopping or driving. Ventilation modes will be activated as well. Figure 2-38 shows some of the traffic control signage in the tunnel.
- **Next steps.** Evacuation will be ordered by the operator or the fire brigade if the situation becomes uncontrolled. If the FFFS is controlling the incident, evacuation will not necessarily be initiated. The fire brigade will be called, and at a minimum, two units will attend. One unit will go to the control room to understand the nature of the incident and will work directly with the operators. The other unit will enter the tunnel via the non-incident bore. The operator's CCTV system tells them which cross passage corresponds to the one nearest the fire; refer to Figure 2-15 for a CCTV display visual.
- **Close out.** The FFFS will not be shut down until the fire brigade orders it shut down. Once the incident is controlled, the fire brigade and police will hand back command to the tunnel operators, and once they confirm the tunnel is safe (engineering checks on the systems and structure), it is reopened to traffic.

2.3.3.3 Auckland Traffic Operations Center Incident Response

There are four parts to the fire incident response plan:

- **Detection.** The operator must declare a fire and then confirm it. The operator will have 60 seconds to respond and confirm or cancel the fire. After this time, the system will default to automatic fire mode. Typically, the AVID system will detect the fire first and the LHD is a backup.
- **Verification.** The operator will verify the fire location via AVID and active cameras, large numbers on the walls, and the FFFS zone number on the CCTV. The FFFS zone at the fire and one upstream will be activated. The FFFS will always be activated at this point if a fire has been confirmed. If there is only visible smoke, the operator may delay the activation.
- **Action.** The operator must decide whether to evacuate the tunnel. In the Victoria Park Tunnel, this will always be the case as there is no staged approach to evacuation. At this point, steps to evacuate the tunnel begin with audio announcements, radio rebroadcast, and variable messaging sign activation. The operator must consider whether there are people or vehicles downstream of the fire. If no cars or people are downstream, then the jet fans start; if the downstream roadway is occupied, fans will remain off.
- **Monitor.** The aim of the response plan is to minimize the operator's decision-making as much as possible. If needed, the operator can always correct a decision. Once the basic steps to the response have been activated, the operator will cycle through a check-list sequentially. This checklist includes the FFFS, ventilation and smoke management, and evacuation. If necessary, the operator can adjust the response.

During a fire incident in one of the Auckland tunnels, the responding fire brigade units will go to the tunnel and to the ATOC. While the fire brigade is in command during an incident, they usually do not operate individual systems. The fire brigade representative at the ATOC will request certain system responses, such as additional ventilation, and the operator will activate the appropriate system. This is considered a reasonable protocol because it is the ATOC operators who have the most experience with the individual systems.

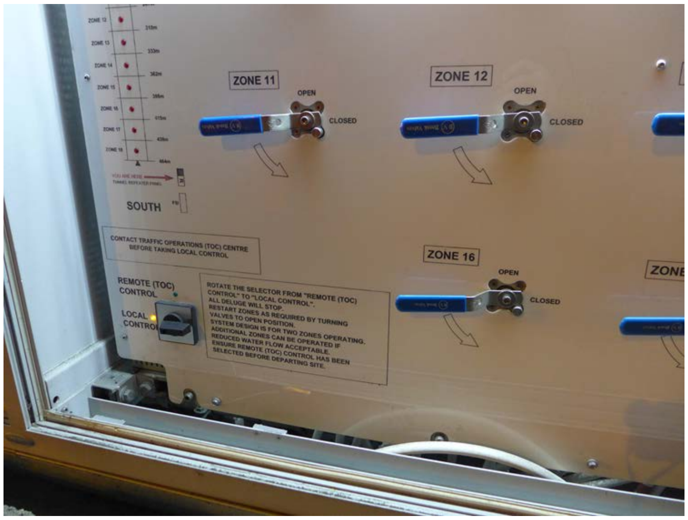

Figure 2-39: Terrace Tunnel deluge control panel for the fire brigade.

Source: FHWA

2.3.4 Fire Brigade Operations

In all tunnels visited, the fire brigade acknowledges the tunnel operator as a valuable resource and critical part of their response. The operator will assist with: (1) operation of the tunnel safety systems such as ventilation, FFFS, and messaging; and (2) providing knowledge of the incident and the people and vehicles involved. The fire brigade will always send an incident commander to the tunnel control room.

At the Waterview Tunnel and the Victoria Park Tunnel, there are video screens provided on site where the operator can replay CCTV footage of an incident, either recorded or in real time, to the responding fire crew. Refer to Figure 2-14 for an example. The fire brigade is also provided with simplified control provisions at the tunnel entrances next to the roadway, or at their usual tunnel entry point, for easy access, which they may or may not choose to use. At the Terrace Tunnel and Mount Victoria Tunnels, there are fan control panels and deluge control panels provided (see Figure 2-39).

2.3.4.1 Exercises

New Zealand

The NZTA and Auckland Motorway Authority have a track record of conducting emergency exercises in tunnels [Ref 29]. Annual exercises are held in the Johnstone's Hill Tunnel and the Victoria Park Tunnel in Auckland, New Zealand. The exercises have alternated between major and minor exercises, but both categories involve fire, police, and ambulance response to a simulated emergency inside the actual tunnel. Emergency systems are operated, including ventilation to manage real smoke, and the FFFS may also be operated depending on the scenario. In some scenarios, a system failure is introduced, such as a communications failure, which may result in the fire brigade having to operate safety features from backup facilities at the tunnel [Ref 29].

One major benefit of these exercises is improved education on the unique environment of a tunnel regarding operation of systems and the need to communicate to ascertain the nature of the incident [Ref 29]. Examples of first responders, fire, and police entering a tunnel and proceeding directly into an active FFFS zone were noted. This resulted in complete disorientation due to loss of visibility and inability to hear when in the FFFS zone [Ref 29]. This example helps illustrate the learning benefit derived from live exercises.

With the Waterview Tunnel, Mount Victoria Tunnel, and Terrace Tunnel included in the exercise rotation, an exercise frequency of once every two or three years was noted by operations staff as too infrequent. With this schedule, it would take 10 years or more to cycle all tunnels through the exercise and employee turnover is typically much more frequent. To achieve more frequent training, mini-exercises are being considered in New Zealand. The NZFS is not necessarily involved, but operation staff go through a small exercise, perhaps involving a smoke machine to add a level of environmental reality. One of the goals is to keep exercises simple to allow them to be done more frequently. A desktop exercise is also conducted once a year for each operator.

M5 East Tunnel

In the M5 East Tunnel, there are quarterly meetings with emergency services. Once a year, an exercise is conducted by desktop or in the field.

Sydney Harbor Tunnel

A controlled burn of a vehicle is periodically conducted in the Sydney Harbor Tunnel. The operator activates the FFFS to control the fire, and the local fire brigade personnel also participate. This gives operators and first responders a first-hand experience of a tunnel fire in a controlled environment [Ref 15]. More detail on the tests is provided in Section 2.5.2 using a specific example of a car fire demonstration in the tunnel.

Live evacuation exercises have also been conducted in the Sydney Harbor Tunnel, where 32 volunteers participated in an exercise to evacuate the tunnel [Ref 30]. A car was burned during the exercise, with the fire brigade in attendance, and participants were provided with instructions to evacuate. Video observations and post-incident questionnaires were used to collect data. One significant finding was the role of social influence, with 94 percent of the participants reporting that their actions were influenced by the actions of other people also in the tunnel.

2.3.5 Collaboration

The Australasian Tunnel Operators Group (ATOG) meets every three or four months to share operational experiences, with the primary goal being to collaborate. Their target audience is tunnel operations managers. The meetings are closed, and invited members openly share good and bad experiences. Participants in the meetings noted that the closed meetings were helpful and encouraged focusing on frank discussions and operational improvements rather than on defensiveness and liability mitigation. Technical guests will occasionally be invited to meetings to share their knowledge. The ATOG was a key element in the success of the Certificate IV certification for tunnel operators (refer to Section 2.3.2).

2.3.6 Minimum Operating Conditions

Most road tunnels do not have specific minimum operating conditions. Typically, the tunnel design has redundant elements like a dual power feed, but this has limitations. For instance, in the FFFS design there are no spare valves. Standards in Australia and New Zealand do not explicitly define minimum operating conditions. Some of the facilities have developed established practices based on their operational experience. Such examples include:

- Tunnel closure if more than four FFFS zones in a row are inactive
- Operator risk assessment if a single zone is not operational

In general, the experience of Australia and New Zealand is that there is a need for more clarity on the minimum operating conditions for road tunnels as this is not something typically addressed during design.

2.3.7 Public Education and Outreach

Public education and outreach is a high priority in Australia and New Zealand. This is achieved by various means, including:

- Public open days when a new facility is opened to the public. For instance, the Waterview Tunnel recently held a public walk through the tunnel prior to traffic operations [Ref 31].
- In the Sydney Harbor Tunnel, a fire demonstration was conducted during the visit. A local television film crew was present to record footage for a story; this is common practice in the Sydney Harbor Tunnel.
- In Wellington, where the tunnels were being rehabilitated for improved fire safety, the NZTA were conscious of the look of the finished tunnels. As the safety features in a tunnel are typically behind the scenes, and not something that the public necessarily sees, the finished look of the tunnel was important. Outreach was also achieved by working with local news media.
- The NZTA and RMS NSW both provide websites dedicated to tunnels and safe driving in their tunnels [Ref 32, Ref 33].

2.4 Maintenance and Inspection

The NZTA uses two policy documents for tunnel maintenance:

- Tunnels Management and Inspection Policy, NZTA S8, 2017 [Ref 34] (referred to as S8)
- Bridges and Other Highway Structures Inspection Policy, NZTA S6, 2017 [Ref 35] (referred to as S6)

S6 covers tunnels and the structural elements. Mechanical and electrical elements as well as building elements of tunnels (stairs, roofs, doors, walkways, and associated control buildings), are covered by S8. S6 makes specific reference to the FHWA tunnel inspection manual [Ref 36]. A general tunnel inspection is required every two years, with a principal inspection required every six years. Special inspections are required following a major fire, earthquake or flood.

The tunnels inspection policy of the NZTA (S8) covers mechanical and electrical equipment. S8 defines a tunnel as any covered roadway structure more than 262 ft (80 m) in length, and anything shorter than this is considered an underpass. The document defines the role of a tunnel manager, safety officer, regional performance manager, operations manager and tunnel inspection engineer. Their roles include the following:

- **Tunnel manager.** Has principal responsibilities for tunnel elements, including fire and life safety systems of the tunnel, meeting statutory obligations to maintain the Building Warrant of Fitness (essential Building Act compliance), maintaining the tunnel asset manual, periodic emergency exercises and training for staff, and reporting on the status once every three years.
- **Safety officer.** An independent person who is responsible for carrying out audits (once every two years) of the operational plans, fire-life safety risk assessments, processes for emergency response, coordination with emergency services, training of tunnel and emergency services staff, tunnel equipment maintenance, and long-term asset management plans.
- **Regional performance manager.** Responsible for the inspection, maintenance and operations of all aspects of the state highway network in each region.
- **Operations manager.** Responsible for the safe real-time operations of the tunnel, and for incident reporting and debriefs when necessary.
- **Tunnel inspection engineer.** Responsible for the overall management and technical supervision of the tunnel mechanical and electrical equipment inspection.

Elements identified in the tunnels inspection policy (S8) include ventilation, lighting, drainage, FFFS, communication systems, CCTV, tunnel operational and plant control systems, monitoring systems, and power supply and distribution. Generally, annual inspection and end-to-end testing from the operations center to the physical system in the tunnel is required for the Building Warrant of Fitness. This includes tunnel mechanical and electrical equipment, with monthly routine surveillance of equipment. Special inspection triggers include fire, flood, or earthquake. Reporting and asset database maintenance are required.

Some observations from the tunnel visits and discussions include the following:

- All the tunnels visited demonstrated a high commitment to maintenance that can be attributed to the integration of their operation and maintenance practices. Maintaining cameras, testing the FFFS, cleaning walls and pavement, and using AVID systems to manage traffic create a synergy in their management processes.

- In Wellington at Terrace Tunnel and Mount Victoria Tunnel, maintenance requires 12 nights of closure per year per tunnel. Maintenance includes routine testing, FFFS zone activation, and end-to-end testing. Subcontractors are involved in the maintenance. A regime is used that includes weekly, bi-weekly, monthly, and annual inspection. Inspectors are independently qualified. Procedures are driven by the Local Council, which is the authority administering NZBC requirements and issuing the annual Certificate for Public Use. Although the building code applies, tunnels are typically held to a higher standard specific to the facility.
- Aging facilities:
    - The Sydney area is made up of limestone, and the groundwater there is extremely basic. This groundwater tends to attack galvanized steel pipe.
    - FFFS valves may need to be drained after activation. Poor procedures with this can cause the system to age prematurely.
    - At the oldest tunnel facility visited, the Sydney Harbor Tunnel, the FFFS was in good working order. This was attributed to regular maintenance and repairs over the life of the system.

2.5 Incident Examples

Several incident examples are covered in this section. These examples are based on discussions with the tunnel operators. Many more incidents than these have occurred in road tunnels with and without an FFFS. The aim of the discussion here is to give an account of the anecdotal evidence observed in relation to actual FFFS performance in the facilities visited. The desk report also provides an account of some previous incidents, refer to Appendix D.4.

2.5.1 Truck Fires

During the visit to the M5 East Tunnel, video footage of two truck fires was shown. One incident occurred inside the tunnel, and the other occurred just outside of the tunnel in a truck stop area. In the latter incident, it is clear the driver realized there was a problem with the vehicle, could drive out of the tunnel, and chose to do so. Both fires were a result of a vehicle fault and there was no initial traffic incident such as a collision.

From the video footage observed, the incident that occurred outside of the tunnel included the following significant events (times are given in minutes and seconds):

- 00:00 – Truck stops in the truck stop area, small amount of smoke observed emanating from the vehicle’s engine compartment. Refer to Figure 2-40.
- 03:30 – The truck is now clearly on fire, with large volumes of smoke coming from the engine compartment. Refer to Figure 2-40.
- 06:30 – Visible flame coming from the engine compartment.
- 12:00 – Fire brigade are on site, and operations to extinguish the fire commence approximately two minutes later. Roadway is closed. Refer to Figure 2-41.
- 16:00 – Fire is being suppressed. Refer to Figure 2-41.
- 33:00 – Roadway reopened.

Figure 2-40: M5 East fire outside of tunnel, start of incident (left) and at 03:30 (right).

Source: RMS NSW

Figure 2-41: M5 East fire outside of tunnel, fire brigade arrives at 12:00 (left) and are suppressing the fire at 16:00 (right).

Source: RMS NSW

The incident inside the tunnel involved a similar truck. The truck was carrying mattresses and came to a stop because of engine problems. Initially, it was not apparent there was a fire and vehicles kept driving past the truck. The following events were observed (times are given in minutes and seconds):

- 00:00 – Truck stops in the tunnel while vehicles continue to drive past.
- 01:00 – The truck driver exits the vehicle and is observed accessing one of the emergency equipment cabinets, but it is not clear if the driver is attempting to fight the fire. There is visible smoke coming from the vehicle. Refer to Figure 2-42.
- 02:00 – There is visible flame. Vehicles appear to be stopped but some are still edging forward, smoke is moving downstream and there is no smoke upstream.
- 03:00 – Flames have grown substantially; vehicles are now stopped. Refer to Figure 2-42.
- 04:30 – The FFFS is activated.
- 05:40 – A second FFFS zone upstream of the vehicle is activated. Refer to Figure 2-43.
- 45:00 – The FFFS is shut down. The fire brigade has extinguished the fire. Refer to Figure 2-43.

There was no evacuation required. Based on occupant reports from vehicles upstream, there was a delay of around 45 minutes. The truck was sufficiently undamaged and could be towed out of the tunnel. A tow truck was on site around one hour after the start of the incident.

These two incidents highlight the potential effectiveness of an FFFS. Both incidents were major and disruptive to traffic. For the incident inside the tunnel, it is noteworthy that the vehicle could be towed, suggesting that the FFFS had prevented a lot of damage to the vehicle. The FFFS was activated around four to five minutes after the truck stopped. For the incident outside the tunnel, where fire suppression was not applied until about 13 minutes after the truck stopped, there was a much larger fire and it is unlikely that the vehicle could have been easily removed.

Finally, in one unusual incident in the M5 East Tunnel, a truck with a burning open top load stopped in a breakdown bay. The tunnel operator detected the stopped vehicle and fire, and activated the FFFS. The fire was extinguished. The truck driver then continued before first responders could arrive to assess and aid in the situation.

Figure 2-42: M5 East fire inside of tunnel, start of incident 00:00 (left) and visible flame at 03:00 (right).

Source: RMS NSW

Figure 2-43: M5 East fire inside of tunnel, FFFS active at 05:40 (left) and deactivated at around 45:00 (right).

Source: RMS NSW

2.5.2 Car Fires

Video footage of a car fire in the M5 East Tunnel demonstrates some useful data on driver behavior:

- The car was stopped and emitting a large volume of smoke. Despite this, motorists continued to drive by the incident vehicle, even when the smoke was very heavy and flames were visible. Refer to Figure 2-44.
- The FFFS was activated and the fire was quickly controlled. The traffic closure signals were active and vehicles continued to drive past the incident. Refer to Figure 2-44.

Figure 2-44: M5 East car fire inside of tunnel, prior to FFFS activation (left) and during activation (right).

Source: RMS NSW

During the visit to the Sydney Harbor Tunnel, the team observed a car burn exercise. As mentioned in Section 2.3.4.1, these exercises are done periodically and they are useful for operators and fire brigade personnel to gain practical experience. Observations from the demonstration include the following:

- A car was used and stripped of the fuel tank and interior seating. The fire brigade was in attendance and configured the vehicle; a combustible gel mixture was spread inside the vehicle and ignited.
- Fire spread relatively quickly through the vehicle. After one to two minutes there were flames extending from the vehicle, refer to Figure 2-45 and Figure 2-46.
- After the FFFS was activated, there was a brief flare up of the fire. Shortly thereafter, the flames were suppressed and restricted to inside the vehicle. Figure 2-47 and Figure 2-48 show regular and thermal images of the fire just as the FFFS was activated.
- The fire was not extinguished by the FFFS because it was inside the vehicle and shielded from the water spray. However, there was significant suppression, and flames were no longer extending out of the vehicle. Figure 2-49 and Figure 2-50 show regular and thermal images of the fire about a minute after the FFFS was activated.
- The FFFS was deactivated after two and a half minutes and the fire brigade extinguished the fire. Refer to Figure 2-51 and Figure 2-52 for regular and thermal images of fire brigade operations. Figure 2-53 and Figure 2-54 show images of the vehicle after the fire had been suppressed.

The design goal of the Sydney Harbor Tunnel suppression system is to provide fire control to mitigate fire spread [Ref 7]. This test provided a demonstration of that function.

Figure 2-45: Sydney Harbor Tunnel live fire and FFFS demo, prior to FFFS activation.

Source: FHWA

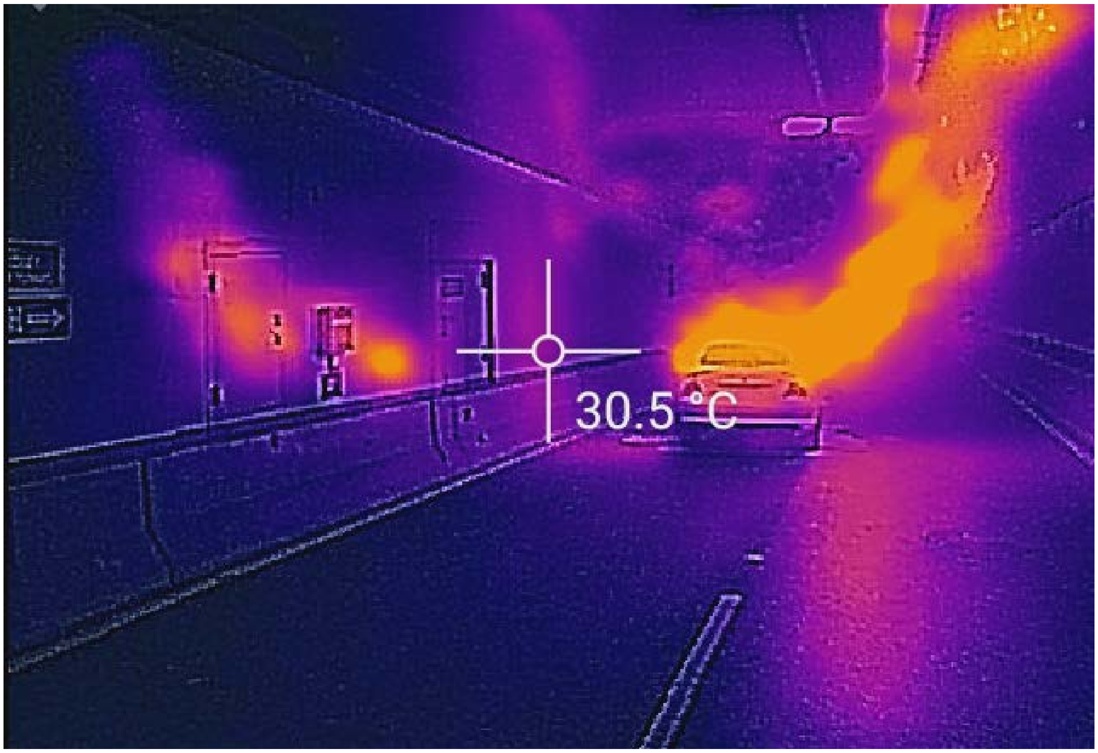

Figure 2-46: Sydney Harbor Tunnel live fire and FFFS demo, prior to FFFS activation, thermal heat map.

Source: FHWA

Figure 2-47: Sydney Harbor Tunnel live fire and FFFS demo at start of FFFS activation.

Source: FHWA

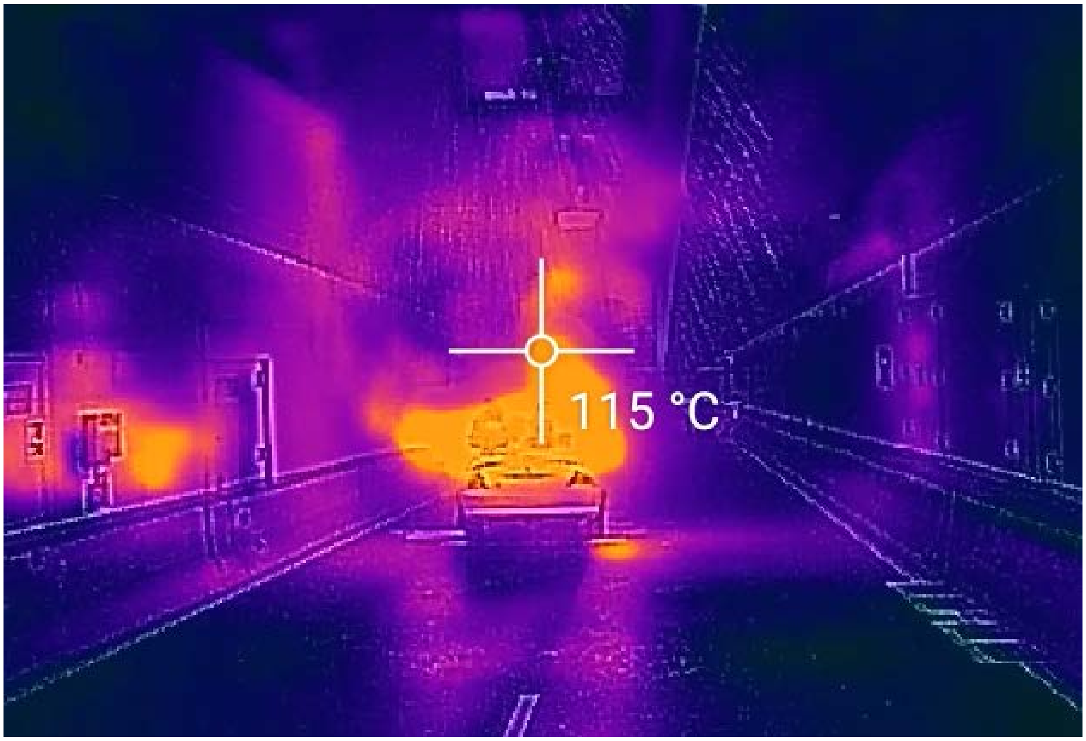

Figure 2-48: Sydney Harbor Tunnel live fire and FFFS demo at start of FFFS activation, thermal heat map

Source: FHWA

Figure 2-49: Sydney Harbor Tunnel live fire and FFFS demo about 1 minute after FFFS activation

Source: FHWA

Figure 2-50: Sydney Harbor Tunnel live fire and FFFS demo about 1 minute after FFFS activation, thermal heat map.

Source: FHWA

Figure 2-51: Sydney Harbor Tunnel live fire and FFFS demo during fire brigade intervention.

Source: FHWA

Figure 2-52: Sydney Harbor Tunnel live fire and FFFS demo during fire brigade intervention, thermal heat map.

Source: FHWA

Figure 2-53: Sydney Harbor Tunnel live fire and FFFS demo, post-test view of vehicle.

Source: FHWA

Figure 2-54: Sydney Harbor Tunnel live fire and FFFS demo, post-test view of vehicle, thermal heat map

Source: FHWA.

2.5.3 Fire Incident Frequency

Fires tend to be rare events, and discussions with operators confirmed this. In the New Zealand Tunnels visited, there were no major fire events to date. Many of the Sydney Tunnels have seen fires occur, though none caused serious injury. One operator mentioned witnessing two fires in an eight-year period at Sydney's Eastern Distributor Tunnel. Based on discussions with operators, the M5 East Tunnel and Sydney Harbor Tunnel have experienced several fires where the FFFS was operated. RMS are currently conducting a study to document fire frequency and FLS system performance in the NSW tunnels.

All Sydney tunnels report a relatively high frequency of over-height vehicle impacts, with many such events occurring every year. The Sydney Harbor Tunnel installed a water curtain stop sign at the portal as a last resort measure to stop over-height vehicles (see Figure 2-55). The water curtain can also be used by tunnel operators as a traffic control measure during a fire emergency.

Figure 2-55: Sydney Harbor Tunnel water stop sign projection.

Source: FHWA

2.5.4 False Activations

False activation of an FFFS is a concern due to the negative impact the system can have on visibility for driving (see Figure 2-36). However, occurrence of such activations is very rare and there is generally an identified cause behind the activation. In all the facilities visited, unintended activation of an FFFS had either never occurred, or, if it had, there was usually a human factor or error at play. None of the accidental activations have caused a serious incident or injury.

One question asked at all facilities was whether the LHD was to blame for any accidental activation. In general, owners and operators stated that if the LHD responds at all in a fire incident, it tends to be late in the event, and operators nearly always discover incidents first with CCTV or AVID systems.

In New Zealand Tunnels, detection by LHD is based on a set temperature and rate of rise. The LHD is not subject to a false alarm unless there is a reason, such as a truck with a diesel generator on the back being parked under the LHD. In one test, the FFFS was accidentally discharged. The system was not isolated, and because of the test, the LHD trip caused a discharge of the FFFS. In one incident in the Victoria Park Tunnel, a drunken person exited a taxi while stopped inside the tunnel, went into the services passage, and activated the FFFS manually.

One tunnel reported that while there have been no false alarms recorded, there have been some infrequent, less than once a year, activations of the FFFS. These activations were attributed to factors such as cross passage maintenance or an accidental operations room activation due to a 'loose click' during an LHD problem investigation.

Naming the zones of the FFFS can lead to accidental activation. When an exercise was being conducted in one of the tunnels and it was closed to regular traffic, the operator accidentally activated a zone in the non-incident tunnel, which was open to traffic. The reason behind the activation was traced back to the same numbering on zones in both bores, and the operator mistakenly activated the bore open to traffic. The activation took place very early in the morning, and the impact on traffic was minor. Naming of the zones was updated because of this incident.

In one tunnel, a portal gate was accidentally deployed and broke a vehicle’s windscreen. The cause was found to be that a slug had worked its way into a motor control box, shorted the circuit, and caused the barrier arm to deploy. Although this is not part of the FFFS, the incident is a good example of how a system intended for safety can unintentionally be deployed and create an unsafe situation.

In conclusion, false activations of FFFSs tend to be rare events. Often, when they are activated, there is usually a need. There will always be some risk of false activations of safety systems, but with good maintenance, regular training, and a “lessons learned” approach, these events are preventable or at worst infrequent.

2.6 Additional Findings and Observations

2.6.1 Project Delivery

Projects in the U.S. tend to be design-bid-build or design-build, such as the Eisenhower-Johnson Memorial Tunnel FFFS retrofit project, or construction manager-general contractor, such as the Twin Tunnels in Colorado. Federal Acquisition Regulations play a major role in the type of project delivery. These methods of delivery, or methods very similar, exist in New Zealand and Australia.

One method of project delivery explored in New Zealand was the alliancing method, which advocates a teaming approach and shared responsibility, liability, and gains. The essence of an alliance project is a “no blame” culture, where the owner, designer and contractor form a team to deliver the project. The team is analogous to a separate company. All parties share in the benefits when the project goes well, and all parties share in the losses if there are problems. The important distinction with this method of project delivery is the “no blame” culture, and in this delivery method, parties are not able to claim against one another. This shifts focus from protection of self-interest, to achieving a “best for project” outcome. Alliance project delivery tends to be most effective on complex projects with significant uncertainty. Figure 2-56 provides a schematic that contrasts alliance project delivery with design-bid-build and design-build project delivery.

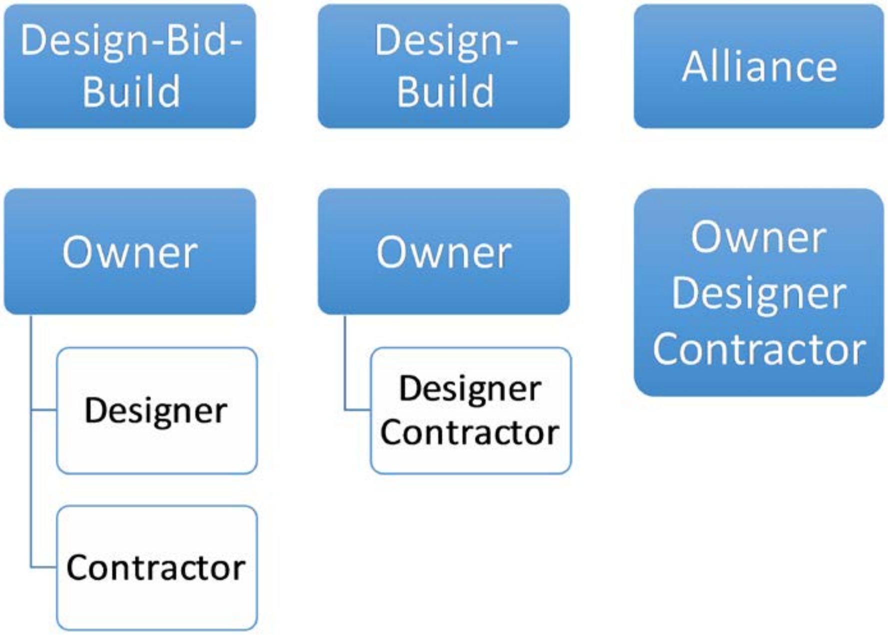

Figure 2-56: Project delivery method comparison.

Source: FHWA

The Victoria Park Tunnel, Waterview Tunnel, and Terrace Tunnel and Mount Victoria Tunnel rehabilitations were all delivered under an alliance project delivery model. The complexity of these projects, coupled with uncertainty in design and cost, made these projects excellent candidates for alliance delivery.

Cost estimation, payments, approach, and scope are developed in three parts on alliance projects in New Zealand:

- Limb 1 - IPAA (Interim Project Alliance Agreement) = scope
- Limb 2 - TOC (Target Outturn Cost) = cost
- Limb 3 - PAA (Project Alliance Agreement) = final scope of work and payment terms

Through discussions, the team learned that alliance projects need careful and experienced management for successful delivery. True and full owner involvement is essential to the success, and staff must be committed to the project by their organizations. Some alliance projects were reported to be quite successful, others less so. The advantage of alliancing is that it provides the owner additional control once the contract is let, while still providing risk protection to the contractor and designer during construction. There is some opinion, expressed in both Australia and New Zealand, that the technology around tunnels has advanced to a point where it is no longer innovative or leading-edge, and innovative contracting methods are not warranted as they once were. In this situation, once an owner has more experience with a certain kind of project, such as tunnel rehabilitation, future projects might be better suited to a more “traditional” delivery method such as design-build. Figure 2-57 provides a useful comparison of different delivery methods. There are dedicated publications that provide more detail on alliance project delivery [Ref 37].

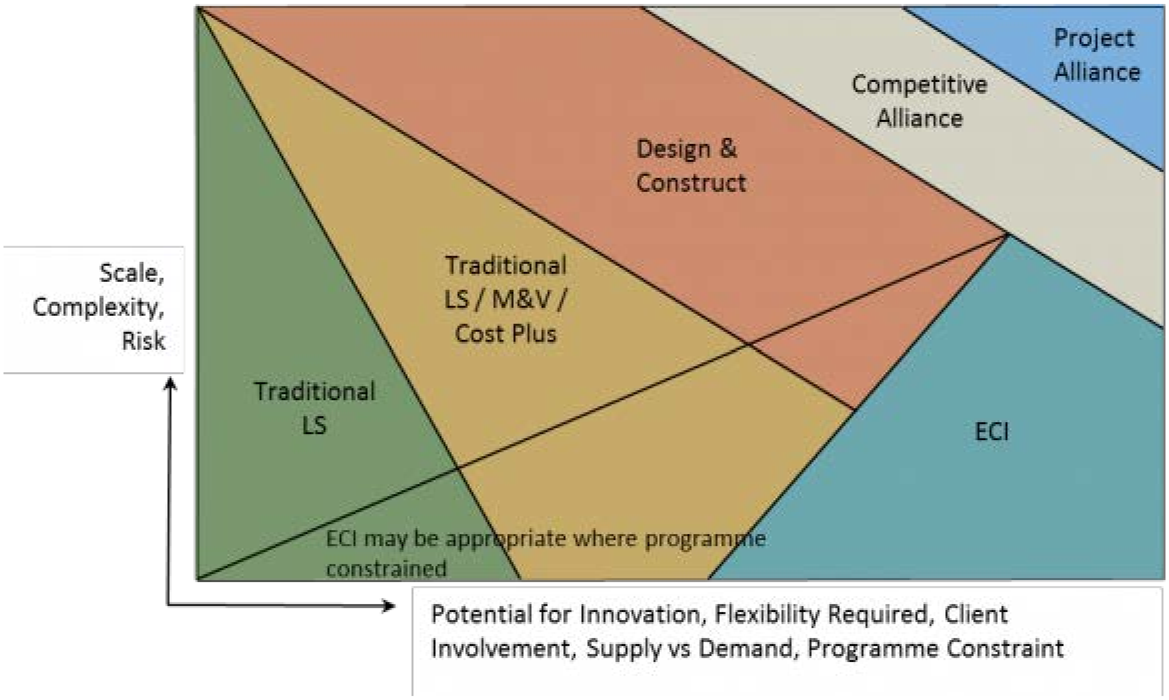

Figure 2-57: Project delivery method guideline with respect to scale and uncertainty.

Source: NZTA

2.6.2 Public Address Systems

In the Arras Tunnel in Wellington, New Zealand and Mount Victoria Tunnel, the NZTA used an innovative public address system. The system uses digital signal processing to introduce a delay between distant speakers, such that the sound waves are timed not to interfere with sound waves originating from other speakers. The system also removes resonant frequencies from the output of the speakers. Resonant frequencies are identified specific to the tunnel geometry. The speakers used are horns (see Figure 2-58) that are mounted flush to a hard surface in the tunnel ceiling. The speakers direct the sound in a focused direction to better control the sound wave interference than would occur from a group of omni-directional sources. It is understood that tunnels in New South Wales, Australia are also starting to adopt this PA system.

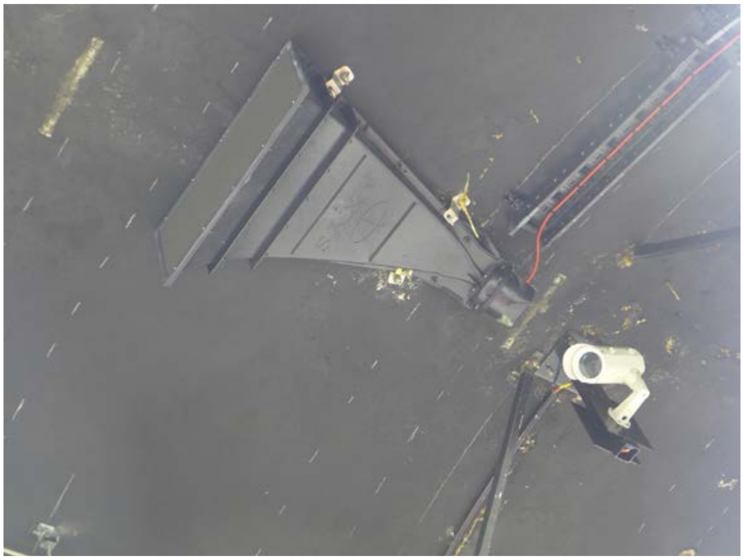

Figure 2-58: Horn speaker example in the Mount Victoria Tunnel

Source: FHWA

2.6.3 Exit Signs

Exit signs were prevalent in all tunnels visited. One notable example is the painting of the tunnel walls with a very large "running man" graphic surrounding the emergency escape doors. This graphic was in addition to the smaller signs directing people to those doors, and distance markers. Figure 2-59, Figure 2-60, Figure 2-61, and Figure 2-62 show some signage examples.

Another feature in several tunnels visited are areas of refuge for evacuees who may have difficulty moving to a safe area, such as to a stairway exit. Figure 2-59 shows a sign for handicapped access at the Waterview Tunnel, and Figure 2-63 shows an area of refuge for wheelchair bound occupants in the Victoria Park Tunnel.

Figure 2-59: Waterview Tunnel exit signage at cross passage egress door.

Source: FHWA

Figure 2-60: Terrace Tunnel with lit directional exit signage on walls.

Source: FHWA

Figure 2-61: Sydney Harbor Tunnel emergency exit signage.

Source: FHWA

Figure 2-62: M2 Tunnel emergency exit signage.

Source: FHWA

Figure 2-63: Wheelchair waiting area in the Victoria Park Tunnel.

Source: FHWA

2.6.4 Lighting

In the Terrace Tunnel and Mount Victoria Tunnel, an innovative lighting feature was used. The device is a LED light powered by induction from a power source buried about two inches down into a concrete curb. Figure 2-64 shows an image of one of the lights. Figure 2-65 shows the effect of the lights in the tunnel. These lights are addressable to the extent that they can be made to blink in sequence to act like an arrow directing the desired direction of egress. The effect is like the lighting on an airport runway approach. The Mount Victoria Tunnel and Terrace Tunnel also employed LED lighting throughout.

2.6.5 Electrical Systems and Redundancy

The tunnels visited by the GBP team were in urban areas and were expected to have reliable and redundant electrical grids. Nonetheless, most facilities had backup generators for life safety systems, and to some degree this included the ventilation system as well.

The Victoria Park Tunnel in Auckland has a generator able to provide full backup power. This was presumably done due to recent history where the city lost all power and because the Victoria Park Tunnel is a critical piece of the transportation infrastructure with no major alternative route. In contrast, the Sydney Harbor Tunnel has backup power supplies sufficient to operate systems to close the tunnel in the event of a major outage, but not enough backup power to continue operation of all major systems. However, the Sydney Harbor Tunnel is in a location where there are major alternative routes.

Figure 2-64: Mount Victoria Tunnel roadway marking lighting and slot for power.

Source: FHWA

Figure 2-65: Mount Victoria Tunnel roadway marking lighting demonstration.

Source: FHWA

2.6.6 Linear Heat Detection

Different LHD options were discussed. Fiber optic, microchip, and LHD technologies are commonly used LHD systems. Practical considerations include the costs of the cable, controllers, and processors, as well as the ease of LHD maintenance and the ability to splice into the cabling network without degrading the signal, such as what would be needed during tunnel rehabilitation or LHD system upgrades.

2.6.7 Cables and Conduit

Tunnels in New Zealand typically do not install cables in conduits. Figure 2-66 shows the arrangement where cable trays and ties are used to mount the cables. In contrast, most U.S. tunnels use conduit for the cables, as shown in Figure 2-67.

Figure 2-66: Cable arrangements in the Mount Victoria and Terrace Tunnel electrical spaces.

Source: FHWA

Figure 2-67: Typical U.S. tunnel cable arrangement with conduit (photo opportunity courtesy of Caltrans).

Source: FHWA

NFPA 502 [Ref 1] provides the following statements in relation to cables:

> *12.3.1 Cables and conductors shall be protected by means of metallic armor/sheath, metal raceways, electrical duct banks embedded in concrete, or other approved methods except as otherwise permitted by 12.3.1.1 or 12.3.1.2.*
>
> *12.3.1.1 Cables and conductors installed in ancillary facilities shall not require additional physical protection as described in 12.3.1 provided that they are installed in a cable tray and are listed for cable tray use.*

The National Electrical Code (NEC) [Ref 38] also provides the following requirements (NEC 708.10.C.1):

> *The wiring of the COPS system shall be protected against physical damage. Wiring methods shall be permitted to be installed in accordance with the following: (1) Rigid metal conduit, intermediate metal conduit, or Type MI cable.*

The different approach between U.S. and New Zealand practice with respect to cable arrangements is based on local interpretation, and perhaps, the NEC. Most electrical facilities in the New Zealand tunnels were provided with gaseous fire suppression and had redundancy in a separate room. Fire rating is a concern, and appears to be based on the hazard specific to the function. For instance, Sydney Harbor Tunnel had cables encased in fire proofing materials in their generator room. Refer to Figure 2-68.

Figure 2-68: Cables coated in fire proofing material, located next to a generator, Sydney Harbor Tunnel.

Source: FHWA

3 OPPORTUNITIES FOR ADVANCING CURRENT U.S. PRACTICE

Several worthwhile practices were identified in Australia and New Zealand that should be considered for implementation in the U.S. These practices are discussed below along with an initial strategy for implementation.

3.1 Training

Action: Develop a training program and qualification framework for tunnel operators.

The Certificate IV training program for tunnel operators, discussed in Section 2.3.2, provides benefits for operators and the agencies that employ them. Through this certification process, tunnel operators have a formal qualification that is recognized in facilities and industries beyond the tunnel where they are employed. Having this qualification gives tunnel operators broader opportunities for development and future employment, and agencies and owners benefit because they have a formal measure of experience and qualification for their staff. One common thread in all the tunnels visited, was reliance on the operator to activate the FFFS and exercise judgment during an emergency. With more formalized training, operators and agencies benefit and the most fundamental objective of protecting the life safety of the public using the tunnel is more effectively achieved.

Implementation of a training program was challenging in Australia and New Zealand and took about six years to formalize. Given the much larger number of state agencies in the U.S., the process could take even longer. In the U.S., implementation could begin at the state level through AASHTO as a voluntary process in response to guidelines developed by the FHWA or AASHTO. The guidelines would establish the core curriculum of the operator training, but leave it to each state agency to customize the program for local jurisdictional practices. Developing a core curriculum at federal level with electives developed specific to states or individual facilities could be one approach. Further review of successful training programs will be needed to decide how rigidly training requirements should be enforced.

3.2 Live Exercises

Action: Conduct periodic live exercises in tunnels and desktop-based exercises to develop operational readiness.

Tunnel operators in Australia and New Zealand regularly conducted exercises in the tunnel involving emergency services agencies. These exercises are desktop-based or occasionally are conducted in the field with members of the public, fire brigade, and, in some cases, a controlled fire.

With or without an FFFS, training and live exercises are of great importance. Training and live exercises are even more important when an FFFS is involved because of the role the operator plays in activating the system. Although actual activation of the FFFS for a live test might appear unnecessary, the exercise allows tunnel operators and emergency services workers to experience the real-feel conditions in the tunnel and control room when the FFFS is operational. When the FFFS is operational, visibility in the tunnel will be reduced and CCTV coverage of the tunnel will likely be obstructed. The experience that all participants obtain from these training exercises better prepares operators and emergency services workers to respond to an actual event. The exercises allow all parties involved to develop and refine procedures, and train staff. Exercises may need to be conducted at regular frequencies to account for staffing changes at a specific facility. Often, this requires annual or semi-annual exercises. Exercises could be integrated into the periodic tunnel inspection process.

3.3 Tunnel Operations Group

Action: Form a tunnel operations group to facilitate better information sharing.

The ATOG was discussed in Section 2.3.5. If not already in place, a similar tunnel operators group should be established in the U.S. Key participants should include staff that supervise the facility operations center and work directly with staff that operate the tunnel. Implementation could be based on a set of objectives and conduct principles. Like the ATOG, meetings could be “closed door” and attendance by invitation only to help establish a more free and open discussion.

3.4 Standards and Guidelines for Tunnel FFFS

Action: Develop an FFFS guideline specific to issues encountered in a road tunnel application of an FFFS.

NFPA standards for FFFSs are already developed, but aimed toward occupied buildings and special storage facilities. Currently, the specific factors and conditions unique to a road tunnel application are not specifically established, these include:

- FFFS application and selection
- FFFS water density rates
- System integration, including CCTV layout, zone identification
- Operational policy (when to activate the FFFS, how to avoid false activations, how to decide when to activate if the traffic is still moving)
- Integration with the tunnel heat detection system
- System commissioning
- Integration with fire brigade operations
- Live exercises involving FFFS operation
- Ventilation integration, and impact of the FFFS on other tunnel systems
- Reliability and maintenance

Guidance on the appropriate approach for most of the above topics is available from the site visit observations reported in Section 2. Guidance on water application rate, which is acknowledged as an area of active research, is discussed further in Section 3.5. NFPA standards could be developed as a stand-alone document, and might eventually form part of a standard such as NFPA 502.

3.5 Water Application Rate

Action: Determine the minimum water application rate to achieve each of the FFFS goals as outlined in NFPA 502.

Water application rate is discussed in Section 2.1.2. NFPA 502 provides definitions of FFFS performance, including fire suppression, fire control, volume cooling, and surface cooling. Presently, FFFS testing has focused on providing sufficient water quantity for control of the fire and has confirmed the water application rates currently used. Given that water volume is a critical parameter that affects many other systems, it would be useful for the industry to know the minimum water application rate necessary to achieve a certain performance goal. If a lower water application rate is possible for meeting FFFS goals, this could pave the way for installation of FFFSs in existing tunnels where space and water capacity are limiting factors. More research, and especially full-scale testing, is needed to quantify FFFS performance relative to water application rate.

3.6 FLS Rehabilitation Guidelines

Action: Develop guidelines specifically focused on FLS provisions and tunnel rehabilitation.

Tunnels in New Zealand have a specific framework around legislative requirements for rehabilitations (see Section 2.1.5). Guideline documents spell out the basic requirements, which include cost-benefit analysis, risk assessment, development of a business case, consideration of “do nothing” as an option, and a clear nomination of the NZTA as the final decision-maker. Often, the risk assessment discusses the challenge of making existing infrastructure comply with modern standards, which may not always be possible.

In the U.S., NFPA 502 does not set specific requirements with respect to the process for FLS system rehabilitation in a road tunnel. Rather, the standard permits modification of requirements by the local AHJ where application of a certain requirement would be impractical. In New Zealand, a process, such as risk assessment or cost-benefit analysis, is identified for the rehabilitation efforts and the AHJ is explicitly nominated.

A similar set guidelines for tunnel FLS rehabilitation, specific to the U.S. could be helpful. These guidelines would cover risk assessment methods, acceptance criteria, AHJ identification, and minimum tunnel operating conditions. The guidelines would also provide a framework for owners to assess whether an FFFS should be retrofitted into a tunnel. Implementation of the guidelines could be progressed through a framework such as the NFPA 502 document, perhaps as an annex, and initially offer project examples. Over a period of several years, this could evolve into a more specific methodology and set of requirements. An AASHTO or ASHRAE group could also be an avenue used to develop guidelines for tunnel FLS rehabilitation.

3.7 Fire Incident Database

Action: Develop a fire incident database specific to road tunnels.

During the site visits, several fire incidents involving an FFFS were observed via video footage provided by tunnel operators (see Section 2.5). These incidents were helpful to better understand real performance and operational nuances. Incident accounts are useful for designers, contractors, and operators because they deepen understanding of the complexities associated with a fire response during an emergency. RMS is currently developing a fire incident database for fires in NSW tunnels. This database, which will initially be historical, will provide a statistical basis to the claimed performance of FLS features in tunnels.

In the U.S., the Federal Emergency Management Agency (FEMA) maintains the National Fire Incident Reporting System (NFIRS) [Ref 39]. Very few tunnel fires occur, and NFIRS captures about 75 percent of all the fires that occur annually in the U.S. [Ref 39]. Because of this, NFIRS does not cover tunnel fires in detail, if at all. NFIRS is more focused on capturing basic information common to any fire, including incident information, fire details, structural fire details, casualty information, emergency medical services aspects, hazardous materials, wildland fire (optional module), apparatus details, personnel, and arson (optional module).

NFIRS has developed a module specifically for wildland fires. Similarly, NFIRS could consider a module specific to road tunnels and operation of an FFFS. This module could collect incident data specific to road tunnels. The data would allow for a better understanding of the issues faced in the field by firefighters, while the focus on road tunnels would provide more in-depth information about the tunnel operator's perspective, system performance, FFFS performance where a system is provided, and motorist behavior.

The implementation strategy for the database could involve NFPA, perhaps initially through NFPA 502, to develop the framework for incident recording. Once the basic framework is in place, it would be necessary to work closely with FEMA and NFIRS to implement the module. Over a period of several years, tunnel fire incident data could be collected to justify and shape future FLS measures and strategies in road tunnels.

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APPENDIX A: Amplifying Questions

The amplifying questions summarize the information that the GBP team set out to explore at commencement of the study.

Fire Suppression Technology in Highway Tunnels

- What technologies and system components (such as sprinkler heads, valves, or fire detection) have proven to be effective?
- What are the important considerations during procurement?
  - Costs?
  - Availability?
  - Proprietary?
- What research, trials, or demonstrations have been conducted?
  - Has the reliability of FFFS systems been evaluated?
  - Has FFFS technology been integrated with other systems such as emergency ventilation?
  - Has FFFS technology been used for structural protection?
- What is the level of industry acceptance for this technology?
- How does the future look for this technology?

Design

- What is the current state of practice? State of the art?
- What is the exposure of designer to risk or litigation?
- Are there guidelines, criteria, codes, or standards for design and application?
- What level of redundancy is recommended?
- What are the potential cost benefits for an integrated FFFS-emergency ventilation system?
- What technologies are most effective when the supply of water is limited at the tunnel facility?

Construction

- What lessons have been learned about deploying this technology in tunnels?
- What are the important points to consider when installing an FFFS in:
  - Newly constructed tunnels?
  - Existing retrofitted tunnels?

Operation

- Has this technology been implemented during an actual fire emergency?
  - Which tunnel(s) used this technology under emergency conditions?
  - How soon was it activated after the event?
  - Was it initiated automatically or manually?

  - How did the system perform?
  - Was data collected during the event?
- What are the different strategies for activating this technology under emergency conditions?
  - Automatic computer algorithm.
  - Tunnel operator by control panel.
- Emergency task force or first responders by:
  - Control panel.
  - Remote controls.

Maintenance and Inspection

- What are the main requirements for long-term maintenance?
- How often are the systems inspected?
- What level of expertise is needed to inspect and test the systems?
- Are there any long-term performance issues with any of the equipment?
- Are measures needed to protect fluids or equipment against freezing in cold weather climates?

APPENDIX B: Team Members

Steve Ernst is a Senior Engineer for Safety and Security in the Federal Highway Administration's (FHWA) Office of Bridges and Structures. He is a registered professional engineer in Virginia and has worked with the FHWA for 33 years, including 9 years as a bridge designer and 20 years as a structural engineer in the FHWA Office of Bridges and Structures. He is currently responsible for bridge technology programs, including policies, procedures, standards and practices related to safety and security in bridge and tunnel engineering.

Steve is the FHWA lead for risk management of critical infrastructure and for interaction with the Department of Homeland Security and other federal agencies on bridge and tunnel security issues. He developed workshops to train engineers to understand and mitigate security threats to highway assets and is involved with research for structural hardening. He led development of the newly published *Bridge Security Design Manual*, and is implementing highway security design guidance and risk management deployment for bridge and tunnel security. He served as liaison to the National Cooperative Highway Research Program (NCHRP) panels investigating fire on bridges, tunnel ventilation and emergency egress for tunnels, and currently serves on the panel developing transportation resilience research.

Steve also served as the FHWA lead for the Blue Ribbon Panel on Bridge and Tunnel Security, co-chair for an FHWA international scan for Underground Structures: Operations, Safety and Emergency Response in Europe, and as a member of the World Road Association's Task Force on Security.

Bill Bergeson is a Senior Tunnel Engineer in the FHWA's Office of Bridges and Structures. Bill is the functional area lead for highway tunnels where he manages a national program that advances strategic goals related to national leadership, system performance, program delivery, and corporate capacity. He also acts as the official liaison to State transportation officials who serve on the National Tunnel Technical Committee. Additionally, Bill works with representatives from the National Academies of Sciences and Engineering, the NCHRP, and the Transportation Research Board on research matters related to tunnels. He also works with technical committee chairpersons from the National Fire Protection Association and the American Society of Heating, Refrigerating and Air-Conditioning Engineers.

As part of his duties, Bill supports specially designated Project Oversight Managers from the Office of Innovative Program Delivery on Projects of Corporate Interest. This allows him to provide consistent high-level technical assistance to facilitate critical engineering decisions. Bill has supported work on multi-billion dollar U.S. highway projects to include the Alaskan Way Viaduct Tunnel, U.S. 58 Midtown Tunnel, East End Tunnel, and the Parallel Shoals Tunnel.

Prior to joining the FHWA, Bill worked in the private sector as a licensed professional engineer where he developed numerous plans, scopes of work, schedules, cost estimates, budgets, and financial plans for high-profile transportation tunnel projects in the U.S. His experience includes working on multi-billion dollar projects with significant tunneling and underground components such as Second Avenue Subway Station Caverns, World Trade Center Transportation Hub, Regional Connector, Cook's Lane Tunnel, Gateway Tunnel, Dulles Corridor Silver Line Tunnel, Caldecott 4th Bore and East Side Access.

Steve Harelson is a Program Engineer for the Colorado Department of Transportation (CDOT) and is responsible for managing the engineering and construction on all state and federal highways in Jefferson, Clear Creek and Gilpin counties in Colorado. These counties, immediately west of Denver, contain the Veterans Memorial Tunnels and the Eisenhower-Johnson Tunnels on Interstate 70, as well as eight smaller tunnels on U.S. 6. Steve was the lead CDOT engineer on the design and construction of the Eisenhower-Johnson fixed fire suppression system that was completed in 2015, and oversaw the widening of the second bore of the Veterans Memorial Tunnel from two lanes to three, completed in 2014. He has served on the American Association of State Highway Transportation Officials (AASHTO) Subcommittee on Bridges and Structures T-20 Tunnel group for the last three years.

Aside from tunnel work, Steve led the team that designed and built a Peak Period Shoulder Lane project on Interstate 70 west of Denver and managed the reconstruction of Colorado Highway 72 in Coal Creek Canyon after it was destroyed in the 2013 Colorado Floods. He has a B.S. in Mechanical Engineering and an M.S. in Civil Engineering. Prior to joining CDOT, Steve was a consulting engineer with experience in Transportation, Residential and Commercial Construction, Water Resources, and Water/Wastewater treatment and transmission systems.

Dan Williams is the Chief Engineer with the Maryland Transportation Authority (MDTA) where he oversees all MDTA's engineering, design, and construction projects with a 6-year budget of $2 billion. Prior to his current position, Dan served as the Deputy Project Manager for the I-95 Express Toll Lanes project ($1 billion project), as the Bridge and Tunnel Manager, Deputy Director of Engineering, and as Director of Engineering. Recent significant projects include the Dehumidification of Suspension Span Cables (first in U.S.), Suspension Span Supplemental Cable, and Tunnel Fan Replacement and Rehabilitation.

For the tunnel fan replacement project, Dan had set the goal to increase the tunnel ventilation capacity from 15 MW to 100 MW. Through many alternatives studies the solution was to increase fan capacity and to use both fresh air and exhaust plenums. He also set his sights on constructing a fire suppression system. Unfortunately, the existing tunnels were found to have significant constructability concerns, limited effectiveness during an event, and a very high cost.

As an active member of the AASHTO Subcommittee on Bridges and Structures, Dan sits on three committees: T-1 Security, T-9 System Preservation and T-20 Tunnels. He actively works with each group to improve safety, to resolve national design or construction challenges, and draft national criteria and design codes. Dan has also participated in many workgroups, committees and expert panels related to tunnels including: the 2011 Boston Central Artery Tunnel Inspection Program Peer Review; development of the FHWA Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual; the National Highway Institute's Tunnel Inspection Requirements, the Specifications for National Tunnel Inventory; and the NCHRP Guidelines for Emergency Exit Signs and Marking Systems for Highway Tunnels (aka, 'Running Man'). Dan has also represented state owners for the development of the National Tunnel Inspection Standards (NTIS).

Dan is a 1998 graduate of the Pennsylvania State University and holds a Bachelor of Science Degree in Civil Engineering.

Matt Bilson is a Senior Supervising Engineer with WSP. His industry expertise is in road and transit tunnel fire safety engineering and ventilation design, and he has over 17 years of experience. Matt has worked on projects involving new tunnel builds and rehabilitation of older tunnels, including projects in Australia, New Zealand, the U.S. and Turkey. Matt's work in Australia and New Zealand involved ventilation and fire-life safety design on several major projects incorporating fixed firefighting systems (FFFS), including the Clem7 Tunnel, Airport Link Tunnel, Northern Busway Tunnel (all in Brisbane), and the Waterview and Victoria Park Tunnels (both in Auckland). Matt's work on these projects provided him with experience at all phases of a project, from initial concept design, analysis and computational fluid dynamics modeling, especially focusing on the interaction of the FFFS with tunnel ventilation, through to witnessing commissioning tests and performance in real fire situations.

Matt was a contributing author of the recently published PIARC (World Road Association) document, Fixed Fire Systems in Road Tunnels: Current Practices and Recommendations. Matt is active in utilizing his industry experience and research skills in the tunnel ventilation and fire-life safety disciplines, with several recent publications on FFFSs and their interaction with tunnel ventilation, structures, and tunnel operations.

Matt is a registered professional engineer in the state of New York. He is graduate of the University of Queensland with an Honors Degree in Mechanical Engineering (1999), and a Doctorate of Philosophy in Mechanical Engineering (2004).

APPENDIX C: SUMMARY OF FACILITIES VISITED AND U.S. TUNNELS WITH AN FFFS

The information in this appendix includes a summary of the salient features of each of the tunnel facilities visited in Australia and New Zealand. A summary of U.S. tunnels using FFFSs is also provided.

C.1 Victoria Park Tunnel

Location	Auckland, New Zealand
Length	1,476 ft (450 m)
Cross section	Cut and cover construction, three lanes wide, 11.5 ft (3.5 m) per lane with a 3 ft (0.9 m) shoulder one side and 1.5 ft (0.5 m) shoulder on the other side, up to 6.2% grade downhill
Tubes	1
Year opened	2012
Year rehabilitated	N/A (new tunnel)
Traffic	Unidirectional traffic, three lanes, steepest grade -6.2%
Urban or rural	Urban
AADT	57,300 vehicles per day (weekday), 4.9% trucks
Vehicles	Cars, trucks and dangerous goods vehicles
Speed	50 mph (80 kph)
Fire detection	Primarily via operations (24/7 operator) equipped with CCTV, linear heat detection system (backup), alarms on doors and cabinets
CCTV	Cameras every 164 ft (50 m), with automatic incident detection
Ventilation (smoke)	Longitudinal using jet fans with portal discharge, design fire is 70 MW, egress passage is pressurized by an independent system
Egress	Pressurized egress corridor running on one side of the tunnel with exits to the portal areas, doors from the tunnel to the passage are provided every 164 ft (50 m)
Communication	Mobile phone support, radio support, phones provided every 164 ft (50 m) for motorist use, PA system
Firefighting	Emergency equipment cabinets every 164 ft (50 m) with fire hose reels and hose connections
FFFS	Yes, deluge system
Zones	82 ft (25 m) long zones, area 3,228 ft^2 (300 m^2), designed for two active at one time, covering roadway width, one zone over the fire and one zone upstream
Water application	0.25 gpm/ft^2 (10 mm/min)
Tanks	Provided
Other	No additional additives to the water
Power	UPS for critical systems, standby generator provided for critical systems such as ventilation
Remarks	Dangerous goods vehicles allowed to use to the tunnel based on a risk assessment that concluded that the risks are not substantially different for this tunnel versus rerouting the vehicles to surrounding roads
	The tunnel is provided with passive fire protection on the structure to enable it to withstand a temperature up to 2,462 deg F (1,350 deg C, RWS curve)

C.2 Waterview Tunnel

Location	Auckland, New Zealand
Length	8,200 ft (2,500 m)
Cross section	Bored tunnel, tunnel boring machine, circular, 42.9 ft (13.1 m) internal diameter, 29.2 ft (8.9 m) from roadway to crown, grade up to 5%
Tubes	2
Year opened	2017
Year rehabilitated	N/A (new tunnel)
Traffic	Unidirectional, up to three lanes in each direction, traffic management devices provided (ITS, portal barriers, radio rebroadcast, LUSs, over height vehicle detection), heavy goods vehicles at around 8%, no dangerous goods
Urban or rural	Urban
AADT	83,000 vehicles per day (expected by 2026)
Vehicles	Cars, trucks, no dangerous goods vehicles
Speed	50 mph (80 kph)
Fire detection	Primarily via operations (24/7 operator) equipped with CCTV and incident detection, linear heat detection system (backup), alarms on doors and cabinets
CCTV	Cameras every 197 ft (60 m) with automatic incident detection
Ventilation (smoke)	Longitudinal using jet fans with portal exhaust (portal emissions allowed subject to meeting external air quality criteria), design fire is 50 MW, cross passages pressurized withe tunnel ventilation strategy
Egress	Cross passages every 492 ft (150 m), directional exit sounders, lights, PA, wheelchair standing areas, strobes
Communication	Mobile phone support, radio support, phones in cross passages to reach the operator
Firefighting	Hose connections every 164 ft (50 m)
FFFS	Yes, deluge system
Zones	98 ft (30 m) long zones, maximum area 3518 ft^2 (327 m^2), designed for three active at one time, covering roadway width
Water application	0.25 gpm/ft^2 (10 mm/min)
Tanks	Provided
Other	No additional additives to the water
Power	Dual feed
Other remarks	Fire rated construction uses polypropylene fibers in the concrete, no reliance on the FFFS
	Flame traps on drainage
	Foam suppression system in low point sump

C.3 Terrace Tunnel

Location	Wellington, New Zealand
Length	1,510 ft (460 m)
Cross section	Arch (roadheader construction)
Tubes	1
Year opened	1978
Year rehabilitated	2010-2012
Traffic	Two northbound lanes, one southbound lane 3% grade with 1476 ft (450 m) radius curve at the north portal Signal intersection near the south portal, sometimes causes congestion in the southbound lane
Urban or rural	Urban
AADT	44,000 vehicles per day
Vehicles	Mostly cars, some trucks (about 3%)
Speed	50 mph (80 kph)
Fire detection	Linear heat detection, CCTV
CCTV	Provided, automatic incident detection included
Ventilation (smoke)	Eight jet fans at 480 lbf (2135 N) per fan, 246 ft (75 m) apart
Egress	Via portals
Communication	Radio rebroadcast, PA
Fire standpipe	Provided
FFFS	Deluge system at 0.16 gpm/ft^2 (6.5 mm/min)
Power	Dual 11 kV supply at each end

C.4 Mount Victoria Tunnel

Location	Wellington, New Zealand
Length	2,044 ft (623 m), 1.8% gradient
Cross section	16.4 ft (5 m) high, arch construction
Tubes	1
Year opened	1931
Year rehabilitated	Circa 2010-2012 (stage 1 NZD 14.5M, stage 2 NZD 25M)
Traffic	One lane in each direction
Urban or rural	Urban
AADT	39,000 vehicles per day, with 1.8% trucks
Vehicles	Cars, pedestrians and cyclists (elevated walkway), trucks (about 1.8%)
Speed	31 mph (50 kph)
Fire detection	Linear heat detection
CCTV	Provided, with automatic incident detection (PTZs + AVIDs)
Ventilation (smoke)	Transverse (supply and exhaust), exhaust fan plant located on top of tunnel on Mount Victoria, supply fan plant located near portals, capacity per exhaust fan 83 kcfm (39 m^3/s), supply fans 64 kcfm (30 m^3/s)
Egress	Via portals
Communication	PA and radio-rebroadcast
Fire standpipe	None, connections 98 ft (30 m) from portals (hydrants along walkway at about 197 ft (60 m) centers)
FFFS	Provided, 0.16 gpm/ft^2 (6.5 mm/min), 21 zones, water from town supply
Power	11 kV feed at each end (175 kVA typical)

C.5 M2 Tunnel

Location	Sydney, Australia
Length	1,510 ft (460 m)
Cross section	Roadheader, arch construction, sufficient for three lanes of traffic, 11.5 ft (3.5 m) wide each with 8.2 ft (2.5 m) wide breakdown lane, 1.6 ft (0.5 m) median shoulder and 2 ft (0.6 m) protected walkway
Tubes	2
Year opened	1997
Year rehabilitated	2011 – 2013, widening from two lanes in each direction to three lanes
Traffic	Unidirectional, tunnel includes tunnel closure system with VMS, signals, gates, three lanes of traffic in each direction
Urban or rural	Urban
AADT	96,000 vehicles per day, with 3% trucks
Vehicles	Cars, trucks, no dangerous goods vehicles
Speed	50 mph (80 kph)
Fire detection	LHD
CCTV	CCTV with automatic incident detection
Ventilation (smoke)	Longitudinal using jet fans, six pairs of jet fans per tube
Egress	Cross passages every 394 ft (120 m)
Communication	Radio broadcast, electronic message boards
Fire standpipe	Fire extinguishers, fire hydrants and hose reels located every 197 ft (60 m),
FFFS	Yes, deluge system
Zones	98 ft (30 m) long zones
Water application	0.25 gpm/ft^2 (10 mm/min)
Tanks	Two tanks, 92,460 gal (350,000 L) each
Remarks	Rehab/widening took place while traffic could use the tunnels

C.6 Sydney Harbor Tunnel

Location	Sydney, Australia
Length	7,544 ft (2,300 m)
Cross section	Combination of arch construction with overhead duct and immersed tube (8 segments each at 394 ft (120 m) long)
Tubes	2
Year opened	1992
Year rehabilitated	N/A
Traffic	Unidirectional
Urban or rural	Urban
AADT	103,000 vehicles per day
Vehicles	Cars, trucks at 3% to 4%
Speed	50 mph (80 kph)
Fire detection	CCTV, heat detector above each lane every 49 ft (15 m), traffic loops in roadway
CCTV	Yes, provided throughout with video smoke detection
Ventilation (smoke)	Semi-transverse ventilation system, designed for a 50 MW fire
Egress	Cross passages every 394 ft (120 m)
Communication	Radio rebroadcast and break-in, advisory message signs, emergency telephones every 197 ft (60 m)
Firefighting	Hydrants, hose reels and portable fire extinguishers every 197 ft (60 m)
FFFS	Yes, deluge system
Zones	98 ft (30 m) long zones, manually operated from control center
Water application	0.25 gpm/ft^2 (10 mm/min) amounting to 1141 gpm (4,320 L/min) water supply rate
Tanks	Mains water supply used
Materials	Galvanized steel water main

C.7 M5 East Tunnel

Location	Sydney, Australia
Length	12,960 ft (3,950 m)
Cross section	15 ft (4.6 m clearance), two lanes of traffic, grades generally less than 4%, however, the grade at the western end is 8%
Tubes	2
Year opened	2001
Year rehabilitated	N/A (duplication project is underway)
Traffic	Unidirectional
Urban or rural	Urban
AADT	100,000 vehicles per day, 78% cars and 8% to 9% trucks
Vehicles	Cars, trucks, no dangerous goods vehicles
Speed	50 mph (80 kph)
Fire detection	LHD (detection primarily by the operator)
CCTV	CCTV with 24-hour monitoring, incident detection
Ventilation (smoke)	Longitudinal using jet fans with mid-tunnel exhaust/supply and near portal cross over ventilation plant (to prevent portal emissions). There is also a filtration plant but it is not currently operated. Cross passage pressurization provided.
Egress	Cross passages every 394 ft (120 m)
Communication	Phones located every 197 ft (60 m), PA, radio broadcast, electronic message boards
Fire standpipe	Fire extinguishers, fire hydrants and hose reels located every 197 ft (60 m)
FFFS	Yes, deluge system
Zones	98 ft (30 m) long zones
Water application	0.25 gpm/ft^2 (10 mm/min)
Tanks	Provided, Arncliffe = 75,289 gal (285,000 L), Bexley = 184,920 gal (700,000 L)

C.8 U.S. Tunnels with an FFFS

Tunnel	Alaska Way Tunnel	Midtown Tunnel	Port of Miami Tunnel	Doyle Drive Tunnels	Eisenhower-Johnson Memorial Tunnel
Location	Seattle, WA	Norfolk, VA	Miami, FL	San Francisco, CA	Dillon, CO
Year opened	Under construction	2016	2014	2015	1979
Length	9,800 ft (2,988 m)	4,054 ft (1,236 m)	4,200 ft (1,280 m)	750 ft (229 m), 790 ft (241 m), 920 ft (280 m), 1,030 ft (314 m)	8,940 ft (2,726 m)
Bores	1, two level	1	2	4 tunnels (2 in each direction)	2 bores
Rehab	N/A	N/A	N/A	N/A	FFFS installed 2016
Traffic	Unidirectional, 2 lanes in each direction	Unidirectional, 2 lanes	Unidirectional, 2 lanes per bore	Unidirectional, 3 to 4 lanes per bore	Unidirectional, 2 lanes per bore, large percentage of trucks, mountain tunnel
AADT	-	40,000	7,000	-	34,000
Speed	50 mph (80 kph)	45 mph (72 kph)	35 mph (56 kph)	65 mph (105 kph)	50 mph (80 kph)
Ventilation	Jet fans, point exhaust	Jet fan, longitudinal	Jet fan, longitudinal	Jet fan, longitudinal	Transverse
Water application	0.30 gpm/ft^2 (12 mm/min)	0.15 gpm/ft^2 (6 mm/min)	0.20 gpm/ft^2 (8 mm/min)	0.20 gpm/ft^2 (8 mm/min)	0.16 gpm/ft^2 (6.5 mm/min)
Urban or rural	Urban	Urban	Urban	Urban	Rural, mountain pass tunnel
Egress	Egress passage, doors spaced at 650 ft (198 m)	Pressurized passage, doors spaced at 500 ft (152 m)	Cross passages, 650 ft (198 m) spacing		Cross passages

The table below of tunnels in the U.S. (and Canada) was adapted from NFPA 502 [Ref 1].

Tunnel	**Battery Street**	**I-90 First Hill Mercer Island**	**Mount Baker Ridge**	**CANA Tunnel**	**I-5 Tunnel**	**George Massey Tunnel**	**East End Tunnel**
Location	Seattle, WA	Seattle, WA	Seattle, WA	Boston, MA	Seattle, WA	Vancouver, BC	Louisville, KY
Year opened	1952	1989	1989	1990	1988	1959	2016
Length	2,200 ft (670 m)	3,000 ft (914 m)	3,500 ft (1,067 m)	1,540 ft (470 m) (NB), 900 ft (274 m) (SB)	547 ft (167 m)	2,067 ft (630 m)	2,000 ft (610 m)
Bores	2	3	3	1	1	2	2
Rehab	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Traffic	4 lanes	8 lanes	8 lanes	3 lanes	12 lanes	4 lanes	2 lanes
FFFS	Deluge	Deluge, foam	Deluge, foam	Deluge, foam	Deluge, foam	Sprinklers	
Water application	0.15 gpm/ft^2 (6 mm/min)						

APPENDIX D: Desk Review Report

This appendix provides a selection of materials from the desk review report that are not covered in the field visit report. Topics covered include the following:

- Highway tunnel FFFSs
- Codes and standards
- Design approaches and guidelines
- Incidents involving an FFFS
- Fire science – testing and analysis
- Other perspectives (fire brigade and insurance industry)
- Global perspectives
- Conclusions and recommendations

D.1 Highway Tunnel Fixed Fire Fighting Systems

Per the World Road Association (PIARC), the term *FFFSs refers to a range of technologies that use water as the suppression agent, or water with an additive or some other extinguishing agent. These systems are installed as part of the tunnel infrastructure and require no additional elements to be added when called upon to fight fires. As such, these systems are part of the fixed installation, having been installed for the specific purpose of controlling a fire incident over a specific area and are activated automatically, semi-automatically, or manually from a remote location* [Ref 3]. This same definition applies to the term "FFFS" within the current report.

Common FFFSs include deluge or water mist systems. The two systems are fundamentally similar in that a series of pipes, valves, pumps, and nozzles are used to provide zoned application of water to target a fire. The primary difference between the two systems is the size of water droplet; water mist systems use a smaller droplet size than deluge systems. The smaller droplet size used in a water mist system means that these systems use less water. Both deluge and water mist systems have certain performance features, advantages, and disadvantages.

Less common FFFSs are foam suppression systems and sprinkler systems. Foam systems are like a deluge system, except that a foaming agent is added to the water. Sprinkler systems that use a frangible bulb sprinkler head for activation, as opposed to a valve with open nozzles, also exist. However, these types of systems are less workable in a road tunnel since heat and smoke can quickly travel long distances in a tunnel. This results in many sprinkler heads activating and has the potential to exhaust the water supply [Ref 40]. Foam systems and sprinkler systems are not considered further in this report.

PIARC also states that *a properly designed, installed, integrated, commissioned, maintained, tested and operated FFFS will* [Ref 3]:

- *Provide early suppression and control of a fire event*
- *Retard the fire growth rate, thereby inhibiting the combustion process and reducing the heat output*
- *Remove heat from the environs of the fire by cooling the surrounding area during an incident*
- *Limit the potential for fire to spread between vehicles*

- *Extend the available escape time for tunnel users*
- *Improve overall tenability for fire fighters, enabling them to respond to the event more effectively*
- *Reduce the likelihood and extent of structural damage such as spalling and local collapse*
- *Limit the severity and extent of damage to tunnel systems and equipment*
- *Allow the asset to return to service in a shorter period of time following a fire*
- *Restore the external road network to full integrity in a shorter period of time following a fire*

D.2 Codes and Standards

There is a wide variation of codes and standards addressing the topic of FFFS application in road tunnels. Information on codes and standards of countries at the forefront of FFFS use, both domestic and international, are summarized in this section.

D.2.1 NFPA 502

NFPA Standard 502 is the North American standard for road tunnel fire protection and fire-life safety design [Ref 1]. The standard covers road tunnels, bridges, and other limited access highways. The standard sets out minimum requirements for fire-life safety provisions including, but not limited to, ventilation, egress, lighting, electrical (power), signage, traffic control, fire standpipe, FFFSs, and incident management plans. To be enforced as a legal requirement, NFPA 502 must be adopted by the AHJ. This is typically done through a fire code or on a project-by-project basis.

NFPA 502 divides tunnels into different categories depending on their length and the volume of traffic. Requirements for an FFFS vary with tunnel length and are described below.

- Category X, tunnel length less than 300 ft (91 m), an FFFS is not required
- Category A, tunnel length more than 300 ft (91 m), an FFFS is not required
- Category B, tunnel length more than 800 ft (244 m), an FFFS is not required
- Category C, tunnel length more than 1,000 ft (305 m), an FFFS is a conditionally mandatory requirement
- Category D, tunnel length more than 3,280 ft (1000 m), an FFFS is a conditionally mandatory requirement

When a requirement is listed in NFPA 502 as conditionally mandatory, it is a requirement to be based on the results of an engineering analysis. An engineering analysis evaluates all factors that affect the fire safety of a facility or a component of a facility [Ref 1]. The scope and ultimate acceptance of an engineering analysis is determined by the AHJ.

One area where an FFFS is more explicitly recognized in NFPA 502 is the demonstration that it creates a tenable environment for egress (Clause 7.16.2), specifically in the case where heavily congested traffic is likely. For this case, Clause 7.6.2(3) of NFPA 502 provides guidance:

> *7.6.2(3) Means shall be provided downstream of the incident site to expedite the flow of vehicles from the tunnel. If it is not possible to provide such means under all traffic conditions, then the tunnel shall be protected by a fixed water-based firefighting system or other suitable means to establish a tenable environment to permit safe evacuation and emergency services access.*

This above requirement could be met by providing one of, or a combination of, the following [Ref 41]:

- **Traffic control and longitudinal ventilation.** During an incident, vehicles upstream of the fire are protected by ventilation. Traffic control enables downstream vehicles to exit the tunnel.
- **Closely spaced egress and longitudinal ventilation**. During an incident, occupants only need to move a short distance to reach a point of safety. The maximum exit spacing allowed is 984 ft (300 m) (NFPA 502 Clause 7.16.6.2).
- **Smoke exhaust.** During an incident, occupants are in a tenable environment except in the region of the extraction points near to the fire.
- **FFFS.** Provide an FFFS and longitudinal ventilation such that vehicles downstream are in tenable conditions during the incident.

Chapter 9 of NFPA 502 outlines the design elements for an FFFS in a road tunnel. It includes topics such as performance requirements and objectives, performance evaluation (such as fire test protocols), impacts on other safety measures, tunnel parameters, system design and installation requirements, and engineering design requirements. Other applicable NFPA standards are also referenced for further compliance requirements, these include NFPA 13 Standard for Installation of Sprinkler Systems and NFPA 25 Standard for the Inspection, Testing and Maintenance of Water-Based Fire Protection Systems.

Annex E of NFPA 502 provides a summary of FFFSs in road tunnels. It includes background on NFPA 502, the evolution of requirements for FFFSs, a summary of U.S. tunnels using FFFSs, and a short summary of international practice in Australia, Japan, and Europe. Factors to consider in the design of an FFFS are explained in detail and the more significant international test programs, such as full-scale fire tests, are briefly discussed.

D.2.2 New York City Fire Code 2014

The New York City Fire Code 2014 Edition recognizes road tunnels and specifically cites NFPA 502 2011 Edition [Ref 42]. With respect to the requirement for an FFFS, the code makes the following modifications to NFPA 502:

- Category X, A, and B tunnels, tunnel length up to 1,000 ft (305 m), requirement for an FFFS changes from non-mandatory to conditionally mandatory.
- Category C and D tunnels, tunnel length more than 1,000 ft (305 m), requirement for an FFFS changes from non-mandatory (Category C) and conditionally mandatory (Category D) to mandatory.

There are no tunnels in New York City that presently have an FFFS installed.

D.2.3 City of Seattle Fire Code

The City of Seattle Fire Code 2012 Edition [Ref 2] recognizes road tunnels and specifically cites NFPA 502 2011 Edition. The code modifies NFPA 502 to require an FFFS in road tunnels in accordance with NFPA 13 Extra Hazard Group 2, which refers to moderate to places with high combustibility contents such as libraries or post offices. NFPA 13 notes that Extra Hazard, Group 2 occupancies are areas *with moderate to substantial amounts of flammable or combustible liquids or occupancies where shielding of combustibles is extensive* [Ref 8].

Extra Hazard, Group 2 sprinklers must provide a water delivery rate 0.30 gpm/ft^2 (12 mm/min) for an area of coverage of 5,000 ft^2 (465 m^2) [Ref 8]. This water application rate tends to be at the high end of the design application rates used in Japan and Australia, which typically use application rates between 0.15 gpm/ft^2 (6 mm/min) and 0.25 gpm/ft^2 (10 mm/min).

D.2.4 Australia and New Zealand Codes

The Australian standard for tunnel fire safety, AS 4825, was first published in 2011 [Ref 17]. The standard covers road, rail, and bus tunnels. It was the first Australian standard on tunnel fire safety. AS 4825 requires an FFFS if the tunnel is greater than 394 ft (120 m) long. It also requires redundant water supply sources be present.

Austroads published a guideline to road tunnel planning, design, and commissioning in 2010, prior to the release of AS 4825 [Ref 18]. The Austroads guide notes that AS 4825, when released, would be the basis for their guideline's FLS requirements. In New Zealand, a supplement to the Austroads guideline is also provided [Ref 21]. The supplement notes that a tunnel less than 263 ft (80 m) in length is not considered a tunnel for imposing system requirements. If the tunnel is between 263 ft and 787 ft long (80 m and 240 m), an engineering assessment is required. If the tunnel is more than 787 ft (240 m) long, then all requirements apply [Ref 21]. In general, this document defers to AS 4825 regarding fire safety features required.

In many instances, the requirements for a tunnel's FFFS are included in the project contract documents. In the state of New South Wales in Australia, this document is referred to as the Scope of Work and Technical Criteria.

D.2.5 Directive 2004/54/EC of the European Parliament and of the Council (EU 54)

European Directive EU 54 sets out the minimum requirements for road tunnel safety in the European Union [Ref 43]. The directive was designed for both new and existing tunnels. Minimum safety requirements cover factors such as emergency exits, drainage, lighting, structural fire resistance, ventilation, emergency stations (phones and extinguishers), signage, control center, cameras, traffic control, and communications. FFFSs are not recognized in the document, but their beneficial effects can be accounted for through risk analysis. EU 54 applies to tunnels 1,640 ft (500 m) or longer.

Most road tunnels in Europe do not currently have an FFFS. However, over the past several years, FFFSs have been implemented in several tunnels. Tunnels in Europe that use an FFFS are now found in several nations, and it is notable that several of these new systems are water mist type [Ref 3]:

- **UK.** Dartford (water mist), Tyne (water mist)
- **Spain.** Calle 30 (Madrid, water mist), De Vielha (deluge)
- **Netherlands.** Roertunnel (water mist), Swalmen (water mist)
- **Finland.** Helsinki City Service Tunnel (water mist)
- **Austria.** Mona Lisa (water mist), Felbertauren (water mist)
- **France**. A86, Paris (water mist)

D.2.6 Japanese Codes

Several Japanese guidelines exist for tunnel fire safety, including MOLIT (2001), JH (1998), MEPC (1993) and HEPC (1996) [Ref 6]. These documents are all in Japanese and a review report was relied on for the account provided herein [Ref 6]. FFFSs were not required in Japanese road tunnels when the first guidelines for fire safety were published in 1967 (JH), but the possibility of a sprinkler in a tunnel was recognized [Ref 6]. After a serious fire in the Nihonzaka Tunnel in 1979 caused seven fatalities and 173 burnt out vehicles, the number of safety features in the JH guidelines was increased from four to 13 [Ref 6]. However, it is not clear exactly when specific FFFS requirements were introduced.

FFFSs are recommended for Japanese road tunnels if the length and vehicle characteristics (number, type) exceed certain limits. The minimum tunnel specification for consideration to include in an FFFS (MEPC guide) is a length of 984 ft (300 m) and 40,000 vehicles per day per tube, up to a length of 3,281 ft (1,000 m) and 40,000 vehicles per day per tube [Ref 6]. For tunnels with fewer vehicles, an FFFS is compulsory if a tunnel is more than 3,281 ft (1,000 m) long with 40,000 vehicles per day per tube, or more than 6.2 miles (10,000 m) long with 4,000 or fewer vehicles per day per tube [Ref 6].

Typical FFFSs in Japan use a 164 ft (50 m) long zone with up to two zones simultaneously operating. The application density is about 0.15 gpm/ft^2 (6 mm/min). FFFSs are generally not automatically activated, and the operator must first confirm that there is a fire and its location [Ref 6]. The goal of the FFFS in Japanese tunnel applications is not to extinguish the fire, but to provide fire control and facilitate firefighter operations.

D.3 Design Approaches and Guidelines

Like codes and standards, there is a wide variety of design approaches and guidelines used in the installation of FFFSs in road tunnels. This section provides information on design approaches and guidelines in countries that are in the forefront of FFFS use, both domestically and internationally. It covers topics such as system performance, coverage criteria, water application rates, and typical system components. Various design approaches are briefly discussed by way of application examples.

D.3.1 World Road Association (PIARC)

The World Road Association, known as PIARC in the industry, is a nonprofit organization whose mission is to improve international cooperation and foster progress in the field of roads and road transport. PIARC Technical Committee C.3.3 Road Tunnel Operations is formed from a global group of participants. Over a period spanning several years, PIARC has produced several reports on road tunnel fire safety including the use and application of FFFSs in road tunnels.

Historically, the PIARC organization was not always in favor of providing FFFSs in road tunnels. As recently as 1999 the position of PIARC was that *sprinklers cannot be considered an equipment to save lives…used to protect the tunnel once evacuation is completed…are generally not considered as cost effective and are not recommended in usual road tunnels* [Ref 44]. The reasons for this recommendation were varied and included the following [Ref 44]:

- *Water can cause explosion in petrol and other chemical substances if not combined with appropriate additives*
- *There is a risk that the fire is extinguished but flammable gases are still produced and may cause an explosion*
- *Vaporized steam can hurt people*
- *The efficiency is low for fires inside vehicles*

- *The smoke layer is cooled down and de-stratified, so that it will cover the whole tunnel*
- *Maintenance can be costly*
- *Sprinklers are difficult to handle manually*
- *Visibility is reduced*

The cooling potential of an FFFS and the mitigation of hazards was acknowledged in the report. One other factor mentioned was that *most fires start in the motor room or in the compartment, and sprinklers are of no use till the fire is open… sprinklers can be used, however, to cool down vehicles, to stop the fire from spreading to other vehicles* [Ref 44]. Because of these factors, the minor impact on life safety goals, and the relatively low effectiveness due to shielded conditions, the PIARC position was to not recommend including FFFSs in road tunnels.

From 1999 to 2016, several major fire events occurred. These include the fires in the Mont Blanc Tunnel (1999), Saint Gotthard Tunnel (2001), and Frejus Tunnel (2005). These fire incidents resulted in multiple casualties and substantial damage to the tunnel structure. The events contributed to PIARC's reconsideration of the potential for FFFSs to provide improved fire safety in road tunnels. Over the next 10 to 15 years, research programs were initiated to better understand the physics of FFFSs operating in road tunnel fires. Eventually, PIARC shifted its position on FFFSs, stating that an owner or operator could install an FFFS subject to verification that the system contributes to overall safety [Ref 45]. Testing conducted in the following years, as well as real incident accounts, demonstrated that concerns related to vaporized steam were not warranted [Ref 3, Appendix 4]. PIARC reports in 2008 concluded that FFFSs are one of many systems available to improve user safety and infrastructure protection, but that the decision on whether FFFSs are appropriate should include verification of the FFFS's applications and the effective value [Ref 46].

The 2016 PIARC report recognized that FFFSs *are increasingly seen as a method that can deliver user safety and infrastructure protection, and can be used as a risk reduction measure* [Ref 3]. The report also noted that *FFFSs may not be the most appropriate measure to adopt in all circumstances or all locations*. The 2016 report was developed *to help provide decision makes and designers with an understanding of FFFSs and to provide guidance on whether to include FFFSs in a road tunnel*. The report is divided up into sections as follows:

1. Introduction
2. Previous work
3. Decision factors
4. Design considerations
5. System definition and procurement
6. Research and analysis
7. Conclusions and recommendations
8. Appendices (global inventory of tunnels that include FFFS, summary of FFFS testing)

Section 3 of the 2016 PIARC report, *Decision Factors*, identifies topics to be addressed when considering installation of an FFFS [Ref 3]. It includes the following:

- **Standards and compliance.** A varying global approach exists regarding whether FFFSs are required. Only Australia and Japan are mentioned as locations that require an FFFS.
- **Risk assessment**. Risk assessment is acknowledged as a tool to understand the level of safety in a tunnel, and a key point raised is that FFFSs do not make a tunnel safe and not

including an FFFS does not make a tunnel unsafe. This is particularly clear in NFPA 502, which recognizes FFFSs, but also allows for a design to provide occupant and fire fighter safety through various means, such as a ventilation and traffic management.

- **Life safety.** Groups for life safety considerations include the tunnel users, operations staff, emergency services, and people external to the tunnel. A key point is that the FFFS can reduce fire growth rate and temperatures, but untenable conditions are still typical near the fire with or without the FFFS.
- **Asset protection.** The Burnley Tunnel incident (see Section D.4.1) shows how FFFSs can reduce damage to tunnels and enable tunnels to be reopened sooner following a major incident. Some tunnels have included an FFFS as a compensatory measure, and in these cases reliability of the FFFS is important.
- **Traffic regimes.** For situations where congested traffic is likely or there is a need to transport dangerous goods, FFFSs are a potential advantageous feature to offset risks.
- **Firefighting.** The benefits of FFFSs for firefighting are significant. If operated properly, an FFFS can make firefighting much safer as the fire will not escalate. However, there are important operational considerations to be considered (see Section D.6.1).
- **Operations and maintenance.** This is a key component in the decision to install an FFFS. Installation should only be considered if the tunnel owner can maintain and operate the FFFS.
- **Cost versus benefits.** Studies have shown that FFFSs have limited or comparable cost effectiveness compared with other safety features such as ventilation, egress, and traffic management [Ref 41]. Considerations here are that replacement of many components is needed every 20 to 30 years, and an FFFS cannot be cost effective in this situation. However, a stakeholder may advocate for inclusion because an FFFS can limit fire severity, and because of the public perception of benefits and risk mitigation. In the future, insurance rates might be reduced because of inclusion of an FFFS (refer to Section D.6.2).
- **Sustainability.** An approach is referenced that shows how an FFFS may contribute to reduce consumption when considering whole life cost and the impact of incidents.
- **Legal factors.** Two legal factors are part of the decision process to install FFFS. The first is in the context of an incident. The second is if an FFFS was included, whether the systems were properly designed, operated, and maintained for the design event.

Section 4 of the 2016 PIARC report, *Design Considerations,* discusses specific design criteria, assuming the decision to install an FFFS has been made [Ref 3]. It covers the following topics:

- **Design fire and objectives.** Objectives can include suppression (sustained reduction in the FHRR), control (minimization of the peak FHRR), and thermal exposure reduction (cooling the surrounding environment). NFPA 502 adopts similar terms, except that thermal exposure reduction is separated into volume cooling and surface cooling. The performance required from the system, and the water application rate, will depend on tunnel design fire characteristics such as large heavy goods vehicle, cars, or buses.
- **Types of systems.** Systems typically employed include water mist (small droplet, low volume of water, water is evaporated to cool the surroundings and reduce heat feedback to reduce the FHRR) and deluge (larger droplet, higher volume of water, water tends to

reach the seat of the fire to achieve FHRR reduction). Further discussion about deluge and water mist is provided in Section D.3.4.

- **Water application rate.** This is related to the type of system, design fire, and objectives. There is no universal method to determine the water application rate, and a combination of experience, testing, and analysis is used. Refer to Section D.3.5 for further discussion.
- **Water supply.** There must be suitable pressure and supply volume available to meet water application rate demands. A typical deluge system can require 1,300 gpm (4,921 L/min) of water. Where the water supply is not sufficient, a booster pump or a storage tank on site may be required; one hour of capacity is a typical requirement.
- **Drainage.** A significant amount of water run off occurs when FFFSs are activated. Without sufficient drainage and pumping capacity, the tunnel will start to fill with water. The drainage system must have sufficient capacity to manage this water and to pump it out of the tunnel. In many applications of an FFFS, there is a need to include flame traps in case of a liquid fuel spill or fire.
- **Environmental effects.** Water runoff from firefighting operations, including the FFFS, is typically contaminated and, depending on local regulations, oil and water separators and possible storage of water will be required for safe removal and disposal.
- **Spatial constraints and space proofing.** Space proofing considerations apply inside and outside of the tunnel:
    - **Inside the tunnel:** A water main for an FFFS can be on the order of 8 inches (0.2 m) in diameter. Dozens of valves are required, and valves can require a space on the order of 2 ft wide by 2 ft deep by 3 ft high (0.6 m by 0.6 m by 0.9 m). Pipe diameter for the branch delivery main can be on the order of 4 inches (0.1 m) in diameter.
    - **Outside the tunnel:** Water tanks, if required, must store enough water for up to one hour supply, which typically equates to 60,000 gallons (227,125 L) or more of water. This applies equally to the tunnel water treatment storage tanks.
- **Fire detection and activation strategy.** To perform the best, the PIARC document emphasizes that the fire must be detected and the FFFS activated early. Fire detection can vary from manual to automatic. Activation of an FFFS can be automatic, semi-automatic with a countdown timer to halt activation, or manual. In many cases, FFFSs are activated by a trained operator, which requires clear procedures for the operator to determine when the system should be activated. It is critical to not activate an FFFS during live traffic, as this will cause confusion for drivers and possibly a collision.
- **System integration.** System integration takes into consideration factors such as traffic control, ventilation, power supply, CCTV, operation, detection, water supply, and drainage. System integration is essential to provide the necessary supporting system functionality and reliability to achieve the FFFS design objectives. Examples of system integration are documented in a separate publication [Ref 16].
- **Interaction with ventilation.** The ventilation system can displace water droplets and disturb a smoke layer. These factors need to be considered when considering the FFFS operation to make sure both systems operate in a complimentary manner.

Other sections of the PIARC report cover topics such as system integration, research programs, and operations and maintenance. One particularly noteworthy section is Appendix 1 of the 2016

PIARC report, which provides a survey of tunnels using or considering use of an FFFS [Ref 3]. The survey contains responses that detail tunnels located in Australia, Austria, China, Denmark, Finland, Japan, Korea, Mexico, Netherlands, Spain, Singapore, Sweden, and UK.

Section 7 of the 2016 PIARC report, *Conclusions and Recommendations,* notes the following [Ref 3]:

Conclusions:

- *Extensive testing has demonstrated that FFFSs have the ability to reduce the FHRR and prevent the fire load from reaching its full potential.*
- *Where installed, maintained and operated effectively, FFFSs have a positive impact on egress by extending the available evacuation time.*
- *The length of tunnel roadway covered by FFFSs is affected by the available water supply and the tunnel width. Operation of FFFSs can reduce visibility for drivers within the area of operation… procedures should be adopted to manage traffic and operate tunnel systems without exposing motorists to additional hazards.*

Recommendations:

Where FFFSs are installed, it is essential that they are correctly designed, installed, and integrated into the tunnel system. They must be properly tested, commissioned, maintained, and operated.

- *FFFSs can be activated in the very early stages of fire development before firefighting activities commence by trained fire fighters. This allows early suppression and minimizes the potential adverse effects of the fire.*
- *FFFSs should be activated only after confirming the fire location and with the incident vehicle stopped. Clear plans and procedures are necessary for tunnel operators to activate the FFFSs.*
- *Feedback from real incidents has been limited. With increased use of FFFSs in tunnels, it is important that data of where and how FFFSs are operated in the future is captured and analyzed*.

D.3.2 UPTUN Design Guidelines

NFPA 502 provides several useful cross-references for system design. Several guidelines are available in addition, and provide general advice. The UPTUN guideline document provides some more detailed design considerations that are specifically appropriate for a tunnel environment [Ref 11]. These tunnel specific considerations might not be documented in NFPA standards for sprinkler or deluge system design, making this document a useful resource. Discussion on maintenance, spare parts, and training is also provided.

The components and design considerations that are included in the FFFS for a typical tunnel can include the following:

- Valves
- Heating or insulation
- Zones
- Activation

- Design fire
- Firefighting
- Integration
- Water supply
- Drainage
- Nozzle design
- Ventilation
- Activation policy

D.3.3 Project Design Requirements

Project design requirements for system procurement should be comprehensive and detailed. However, the level of detail will depend on the procurement method and stage of the project. Several project design requirement documents are available from previously conducted projects. Some reference projects are provided below.

Clem7, Brisbane, Australia [Ref 14]: A design-build project for a 2.9-mile (4.7 km) tunnel under the Brisbane River, with a reference design produced by Brisbane City Council, the project proponent. Engineering detail in the reference design is preliminary, with the contractor required to complete detailed design and procurement documentation. Some key extracts from the engineering design requirements related to the FFFS are [Ref 14]:

- *A deluge system must be provided to protect all roadways within the tunnel.*
- *The proposed area of operation of a deluge valve in a typical section of 30 ft wide (9 m), two lane tunnel is to be a maximum of 98 ft (30 m). The system must be designed for at least two adjacent zones to operate simultaneously.*
- *The discharge density must be 0.25 gpm/ft^2 (10 mm/min). In single lane tunnels, the length of a deluge zone must remain at 98 ft (30 m). In areas of lane merging where the tunnel is three lanes wide or more, the deluge area of operation must be no greater than the area of operation for a two-lane section of tunnel, which will result in a shorter deluge zone length.*
- *A reliable water supply equivalent to at least AS 2118 "Automatic Fire Sprinkler Systems" Grade 1 must be provided.*

Alaska Way Replacement, Seattle, U.S. [Ref 47]: This project, currently under construction, requires an FFFS installed in the new tunnel roadway spaces. The performance requirements cover about nine pages. Notable aspects include:

- Water application rate of 0.30 gpm/ft^2 (12 mm/min).

Eisenhower-Johnson Memorial Tunnel [Ref 48, Ref 49]: This project involves the retrofitting of an FFFS in the 37-year-old Eisenhower-Johnson Memorial Tunnel in Dillon, Colorado. This is the first road tunnel to have an FFFS retrofit in the U.S. Some features of the project documents include the following, which tend to be performance requirements:

- An FFFS provided as follows:
    - A system to suppress fires within the roadway space.

  - The FFFS system could consist of various fire suppression technologies, including but not limited to deluge, sprinkler, mist, or foam. A hybrid of multiple types of technologies would have been an acceptable solution. A hypoxic system had been determined to be inappropriate for this application.
- Design and construction of the fire detection system and the FFFS should limit the design fire with a growth rate of 20 MW per minute (68.2 MBtu/hr per minute) to a maximum heat release of 35 MW (119 MBtu/hr) for one hour.
- Any proprietary components should have a life span of 30 years. If these components have a life span less than 30 years, replacement components must be supplied and included the spare parts list.
- The performance of the FFFS proposed must limit the maximum heat release rate to 119 MBtu/hr (35 MW) under the following cases:
  - Fuel tanker fire, assuming rupture of the tanker and a liquid fuel spill on the roadway. The unconstrained maximum heat release rate growth had to be 68.2 MBtu/hr per minute (20 MW per minute).
  - Heavy goods truck with a fire occurring in an enclosed trailer. The unconstrained maximum heat release rate growth should be 68.2 MBtu/hr per minute (20 MW per minute).

D.3.4 Deluge and Mist Systems

Deluge and water mist systems have been applied in several road tunnel configurations. The two systems are fundamentally similar in that a series of pipes, valves, pumps, and nozzles are used to provide a zoned application of water to target a fire. The primary difference between the two systems is the size of water droplet; water mist systems use a smaller droplet size than deluge systems. The smaller droplet size of a water means that water mist systems use less water. Both systems have certain features, advantages, and disadvantages. Table D- 1 provides a summary of the system features.

Both systems have been tested for road tunnel application in full-scale test configurations. Two examples are provided below. Further discussion and details of tests is provided in Section D.5.

- **Deluge systems.** A deluge system was tested with a water application rate ranging from 0.20 gpm/ft^2 (8 mm/min) to 0.30 gpm/ft^2 (12 mm/min) on wood pallets in a test tunnel. The wood pallets had a potential peak FHRR of 511.8 MBtu/hr (150 MW). The FFFS could keep the FHRR to less than 170.6 MBtu/hr (50 MW) [Ref 50].
- **Water mist systems.** A water mist system was tested with a water application rate of 0.10 gpm/ft^2 (4 mm/min). The FHRR was 68.2 MBtu/hr (20 MW) when then FFFS was activated, and after this time the FHRR did not increase, although the estimated potential peak FHRR was 136.5 MBtu/hr (40 MW). Temperatures downstream of the fire were reduced from a range of 392 deg F to 570 deg F (200 deg C to 300 deg C) to less than 212 deg F (100 deg C) [Ref 51].

Table D- 1: Deluge and water mist system characteristics [adapted from Ref 3].

Characteristic	Deluge	Water mist
General	Open nozzles, attached to piping and arranged in zones, connected to valves that are activated to deliver water to a desired zone (i.e., location of the fire). Typically zones either side of the target zone will be activated. Typical zone dimensions are 30 ft (9 m) wide and 100 ft (30 m) long (i.e. for two lanes of traffic). Water mains are filled (wet) up to the valves.	
Drop size	0.04 inches (1,000 µm) or greater	Low pressure: > 0.02 in. (400 µm) Medium pressure: 0.008 to 0.02 in. (200 to 400 µm) High pressure: < 0.008 in. (200 µm) [Ref 11]
Pressure	21.8 psi to 72.5 psi (1.5 bar to 5 bar)	Low pressure: < 232 psi (16 bar) Medium pressure: 232 to 870 psi (16 to 60 bar) High pressure: > 870 psi (60 bar) [Ref 11]
Pipe materials	Galvanized steel, or similar depending on project requirements	Stainless steel may be required (see "Cons" below)
Proprietary specific	Deluge systems tend not to be specific to one supplier and "off-the-shelf" components used in a typical building sprinkler system can be used to construct a system	Water mist systems for tunnels are generally sold as a complete system by a specialized supplier
Fire suppression	The dominant cooling mechanism is water application to the burning surface, and cooling of the surrounding environment next to the fire. The large droplets can penetrate the fire plume.	The dominant cooling mechanism is cooling of the surrounding environment next to the fire. The droplets are smaller and entrainment into the fire plume occurs for delivery to the fire site.
Water application rate	**Japan:** 0.15 gpm/ft^2 (6 mm/min); **Australia:** 0.15 to 0.25 gpm/ft^2 (6 to 10 mm/min); **U.S.:** 0.15 to 0.30 gpm/ft^2 (6 to 12 mm/min) Two or three active zones at 30 ft by 98 ft (9 m by 30 m), at 0.25 gpm/ft^2 (10 mm/min) equates to 2,210 gpm (8,365 L/min)	Typical values quoted are 0.05 gpm/ft^2 to 0.1 gpm/ft^2 (2 mm/min to 4 mm/min), although some tunnels (A86, Paris) use up to 0.15 gpm/ft^2 (6 mm/min) [Ref 3] Two or three active zones at 30 ft by 98 ft (9 m by 30 m) zones, at 0.1 gpm/ft^2 (4 mm/min) equates to 884 gpm (3,346 L/min)
Pros	Relatively simple to design using standard sprinkler system components, potentially fewer components than a water mist system and more flexibility with materials. Potential for water application directly to the burning surface.	Potentially lower water application rate, which means this system type has advantages in retrofitting applications where space, drainage and pumping may be limited.
Cons	Larger water application rates and spatial requirements for valves, piping, drainage and pumps. Water volumes are larger and on site infrastructure can require a substantial amount of space.	More specialized equipment used due to higher pressures, increased need to keep nozzles free from blockages and filtration of the water may be needed to eliminate small particles, and less direct cooling of the fire's burning surface. Materials may need to be stainless steel to prevent corrosion and mitigate potential for particles in the water stream.

D.3.5 Water Application Rate

Water application rate is a key parameter for an FFFS design, whether the system is a deluge or water mist system. Tunnels around the world have applied a different range of water application rates, and there is no accepted methodology or standard that mandates a water application rate to achieve certain design objectives such as suppression, control, and cooling. A detailed survey of water application rates is provided in Table D-2.

CFD can model some aspects of fire suppression, and investigations have been conducted into water application rate effects [Ref 3, Ref 12]. The field of CFD is not advanced enough to make deterministic predictions of water application rate, but studies have revealed some insights that are likely to be improved on as tests and models improve [Ref 12]:

- **0.05 gpm/ft^2 (2 mm/min).** Water application rates of 0.05 gpm/ft^2 (2 mm/min) have the potential to control burning. It is more likely that this application rate provides a form of exposure protection (cooling goal as per NFPA 502).
- **0.15 gpm/ft^2 (6 mm/min).** The water application rate could keep the FHRR from reaching the unsuppressed potential.
- **0.25 gpm/ft^2 (10 mm/min).** This water application rate was a transition point. At this application rate and above the FHRR was restricted to values much less than the unsuppressed case.

Table D-2: Survey of FFFS water application rates.

Water application rate	Test programs	Examples	Standards
0.30 gpm/ft^2 (12 mm/min)	LTA tests [Ref 50]: Potential FHRR of 511.8 MBtu/hr (150 MW) was restricted to less than 170.6 MBtu/hr (50 MW). LTA tests [Ref 50]: FFFS operation was delayed until the FHRR approached 341.2 MBtu/hr (100 MW). The system could reduce the FHRR to less than 170.6 MBtu/hr (50 MW). Benelux tests [Ref 52]: The FFFS was unable to extinguish a fire within a closed vehicle. Neighboring vehicles were cooled, reducing the likelihood of fire spread.	Alaska Way Tunnel [Ref 47] (under construction)	AS 2118.3 [Ref 9]: 0.31 gpm/ft^2 (12.5 mm/min), nitrocellulose manufacturers NFPA 15 [Ref 10]: For extinguishment requires 0.15 gpm/ft^2 (6.1 mm/min) to 0.51 gpm/ft^2 (20.4 mm/min) NFPA 13 [Ref 8]: Allows 0.37 gpm/ft^2 (14.7 mm/min) for a varnish and paint dipping application (Extra Hazard, Group 2)
0.25 gpm/ft^2 (10 mm/min)	Sydney Harbor Tunnel [Ref 15]: Test vehicle was fully involved at the time of activation (flames reaching ceiling) and the fire was shielded (inside vehicles). Fire was controlled about 90 seconds after deluge activation. Arvidson [Ref 53]: An application rate of 0.25 gpm/ft^2 (10 mm/min) can provide fire suppression for an unshielded fire. For a shielded fire, all the combustibles were consumed although there was evidence of fire control once the fire burned through the shield.	Australian tunnels with 0.25 gpm/ft^2 (10 mm/min): Lane Cove, Sydney; M5 East, Sydney; Cross City Tunnel, Sydney; Sydney Harbor Tunnel, Sydney; Eastern Distributor, Sydney; Clem7 Tunnel, Brisbane; Airport Link Tunnel, Brisbane Clem7 Incident, October 2010 [Ref 54]: A car caught fire and was fully alight by the time FFFS was activated. The FFFS quickly controlled the fire.	AS 2118.3 [Ref 9]: Ammunition filling plants, explosives manufacturing, fireworks manufacturing, tar distillers NFPA 15 [Ref 10]: Not less than 0.26 gpm/ft^2 (10.2 mm/min) for exposure protection NFPA 13 [Ref 8]: Allows 0.27 gpm/ft^2 (10.6 mm/min) for an aircraft hangar (Extra Hazard, Group 1)
0.20 gpm/ft^2 (8 mm/min)	LTA [Ref 50]: Potential FHRR of 511.8 MBtu/hr (150 MW) was restricted to less than 170.6 MBtu/hr (50 MW).	Port of Miami Tunnel. Tunnels with 0.19 gpm/ft^2 (7.5 mm/min): Burnley Tunnel, Melbourne, Australia. Burnley Incident, 2007 [Ref 5, Ref 13]: Several vehicles involved, including a large truck. The fire started because of a collision. The FFFS was effective in suppressing the FHRR such that the fire service could finally extinguish the fire.	AS 2118.3 [Ref 9] 0.19 gpm/ft^2 (7.5 mm/min): Aircraft hangars, chemical manufacturers, petrochemical processing plants, paint manufacturers, resin, and turpentine manufacturers
0.15 gpm/ft^2 to 0.16 gpm/ft^2 (6 mm/min to 6.5 mm/min)	Arvidson [Ref 53]: An application rate of 0.125 gpm/ft^2 (5 mm/min) can provide fire control for an unshielded fire. For a shielded fire, all the combustibles were consumed although there was evidence of fire control once the fire burned through the shield. Japanese Road Tunnels [Ref 6]: The cooling effect for deluge has been verified during experiments, including an experiment to verify prevention of fire spread (prevented spread to two cars either side of a burning vehicle with a ventilation velocity of 985 fpm (5 m/s). A test with a fire on or within a truck showed that the fire could be extinguished when the water spray could reach the fire. If the fire was within the truck, it could not be extinguished. Fire spread from one vehicle to another is an “unshielded” process.	Midtown Tunnel, Norfolk, VA (0.15 gpm/ft^2) and Eisenhower-Johnson Memorial Tunnel, CO (0.16 gpm/ft^2) Australian tunnels with 0.16 gpm/ft^2 (6.5 mm/min): Boggo Road Busway, Brisbane; Northern Busway, Brisbane; ICB, Brisbane (sprinkler) JH experiences 10 to 16 fires per year, with two or three requiring deluge. Per accounts of significant tunnel fire incidents, the last serious fire incident occurred in 1981 [Ref 6]. Sprinklers have been included in Japanese road tunnels since at least the 1970s [Ref 6].	NFPA 13 [Ref 8]: Allows 0.16 gpm/ft^2 (6.4 mm/min) for an exterior loading dock (Ordinary Hazard, Group 2)
<0.15 gpm/ft^2 (<6 mm/min)	A water mist system was tested with a water application rate of 0.10 gpm/ft^2 (4 mm/min). The FHRR was 68.2 MBtu/hr (20 MW) when then FFFS were activated, and after this time the FHRR did not increase, although the estimated potential peak FHRR was 136.5 MBtu/hr (40 MW). Temperatures downstream of the fire were reduced from 392 to 570 deg F (200 to 300 deg C) to less than 212 deg F (100 deg C) [Ref 51].	Tunnels with less than 6 mm/min: Kemp Place, Brisbane, Australia (sprinklers)	NFPA 13 [Ref 8]: Allows 0.1 gpm/ft^2 (4 mm/min) for an automobile parking area (Ordinary Hazard, Group 1, e.g. automobile parking, electronic plants)

D.4 Incidents Involving an FFFS

An account of selected incidents is provided below. This is a summary of a few key incidents to highlight the role of FFFSs during a real fire incident and is not intended to be an exhaustive list.

D.4.1 Burnley Tunnel Fire 2007

In the most recent PIARC report, data available on real incident experience with an FFFS are limited [Ref 3]. A good account of FFFS performance in a major incident can be learned from the Burnley Tunnel fire of 2007, which occurred in Melbourne, Australia [Ref 4].

A series of collisions occurred in the Burnley Tunnel on the morning of March 23, 2007. One of the vehicles involved in the initial collision was a truck. These initial collisions resulted in a lane closure and slowing of traffic. Shortly after, a faster moving truck changed lanes and initiated a secondary series of collisions, directly impacting five cars and two other trucks [Ref 13]. A series of explosions and fires occurred because of the collisions. The remaining traffic came to a standstill behind the trucks, and people began to evacuate. In less than two to three minutes, a large fire resulted involving several vehicles [Ref 13]. Emergency ventilation and the FFFS was activated about two minutes after the fire ignition [Ref 4].

Three people were killed in this incident, all because of the initial collisions [Ref 4]. While the FFFS did not extinguish the fires, it kept the fires small enough to allow emergency services to intervene and limited damage to the structure. The Burnley Tunnel reopened to traffic only three days after the incident, as opposed to many months. After the Mont Blanc Tunnel fire, which was similar in terms of the primary fire vehicle, the tunnel remained closed for three years [Ref 13].

The Burnley Tunnel fire confirmed that FFFS performance was consistent with observations made in theoretical research and controlled tests, and clearly demonstrated the potential benefits of an FFFS. In a case where there was potential for much more serious fire, the system kept the fire in a relatively controlled state. It also demonstrated the life safety and structural protection potential of an FFFS.

D.4.2 Minor Incidents Involving FFFS

Miscellaneous minor incidents are reviewed below. These incidents are useful for providing deeper insights into the positive role FFFSs can play in a tunnel, and provide a sample of scenarios where the FFFS was proven to be effective.

- **Dartford Tunnel, United Kingdom, 2016**. A car fire caused panic among other motorists as they quickly evacuated the tunnel. The tunnel sprinkler system was deployed. No injuries were reported [Ref 55].
- **Airport Link Tunnel, Brisbane, Australia, 2015.** A small van caught fire, sprinklers were activated, and fire brigade crews extinguished the fire relatively quickly [Ref 56].
- **Airport Link Tunnel, Brisbane, Australia, March 2015.** A blown tire on a truck started a small fire. The FFFS was used during the incident, which was cleared in just over one hour [Ref 57].
- **M5 East Tunnel, Sydney, Australia, 2014.** A car fire was reported and *the tunnel's sprinkler system doused the fire to a controllable level before fire fighters made their way to the scene* [Ref 58].

- **Clem 7 Tunnel, Brisbane, Australia, 2010.** A sedan travelling in the northbound tunnel caught fire. The driver stopped and evacuated from his vehicle. Tunnel operators activated the FFFS, and successfully controlled the fire. There were first-hand accounts of people continuing to drive through the tunnel [Ref 54].
- **Over-height truck, Sydney, Australia, 2015.** An over-height truck drove into one of Sydney's tunnels, causing extensive damage to the tunnel's FFFS piping for the first 328 ft (100 m) of tunnel [Ref 59].

D.5 Fire Science – Testing and Analysis

There are numerous references to testing and analysis of FFFSs in road tunnels. This is an area of high interest and development in the industry, with ongoing research programs and independent research being performed by industry professionals.

D.5.1 Testing

A comprehensive summary of fire tests is provided in the most recent PIARC report and recently published textbooks [Ref 3, Appendix 4, Ref 4]. Some of the notable tests include the following:

- **Singapore Land Transport Authority (LTA) tests [Ref 50].** These tests were conducted on a fire load with a potential FHRR of 511.8 MBtu/hr (150 MW). The tests showed that a water application rate for a large drop deluge system in the range of 0.2 gpm/ft^2 to 0.3 gpm/ft^2 (8 mm/min to 12 mm/min) was sufficient to reduce or keep the FHRR to less than 170.6 MBtu/hr (50 MW). In one test, the activation of the FFFS was delayed and the FHRR reached around 341.2 MBtu/hr (100 MW). Once the system was activated, it reduced the FHRR.
- **Safety of Life in Tunnels (SOLIT) Tests 2008 and 2012 [Ref 60, Ref 61].** Many fire tests were carried out in the San Pedro de Anes Tunnel in Spain to test water mist systems. Test data demonstrated that the fires were controlled and the FHRR was kept below the potential peak FHRR [Ref 60]. Tests conducted during 2012 involved wood pallets and diesel pools with water mist systems activated to control the fires [Ref 61]. Wood pallet fires were restricted to 51.2 MBtu/hr (15 MW) for unshielded fires and 102.4 MBtu/hr (30 MW) for shielded fires.
- **SP Technical Research Institute of Sweden (SP) Tests [Ref 62].** A series of six tests were conducted by SP in 2013. The fuel was wood pallets. A peak FHRR of 341.2 MBtu/hr (100 MW) was estimated. A water application density of 0.25 gpm/ft^2 (10 mm/min) was applied. The FFFSs were activated after detection, based on a gas temperature of 286 deg F (141 deg C). Due to the FFFS, the FHRR was restricted to less than 170.6 MBtu/hr (50 MW). There was a target fuel of wood pallets positioned 16 ft (5 m) from the fire and the FFFS prevented fire from spreading to the target.

The Sydney Harbor Tunnel was one of the first Australian road tunnels to include an FFFS. The operator of the tunnel regularly conducts tests in the tunnel where a full-scale car is burned and the FFFSs are deployed [Ref 15]. A test conducted in 2008 was instrumented to record temperatures and radiation heat flux, and filmed to document the performance of the FFFS. The peak FHRR was on the order of 17.1 MBtu/hr (5 MW). Radiation heat flux was recorded to the side of the vehicle and the peak level was on the order of 6,974 Btu/(hr·ft^2) (22 kW/m^2). When the FFFSs were activated, the heat flux decreased to less than 634 Btu/(hr·ft^2) (2 kW/m^2) within seconds of the FFFS activation [Ref 15]. Temperature measurements showed similar rapid reduction once the FFFSs were activated. The published paper provides screen shots from the video, which clearly show the ability of the FFFS to control the fire. Two particularly interesting points from the video screen shots are that: (1) The FFFS took about 30 seconds after activation to achieve a good flow of water; and (2) The fire was somewhat shielded from the FFFS spray, yet the FFFS had a controlling effect on the fire.

D.5.2 Analysis

CFD analysis is a useful tool to provide cost effective analysis of the impact of FFFSs on tunnel fires. CFD models with a prescribed FHRR can be used with a high degree of confidence to predict fire cooling. Published studies are available which validate CFD models for prediction of temperature when the FHRR is prescribed and the FFFS is activated [Ref 63, Ref 64]. Methods to predict FHRR with CFD are less advanced and still under development. At present, results from full-scale tests are relied on to quantify the impact of the FFFS on the FHRR [Ref 3, Appendix 4].

One active area of discussion in the industry centers on whether an FFFS can be used to offset or reduce other design features such as ventilation or structural fire protection.

For ventilation, several published studies show that FFFSs can reduce the critical longitudinal velocity for smoke control:

- A reduction in critical velocity was observed due to the cooling effect of the water for a 341.2 MBtu/hr (100 MW) FHRR. Critical velocity went from 660 fpm (3.35 m/s) with no FFFS, to 540 fpm (2.75 m/s) with an FFFS operating at 0.2 gpm/ft^2 (8 mm/min) [Ref 65]. This analysis had no reduction in the FHRR modelled due to the FFFS application. A reduction in the thrust required from jet fans, used for a longitudinally ventilated tunnel, was also determined based on the lower gas temperatures downstream.
- The velocity to control smoke was reduced by around 50 fpm (0.25 m/s) when the FFFS was considered [Ref 66]. The FFFS water was found to absorb between 35 percent and 60 percent of FHRR energy for the range of FHRRs investigated.

For passive fire protection, there is a reduction in the gas and wall temperatures due to activation of the FFFS. Whether this temperature reduction is enough to eliminate passive fire protection is dependent on the specific situation, but the practical experience is that the FFFS protects the structure and allows for a quicker reopening of the tunnel following a major incident (see Section D.4.1). Studies of ceiling and wall temperatures due to FFFS activation during a fire include the following:

- A modified time-temperature curve for the structure, based on inclusion of an FFFS, was developed using results from CFD simulations [Ref 67]. The authors argue that a reduction of the FHRR from 682.4 to 341.2 MBtu/hr (200 MW to 100 MW) is reasonable for a tunnel with an FFFS included. A significant reduction in ceiling temperature is reported.
- CFD analysis was used to investigate wall temperatures for a large heavy goods vehicle fire of 341.2 MBtu/hr (100 MW) [Ref 68]. Like previous studies, analysis showed that the heat-affected area of tunnel was greatly reduced when the FFFSs were operated. A model of tunnel spalling was also included, and the area of damage to the tunnel was vastly reduced when the FFFSs were included.

Analysis of FFFSs is an evolving practice. As more testing is conducted and experience is developed, it may be possible to use this analysis to justify savings in other fire safety provisions when the FFFSs are included. A key component if this determination will be the reliability of the FFFS, as the process of optimizing design features means there is an increased risk due to possible FFFS failure. Although the overall risk is small, it is still significant due to the consequences of system failure in a large fire event. Therefore, risk analyses and cost-benefit considerations will form one part of the decision-making process in this area. The risk analysis is a useful tool because it allows uncertainty such as system reliability and performance to be considered [Ref 41].

D.6 Other Perspectives

Two other important stakeholders in the consideration of FFFSs in road tunnels include fire brigades and the insurance industry. These stakeholders are important at the design and operational phases of FFFS projects and both entities are important and deciding voices in deciding to install an FFFS in a road tunnel.

D.6.1 Fire Brigade

Fire brigades are generally in favor of active fire protection systems, such as sprinklers, in most facilities. This is reflected in fire codes, where some jurisdictions require an FFFS to be installed [Ref 42, Ref 2]. It is useful to review lessons learned by fire brigades in jurisdictions where FFFS have been employed in a road tunnel.

The Australasian fire brigade experience with FFFSs in road tunnels, both in real incidents and exercises, is generally positive. However, the systems are more complex in a tunnel than a building, and there is a strong need for frequent training and exercises to provide the fire brigade and tunnel operators with clarity on operation and use of the systems [Ref 69]. Some experiences, documented in recent conference proceedings, are outlined below and offer valuable lessons for designers and operators.

The intuitive reaction to the impact of FFFSs in a road tunnel is that the systems would surely help firefighting operations. While this is true, the volume of water introduced to the region of a fire causes problems including:

- **Loss of visibility.** This can hinder the ability of the fire crew to locate the fire and create a collision hazard. It also can make it difficult for search and rescue operations. In a car fire in the Clem7 Tunnel, one of the firefighter's comments was that *the deluge was so thick that the crew almost ran into the car in question* [Ref 69]. The loss of visibility can also interfere with fire brigade operations to establish the number of vehicles, whether dangerous goods are involved, and whether people need rescue.
- **High level of noise.** Noise from the FFFS can interfere with person-to-person and radio communications. In a car fire in the Clem7 Tunnel, one of the firefighter's comments was that *the force and noise of the deluge made it impossible to use radio communications* [Ref 69].

Road tunnels in Australia and New Zealand that employ FFFSs typically rely on a trained human operator to identify the fire location on the CCTV system and activate the FFFS. Automatic activation systems are installed, but usually used only as a backup. The high degree of surveillance required for a road tunnel's normal operations means that operational staff are usually aware of a potential fire and able to respond well before any automatic detection system has been activated or fire brigades arrive are on site. Given that it can take up to 30 minutes for a fire brigade to arrive on site and be prepared to act, there is a benefit to relying on a trained tunnel operator to act during an incident [Ref 69].

A fire in a road tunnel is a different situation to the one fire brigades face most commonly, a fire in a building. In buildings, fire protection systems tend to be automatically activated. This difference means that there is a significant need for firefighter education and familiarization with tunnel facilities and operational procedures to avoid confusion and delay in responding to an incident [Ref 69]. Some factors encountered by firefighters, that are unusual relative to a typical building, include the following [Ref 69]:

- **Volume of water.** A typical water flow rate from an FFFS can be on the order of 1,300 gpm (4920 L/min). This water is potentially contaminated, and when it flows away from the zone of application the volume is such that it will not be restricted to the zones of operation. Other systems such as separators, sumps, pumping, and storage will be relied on [Ref 69].
- **Wet fire fighter clothing.** Wet firefighting clothing can be hazardous to firefighters because the wet clothing does not provide full thermal protection [Ref 69]. When a firefighter enters an active FFFS zone, they will be soaked. The volume of water typically applied (0.15 gpm/ft^2 to 0.25 gpm/ft^2) (6 mm/min to 10 mm/min) is well beyond a 1-in-100-year tropical downpour (0.07 gpm/ft^2 (2.8 mm/min) [Ref 70]). It can be necessary for a firefighter to enter an active FFFS zone, and there is a need for the fire brigade to have sufficient resources that assure enough personnel are available to safely respond [Ref 69].
- **Activation and deactivation of an FFFS.** Normal fire brigade operations regarding sprinklers in buildings involves activating or deactivating valves as required. In road tunnel FFFSs, the fire brigade may need to deactivate the FFFS to approach the fire. When doing this, there is a risk that the fire could flare up. As such, procedures need to be in place to make sure fire hoses are in position and charged to enable direct application to the seat of the fire. Deactivating the FFFS should occur in close coordination with tunnel operations [Ref 69].
- **FFFS zone identification.** FFFSs are typically zoned, with a zone length of around 100 ft to 200 ft (30 m to 60 m). The tunnel operator will identify the zones where it is necessary to activate the FFFS, usually via the CCTV system. If the fire brigade need to deactivate or activate zones, they will need clear means to identify the correct zone and must be able to stop one zone and start another. Visibility is frequently very restricted, and several attempts may be needed to accurately target the fire [Ref 69].
- **Ventilation.** Operation of the ventilation system is important because it is usually coordinated with FFFS zone operation. Changes to the ventilation system during the incident can affect smoke movement, possibly clashing with firefighting operations [Ref 69].

The factors above all point to a need to work closely with fire brigades during the design and operation of the FFFS to achieve the purported benefits of FFFSs. The practice of emergency exercises, where the FFFSs are activated inside the tunnel, is one way that fire fighters and operators can better familiarize themselves with systems, procedures, and the likely environment during a fire.

D.6.2 Insurance Industry

The insurance industry's interest in FFFSs is primarily concerned with asset protection and the cooling potential of sprinklers. The benefits of FFFSs in incidents such as the Burnley Tunnel are known in the industry [Ref 71]. A research article from the insurance industry recommended inclusion of "automatic water-based firefighting systems" unless engineering analysis can be used to prove that other systems are sufficient to provide safety and mitigate property loss [Ref 72]. Major fires such as the Channel Tunnel fire and Mont Blanc Tunnel fire have caused damage on the order of several hundred million dollars for each incident, and FFFSs are sparking interest in the industry as a fire protection method. Further developments may arise in the road tunnel environment in coming years, and they will in part be motivated by the requirements of insurers seeking assurance that property is adequately protected.

D.7 Global Perspectives

D.7.1 Survey of Tunnel Owners and Operators

Two questionnaires were developed to collect data pertinent to the desktop study. One questionnaire focused on the tunnel owner's perspective regarding an FFFS, and the other questionnaire focused on the tunnel operator's perspective, refer to Section D.8 and Section D.9. The questionnaires were sent to countries with major highway tunnels using FFFSs. The countries were selected to supplement and confirm information contained in the PIARC document [Ref 3].

D.7.2 Comparison of U.S. Practice to International Practice

Installations of FFFSs in U.S. road tunnels must comply with U.S. codes and standards to the extent that the tunnel owner or the AHJ adopts them. For road tunnels, the industry standard is NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways [Ref 1]. NFPA 502 references other standards, such as NFPA 13, NFPA 15, and NFPA 750, which cover deluge and mist spray systems. NFPA 502 does not explicitly require FFFSs to be installed in road tunnels, but does provide requirements for the design of such systems when they are elected to be installed. NFPA 502 also invokes NFPA 25 for inspection, testing, and maintenance requirements of any type of FFFS.

The U.S. approach to determination of water application rate is based on the mode of cargo transport. Because so much cargo travels in enclosed trailers, fire is assumed to be shielded from the water spray. This means that the design objective is fire growth control, and the primary objective is to prevent the spread of fire to other vehicles. In addition to knowledge derived from guidelines and best practices, analysis and modeling is used to determine a water application rate that accomplishes this objective. Concurrence with the approach is sought from the AHJ. Once all parties agree, detailed analysis and design of the FFFS is performed. In Japan and Australia, water application rate is typically mandated by standards or project requirements.

Until recently, only the City of Seattle required installation of FFFSs in their road tunnels. This requirement first began back in 1952, with the construction of the SR99 Battery Street Tunnel. Since then, FFFSs have also been installed in the Mount Baker Ridge and Mercer Island Tunnels along I-90 as well as the I-5 Convention Center Tunnel. The new two-mile-long Alaskan Way Viaduct Tunnel currently under construction will also incorporate an FFFS. FFFS installations are also required in the city's transit and bus tunnels.

In Boston, during the 1990s planning of the Central Artery/Ted Williams Tunnel Project, the city's fire brigade decided not to require the installation of an FFFS. This decision was partially based on poor operational experiences with FFFSs that had been installed in Boston's Central Artery North Area (CANA) Tunnel. After a series of false alarms and accidental activations that tunnel's FFFSs remain deactivated.

Consistency in the application of FFFSs in road tunnels varies throughout the U.S. This is partially due to the current recognized U.S. standard for road tunnel fire protection and life safety requirements. NFPA 502 leaves the determination of requiring an FFFS to the local authorities or agencies having jurisdictional responsibility for the facility. Recently opened road tunnels, including the Devil's Slide Tunnel and the Caldecott Tunnel 4th Bore, are not equipped with an FFFS. However, other recently completed U.S. road tunnels have been designed with FFFSs. This includes the Presidio Parkway Tunnel in San Francisco, the Elizabeth River Midtown Tunnel in Norfolk, Virginia, and the Port of Miami Tunnel.

Several older U.S. road tunnels have recently been, or are planned to be, refurbished and upgraded. So far, these refurbishments have not included the addition of FFFSs. The reasons for this include existing spatial constraints, insufficient drainage systems, and cost. As mentioned previously, the 37-year-old Eisenhower-Johnson Memorial Tunnel in Dillon, Colorado was recently retrofitted with an FFFS after it was determined by the tunnel operator that such a system was necessary to allow safe passage of the local traffic mix.

D.7.3 Status of FFFS Application in International Road Tunnels

Internationally, the countries with the most experience with FFFSs in road tunnels are Japan, New Zealand, and Australia. This is primarily because FFFSs are either legislatively required or requirements are motivated by previous application precedence and the AHJ. The almost universal use of FFFSs in Australian road tunnels was based on their prior use in the Sydney Harbor Tunnel. Rather than following a discernment process to support the use of FFFSs, implementation was based on precedence.

The need to include an FFFS in a road tunnel facility is determined by a variety of parameters. In Japan, New Zealand, and Australia, the use of an FFFS is predetermined by local codes and ordinances. These codes and ordinances typically require the use of an FFFS for high-traffic volume tunnels of a minimum length, or for tunnels that permit the bulk transport of flammable or hazardous cargoes. In many parts of the world, including the U.S. and many European countries, there are no prescriptive requirements for the installation of an FFFS; determination of the need for an FFFS is relegated to the tunnel's owner or jurisdictional authority. In these cases, important contributors to the decision-making process include fire risk assessment, capital and life cycle costs, vehicle mix and transported cargo, traffic volumes, other available tunnel safety systems, and socio-economic impacts due to potential loss of use of the facility.

D.8 Tunnel Operator/Owner Survey

Facility Characteristics

Name:

Contact details:

Tunnel agency:

Tunnel name:

Tunnel built/opened:

Is the tunnel under supervision?

- ☐ 24-hour supervision
- ☐ Supervised, except at night time
- ☐ Not supervised
- ☐ Other (please specify):

What type of vehicles use the tunnel?

- ☐ Cars only
- ☐ Cars/buses only
- ☐ Cars/buses/trucks
- ☐ Hazardous cargo vehicles
- ☐ Other (please specify):

Fire safety provisions (tick those that apply):

- ☐ Ventilation
- ☐ Fixed firefighting system (FFFS)
- ☐ Standpipe
- ☐ Fire extinguishers
- ☐ Egress passages
- ☐ Traffic control
- ☐ Emergency response plans
- ☐ Other (please specify):

If you ticked “Fixed firefighting system (FFFS)” please continue to the next page

Sprinklers / Fire Suppression Systems / FFFS

What criteria are used to determine whether to install an FFFS?

- ☐ Standard or code (note which one if known):
- ☐ Local fire brigade requirement
- ☐ Other (please specify if known, such as a special feature of the tunnel such as length, location, number of lanes, traffic volume, allowance of hazardous cargo transportation):

What standards, codes or guidelines were used to design the FFFS:

- ☐ NFPA, ISO, EU (please specify which documents if known):
- ☐ No specific requirements, custom for tunnel application (please note any details):

What type of FFFS?

- ☐ Water mist
- ☐ Deluge
- ☐ Foam system
- ☐ Automatic sprinklers
- ☐ Water application rate (if known):

Has the system ever been used for a fire event, was it effective (check boxes below as applicable, additional space provided on the back page for more events)?

- ☐ Yes:
  ☐ Car ☐ Bus ☐ Truck ☐ Other (please note)
  ☐ FFFS not effective ☐ Fire significantly suppressed ☐ Fire extinguished
- ☐ Any other remarks:

How is the FFFS activated during a fire emergency?

- ☐ Operator (human) activation from local/remote control room after confirmation of fire
- ☐ Other considerations (for operator (human) activation)
  - Smoke visible
  - Flame visible
  - Traffic stopped
  - Motorist evacuation complete
  - ☐ Other (please note)
- ☐ On site activation by fire brigade
- ☐ Automatic activation based on a fire detection system

Has there ever been a discharge of the FFFS during live traffic (please check boxes below as applicable)?

- ☐ Yes:
  - ☐ System malfunction
  - ☐ Human error
  - ☐ Fire
  - ☐ Other (please note)
- ☐ Impact of discharge:
  - ☐ No impact
  - ☐ Short disruption
  - ☐ Tunnel closure
  - ☐ Accident

What readiness testing of the FFFS is conducted?

- ☐ Regular system maintenance tests at isolation valves
- ☐ Full discharge of the FFFS onto the roadway during a closure
- ☐ Full discharge of the FFFS onto a controlled fire / burn

How frequently does FFFS maintenance require a tunnel closure?

☐ Monthly ☐ Quarterly ☐ Semi-annually ☐ Annually

Additional Information / Questions

Please provide any additional information related to the following topics:

- ☐ Local fire brigade testing of the FFFS

  ____
- ☐ Special expertise needed from tunnel maintenance personnel

  ____
- ☐ Special equipment or suppliers needed to maintain the system

  ____
- ☐ Any significant system repairs needed, such as pipe replacement due to freezing, vehicle impact, corrosion

  ____
- ☐ System reliability

  ____
- ☐ Construction issues

  ____
- ☐ Freezing problems or other natural environment impacts

  ____
- ☐ Any other remarks:

  ____

Additional Fire Events

Has the system ever been used during a fire event, was it effective (check boxes below as applicable, additional space provided on the back page for more events)?

- ☐ Yes:
  ☐ Car ☐ Bus ☐ Truck ☐ Other (please note)
  ☐ FFFS not effective ☐ Fire significantly suppressed ☐ Fire extinguished
- ☐ Any other remarks:

Has the system ever been used during a fire event, was it effective (check boxes below as applicable, additional space provided on the back page for more events)?

- ☐ Yes:
  ☐ Car ☐ Bus ☐ Truck ☐ Other (please note)
  ☐ FFFS not effective ☐ Fire significantly suppressed ☐ Fire extinguished

Any other remarks:

D.9 Agency Survey

Agency Characteristics

Name:

Contact details:

Agency:

Sprinklers / Fire Suppression Systems / FFFS

What criteria are used to determine whether to install an FFFS?

- ☐ Standard or code (note which one if known):
- ☐ Local fire brigade requirement
- ☐ Other (please specify if known, such as a special feature of a tunnel such as length, location, number of lanes, traffic volume, allowance of hazardous cargo transportation):

What standards, codes or guidelines are used to design the FFFS:

- ☐ NFPA, ISO, EU (please specify which documents if known):
- ☐ No specific requirements, custom for tunnel application (please note any details):

Is there a policy for a particular kind of FFFS?

☐ Yes
☐ No
If "yes", what type of system:
☐ Water mist
☐ Deluge
☐ Foam system
☐ Automatic sprinklers
☐ Water application rate (if known):

What is the policy for FFFS activation during a fire emergency?

- ☐ Operator (human) activation from local/remote control room after confirmation of fire
- ☐ Other considerations (for operator (human) activation):
  - o Smoke visible
  - o Flame visible
  - o Traffic stopped
  - o Motorist evacuation complete
  - o Other (please note)
- ☐ On site activation by fire brigade
- ☐ Automatic activation based on a fire detection system

Has there ever been a discharge of the FFFS during live traffic in your facilities (please check boxes below as applicable)?

- ☐ Yes:
  - ☐ System malfunction
  - ☐ Human error
  - ☐ Fire
  - ☐ Other (please note)
- ☐ Impact of discharge:
  - ☐ No impact
  - ☐ Short disruption
  - ☐ Tunnel closure
  - ☐ Accident

Additional Information / Questions

Please provide any additional information related to the following topics:

- ☐ Local fire brigade testing of the FFFS

  ____
- ☐ Special expertise needed from tunnel maintenance personnel

  ____
- ☐ Special equipment or suppliers needed to maintain the system

  ____
- ☐ Any significant system repairs needed in specific facilities, such as pipe replacement due to freezing, vehicle impact, corrosion, or system rehabilitations

  ____
- ☐ System reliability policy / requirements

  ____
- ☐ Construction issues

  ____
- ☐ Freezing problems or other natural environment impacts

  ____
- ☐ Any other remarks:

  ____

Fire Events

Have any of your tunnels with an FFFS experienced a fire where the FFFS was used, was it effective (check boxes below as applicable, additional space provided on the back page for more events)?

☐ Facility name:
☐ Date of incident:
☐ Yes:
  ☐ Car ☐ Bus ☐ Truck ☐ Other (please note)
  ☐ FFFS not effective ☐ Fire significantly suppressed ☐ Fire extinguished
☐ Any other remarks:

Have any of your tunnels with an FFFS experienced a fire where the FFFS was used, was it effective (check boxes below as applicable, additional space provided on the back page for more events)?

☐ Facility name:
☐ Date of incident:
☐ Yes:
  ☐ Car ☐ Bus ☐ Truck ☐ Other (please note)
  ☐ FFFS not effective ☐ Fire significantly suppressed ☐ Fire extinguished

Any other remarks: